Ad Hoc Study of Certain Safety-Related
Aspects of Double-Bottom Tankers
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AD HOC STUDY OF CERTAIN SAFETY-RELATED ASPECTS OF DOUBLE-BOTTOM TANKERS

Final Report

Contract No. MPA-78-002A

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Highway Safety
Research Institute

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16. Abstract

In light of rising concern of the number of accidents of fuel-carrying "double-bottom" tankers, the Governor of the State of Michigan requested, and the Office of Highway Safety Planning, State of Michigan, supported this study. A research study is described examining the stability of Michigan double tankers relative to other fuel-hauling vehicles. A means for modifying double tankers so as to improve dynamic stability is developed and demonstrated in full-scale tests. The study concludes that the Michigan double bottom is a uniquely hazardous vehicle with a propensity for rollover of the second trailer, particularly in accident-evasion maneuvers. The modified double is seen to yield a factor of two improvement in stability over the baseline double.

It is recommended that use of the present Michigan double tanker be discontinued. In the near term, use of the modified version of the vehicle is advocated. It is suggested that safer vehicles for the future can be designed using existing technology. In making recommendations, consideration is given to both the stability of individual vehicles and to accident exposure issues involving the overall makeup of the tanker fleet.

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Amoco Corporation

Dearborn Transportation Company

Ray Molder Corporation

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1.0 INTRODUCTION

This document constitutes the final report on a research study entitled "Ad Hoc Study of Certain Safety-Related Aspects of Double-Bottom Tankers," sponsored by the Office of Highway Safety Planning, State of Michigan.

The project was requested by the Governor of Michigan, William G. Milliken, to provide information concerning special safety problems which have arisen in the use of heavy tankers hauling flammable fuels. Tanker safety in Michigan became an emergency level issue in late 1977 as a result of a rash of accidents, primarily in the Detroit area, involving tankers of the so-called "double-bottom" configuration. Following a number of rollover accidents which included large gasoline fires, a certain hypothesis began to develop that Michigan's large double tankers possessed peculiarly low levels of rollover stability. The subject study was designed primarily around this hypothesis.

This project was "ad hoc" in character insofar as it has addressed, in a limited term, only the immediate problem of rollover stability of a specific vehicle configuration. Further, among many vehicle designs which can be generically classed as double-bottom tankers, this study has focused on the largest of such vehicles, the eleven-axle, 17,000-gallon double with 55 feet nominal length, hereafter referred to as the "baseline double-bottom tanker." The term "double-bottom tanker" pertains to a tank-type vehicle comprised of two trailers which are towed by an independent power unit, or tractor. The "-bottom" designation is simply a popular jargon term held over from an earlier era of the trucking industry and, perhaps, originating in nautical terminology, referring to a cargo-carrying space in a vessel (or vehicle).

In Michigan, double-bottom tankers and other heavy transport vehicles are built to fit within a road-use formula which constrains

the number of axles, the loading and spacing of those axles, and also the outside vehicle dimensions, but which permits unusually large gross vehicle weights. The vehicle of focal interest here is typically loaded to 152,000 pounds gross weight and the load is carried at a high center of gravity. This vehicle was chosen as the baseline because it appears to be the most numerous in the fleet of double tankers hauling flammable fuels, and because certain features of the vehicle suggest a rollover stability level which will be the lowest among double tankers.

The project has sought to evaluate the rollover stability level of the baseline vehicle through both analytical and experimental efforts. Upon determining that the baseline double was exceptionally low in rollover stability, efforts were then devoted to determining a means of modifying existing vehicles so as to improve safety performance. A field survey task was also conducted to evaluate the patterns of tanker usage in normal fuel transport service.

The study is primarily an exercise in vehicle dynamics research, dwelling heavily upon mathematical analysis for investigating vehicle stability matters and then applying techniques of experimentation to obtain the hard numbers needed in making safety policy decisions. Recognizing that the project is of immediate public and legislative interest but has been heavily technical in nature, we have chosen to arrange the report in a way that meets the needs of different types of readers:

1) Persons without interest in technical details can get an overview of the results by reading the discussion in Section 2.0, as well as by consulting the conclusions and recommendations, Sections 4.0 and 5.0, respectively.

2) Any reader desiring to assess the manner and depth of the approach used here can obtain a summary view of these in Section 3.0, "Tasks of the Study."

3) The technical community, particularly those concerning themselves with engineering analysis, would be advised to consult Appendices A, B, and C for a satisfactory level of explanation of methods.

Other appendices present the following material:

Appendix D - Detailed results of the field survey of tanker operations, including raw and processed data obtained from the on-site survey of 14 fuel terminals in Michigan.

Appendix E - Maneuverability of tankers—presenting measurements of the different amounts of space needed to maneuver different tankers in and around service stations.

Appendix F - Estimation of the relationship between tank volume, rollover stability, and rollover accident involvement. This appendix discusses the exposure of Michigan traffic to tanker rollover accidents, as it derives from the combined effects of numbers of tankers in service and relative rollover stability of the various types of vehicles making up the fleet.

Appendix G - Maximum structural loading to be expected on modified double-bottom tankers. A set of loading conditions are defined which constitute a design aid for those seeking to analyze structural stresses on modified doubles.

Regarding conclusions and recommendations, we must emphasize that only a limited effort has been applied here to a problem having many complexities. The study has been designed to obtain accurate

measurements of only a few factors, general estimates of many more factors, and only a simple basis for understanding of others. Nevertheless, certain conclusive statements and recommendations are judged to be warranted, even though they extend beyond the set of factors which were accurately measured. Such judgments can only be defended in the light of the state-of-the-art of vehicle dynamics research, particularly as it has advanced in the last eight to ten years in heavy vehicle areas.

2.0 DISCUSSION OF RESULTS

The study has provided two basic categories of results—those that pertain to the baseline double-bottom tanker, and those that pertain to the same vehicle when modified by certain hardware changes. In this section, the findings pertaining to the stability of both vehicle configurations will be discussed, along with other considerations pertinent to tanker safety.

2.1 Baseline Double-Bottom Tanker

As will be detailed later, we find the baseline double-bottom tanker to be exceptionally low in dynamic stability. The basic mechanisms underlying this low level of stability involve the interactive motions of the four elements of this vehicle—tractor, semi-trailer, dolly, and pup trailer, as shown in Figure 2.1. Analysis

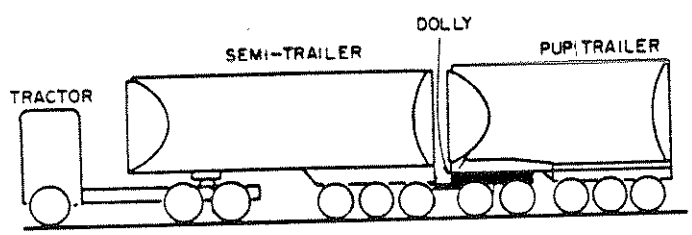

Figure 2.1. Baseline double-bottom tanker.

and tests show that the dominant yawing* motions arise as an interaction of the dolly and the pup trailer. This interactive mode of motion is the one which has been most easily observable by motorists

*Jargon terms which are often applied to describe this phenomenon are "swaying, snaking, whipping, whipsawing," and the like. The term "yawing" is proper to the study of vehicle dynamics, applying to rotations of a vehicle in the yaw degree of freedom; i.e., around a vertical axis of rotation.

traveling behind conventional double-bottom tankers. As components of the hitching mechanism become worn, this interactive dolly-pup motion can be self-sustaining at higher speeds. Also, even with new hitch hardware, analysis shows that this motion will self-sustain at highway speeds if the pup trailer is operated with only its aft fluid compartment loaded.

The primary safety issue, however, is not simply determined by the vehicle's ability to sustain steady oscillations, but rather by its tendency to produce exaggerated motions of the pup trailer during accident-avoidance maneuvers. This characteristic, by which the pup trailer experiences an amplified yawing motion in response to a fast lane change initiated at the tractor, results in premature rollover of the pup trailer. It is suggested that this anomaly accounts for the preponderance of accidents in which the pup trailer rolls over by itself, leaving the tractor and semitrailer still standing.

In technical terms, it was found that the pup trailer of the baseline double reaches a rollover threshold at a tractor "lane change level" of 0.17 g, lateral acceleration. This measure, pertaining to the reference lane change described in Appendix A, establishes a limit condition against which other vehicles can be measured. The reference lane change is characterized by a form of steering wheel rotation which starts on center, goes left, then right and then back to center—over a two-second time period. This form has been used in numerous research studies investigating the dynamic properties of cars, trucks, and tractor-trailers [e.g., 1, 2, 3].

When this emergency lane-change maneuver is conducted with the baseline double at a speed of 45 mph, we find that the pup trailer amplifies the tractor motions by a factor between 2 and 3. Observing that the height of the pup trailer's center of gravity is only about 1.2 times that of other conventional fuel tanker vehicles, we clearly see that the dominant problem regarding the double-bottom tanker involves the exaggerated yawing motions and not merely the higher center of gravity. Further, since the design of the baseline

double affords no rollover restraint in the coupling between the semi and the pup trailer, the free rollover of the pup trailer is a ready conclusion to the amplified yawing.

An additional design feature which further reduces the roll stability of the double tanker, but which is known to be common to most other commercial vehicles, is the free clearance which exists in the vertical travel of the suspension springs. This free travel permits the tank body to rotate through part of its roll motion without any spring restraining mechanism at work. Accordingly, a 10-15% reduction in dynamic roll stability was seen to derive simply from this suspension detail. While this feature is not unique to the double-bottom tanker, it was clear that elimination of these excessive clearances would help to increase the double's depressed stability level.

Regarding other conditions in which loss of control can endanger the double-bottom tanker, three additional types of incidents should be mentioned. Blowout of a tire on the steering axle of the tractor is a hazard which has apparently accounted for certain of the recently logged accidents with doubles. Two observations are in order here. First, the blowout of a tire on a double tanker vehicle should be no more likely than blowout incidents on other comparably loaded vehicles. Although heavy double tankers operate with high levels of front axle load, it appears that the properly up-sized tires are always being employed. When a tire does blow out on the steering axle, however, a common occurrence is loss of control such that the vehicle may abruptly depart from the roadway. In such situations, the baseline double tanker could experience the same yawing type of response such as causes rollover in an emergency lane change. Thus the tire blowout hazard which is peculiar to the baseline double tanker can be viewed, not as something intrinsic to blowout events, but rather as another case of the hazard involved in exaggerated yawing motions.

Another incident which has precipitated certain of the recorded accidents is jackknife of the tractor. This phenomenon

involves a large uncontrolled rotation of the tractor, usually concluding with the tractor's cab striking the semitrailer. Total loss of control of the vehicle ensues and a variety of final accident scenarios can result, including departure from the roadway, rollover, and impact with other objects. We see no aspects of the jackknife hazard, however, which are peculiar to the double-bottom tanker. Rather, jackknife is recognized as a hazard which imperils all tractor-semitrailers, resulting in 4-5% of all serious tractor-trailer accidents nationally.* Indeed, we suggest that the greater maneuverability of double-trailer vehicles actually renders jackknife less likely than is the case for large, single semitrailers such as incorporate, for example, 6, 7, and 8 axles.

Regarding loss of control during heavy braking, it would appear that the multiple pivot points of the baseline double yield a somewhat greater hazard. The hazard consists in the likelihood that the dolly or pup trailer elements could pivot rapidly under certain conditions of brake imbalance, disturbing the vehicle to the point of rollover. While this condition is not seen as the primary problem with the double, any vehicle modifications which constrain or eliminate pivot motions on the vehicle would be seen as desirable for reducing hazards associated with heavy braking.

2.2 Modification of the Double-Bottom Tanker

Since the primary stability problem with the double tanker consists not in an essential property like c.g. height, but rather in the amplified yawing motions which lead to rollover, a practical set of hardware modifications serving to upgrade the safety of the double is feasible. The primary functions of such modifications are to:

1) tame the oscillatory behavior of the pup trailer,
2) rigidly couple the pup trailer to the semitrailer so as to arrest the free roll motion of the pup, and

*Based upon analysis of the accident files gathered by the Bureau of Motor Carrier Safety, U.S. Dept. of Transportation.

3) provide that the springs restrain the rolling of the tank body throughout the full range of motion.

In this study a set of modifications were analyzed, designed, and constructed. The modifications are viewed as a package of retrofits which may be applied to the existing fleet of double tankers—not as an approach toward constructing new vehicles.

The modified double incorporates an altered drawbar hitch connecting the two trailers and a number of bolts which are added to the trailer suspensions to take up the excessive clearances in the spring travel. The hitch mechanism is the primary modification improving the stability of the double, serving to greatly reduce yawing motions while also coupling together the roll action of both trailers. Yaw motions are reduced because the modified hitch eliminates one pivot in the vehicle train, causing the dolly to track directly behind the semitrailer.

Analyses and tests of the modified double tanker show that at least a factor of two improvement in dynamic stability is gained over the performance level of the baseline double. Measured in the emergency lane-change test, the modified double is stable in tractor maneuvers up to the .33 to .37 g level. In Figure 2.2, the baseline and modified doubles are most directly compared by way of the lateral acceleration waveforms prevailing at the tractor at the limit maneuver level. We see that the modified double reaches its stability limit with a much larger wave than the baseline double—reflecting the fact that a much more severe maneuver can be handled in a stable fashion. Figure 2.2 also shows that the modified double exhibits a limit performance which is virtually the same as that of the "short single" tractor-semitrailer (i.e., the tractor-semitrailer which remains when the pup trailer is removed from the double tanker).

The baseline double, modified double, and short single are the three vehicle configurations which were physically tested. To assist in interpretation of these data, Figure 2.3 shows the measured stability limits of the three test vehicles, together with the

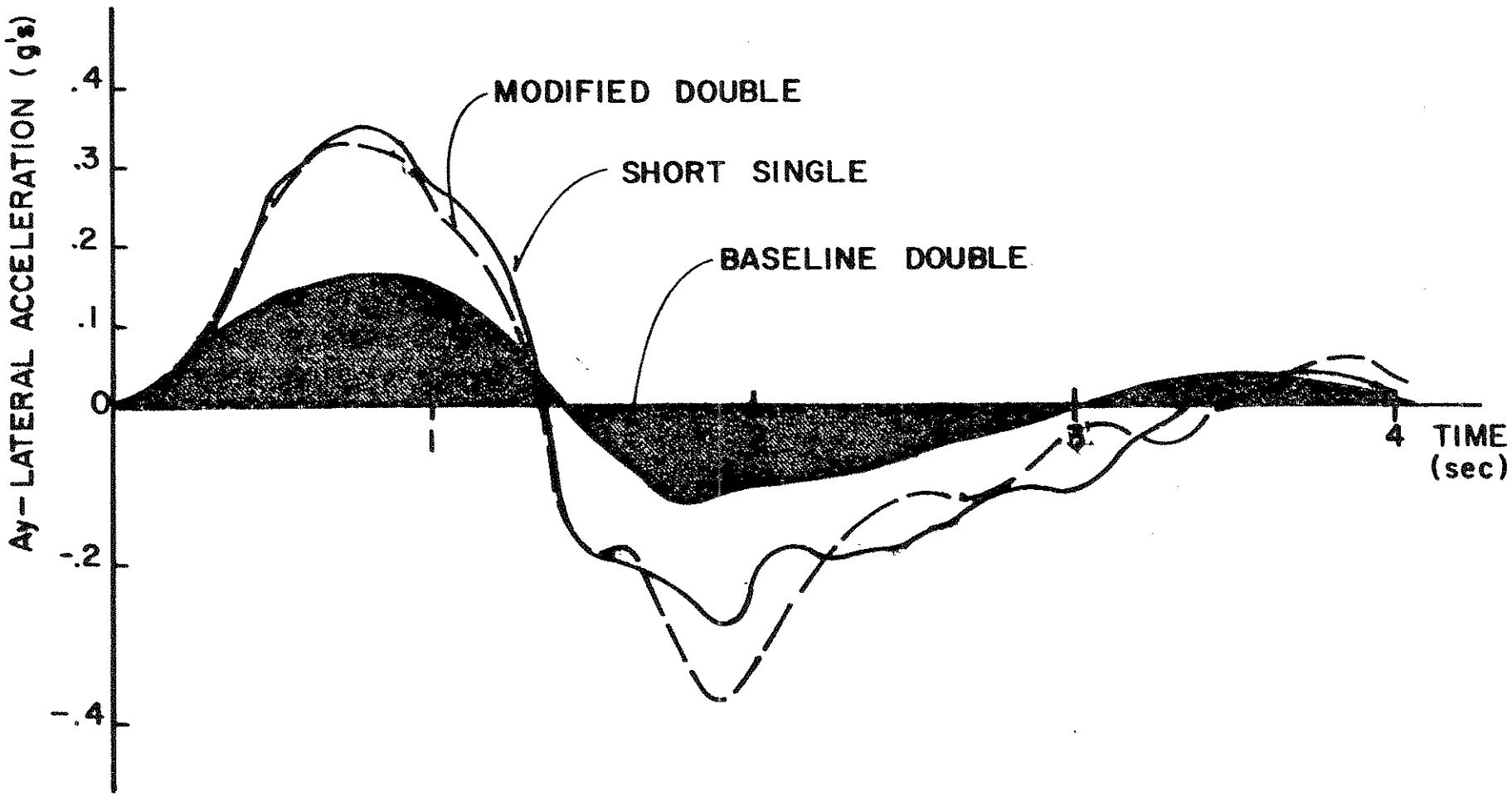

Figure 2.2. Tractor lateral acceleration time histories at the lane-change maneuver limit for three vehicle configurations.

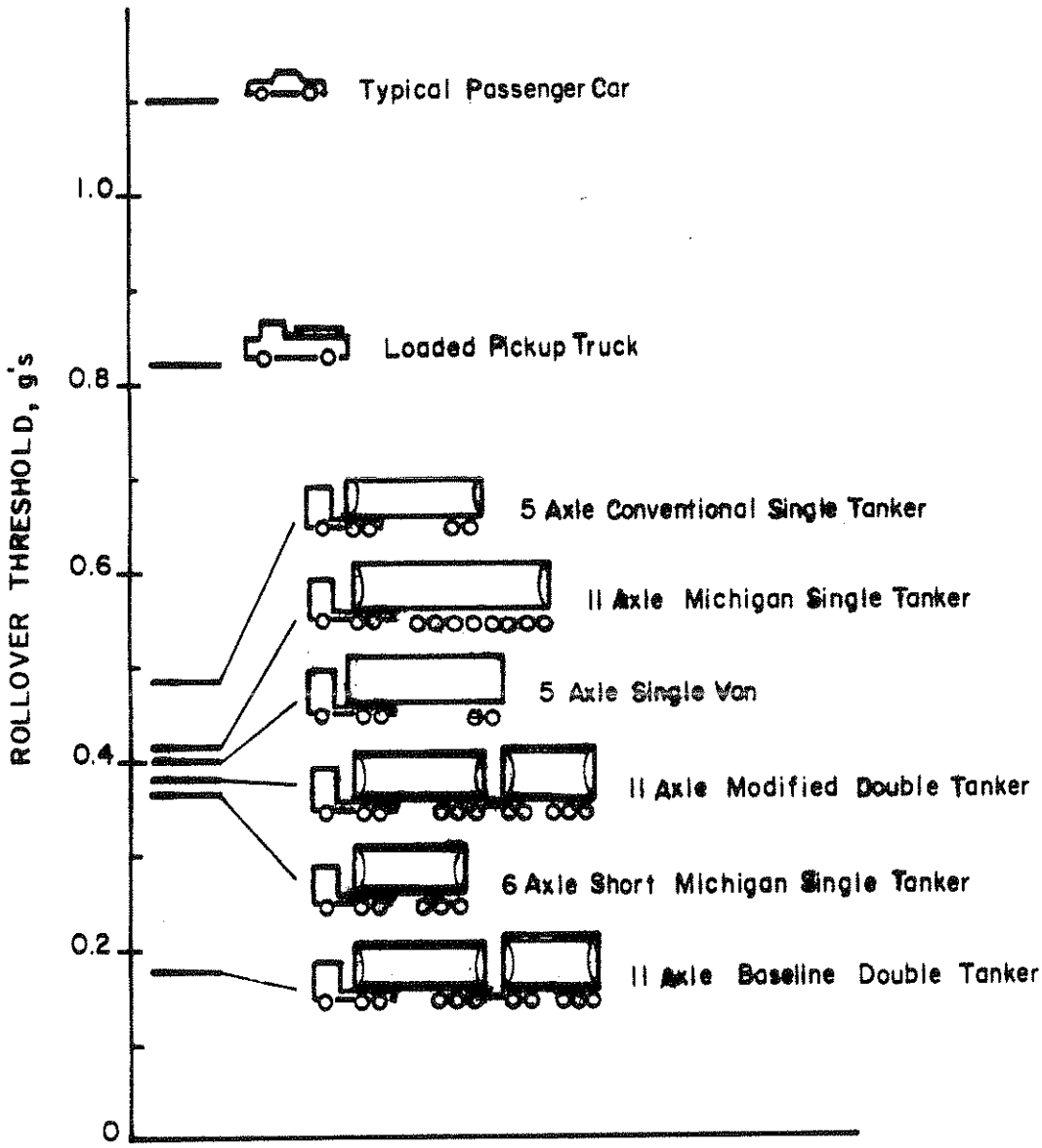

Figure 2.3. Rollover stability thresholds of various highway vehicles.

predicted limits of other commercial vehicles which were analyzed (see Appendix B), as well as the nominal stability limit of a typical passenger car and a loaded pickup truck. This chart is useful for placing into perspective the relative hazards linked with rollover instabilities. While higher stability levels are desirable, no road vehicle is immune to rollover. The modified double exhibits a stability limit which is comparable not only to that of the short single tanker, but is also comparable to other large single-bottom tankers and to fully-loaded van-type semitrailers which haul dry freight.

In suggesting modification of the double-bottom tanker, three practical aspects deserve consideration. We need to consider the vehicle's basic transport mission, its structural integrity and maintainability in serving that mission, and the costs associated with retrofitting.

Insofar as the typical usage of the double-bottom tanker involves delivery of fuel from terminal facilities to dispensing facilities, the maneuverability of the vehicle in areas of confined access pose a special problem. Since the modified hitch does serve to restrain articulation of the dolly, the resulting maneuverability of the modified double was a concern and was addressed in this study through direct measurements and through a mock fuel delivery exercise in and out of selected service stations (see Appendix E). It was determined that the modified double exhibits nearly all of the maneuverability of the baseline vehicle. Shown simply in Figure 2.4 is the extra space required for a baseline double, a modified double, and a conventional 9,000-gallon single tanker to negotiate a 50-foot radius turn. We see that the modified double needs 26% more space than the baseline double and a conventional five-axle single requires 160% more space.

Regarding maintainability, minor pluses and minuses are seen for the modified double as contrasted with the baseline double. The mounting of all four connections of the modified drawbar element in

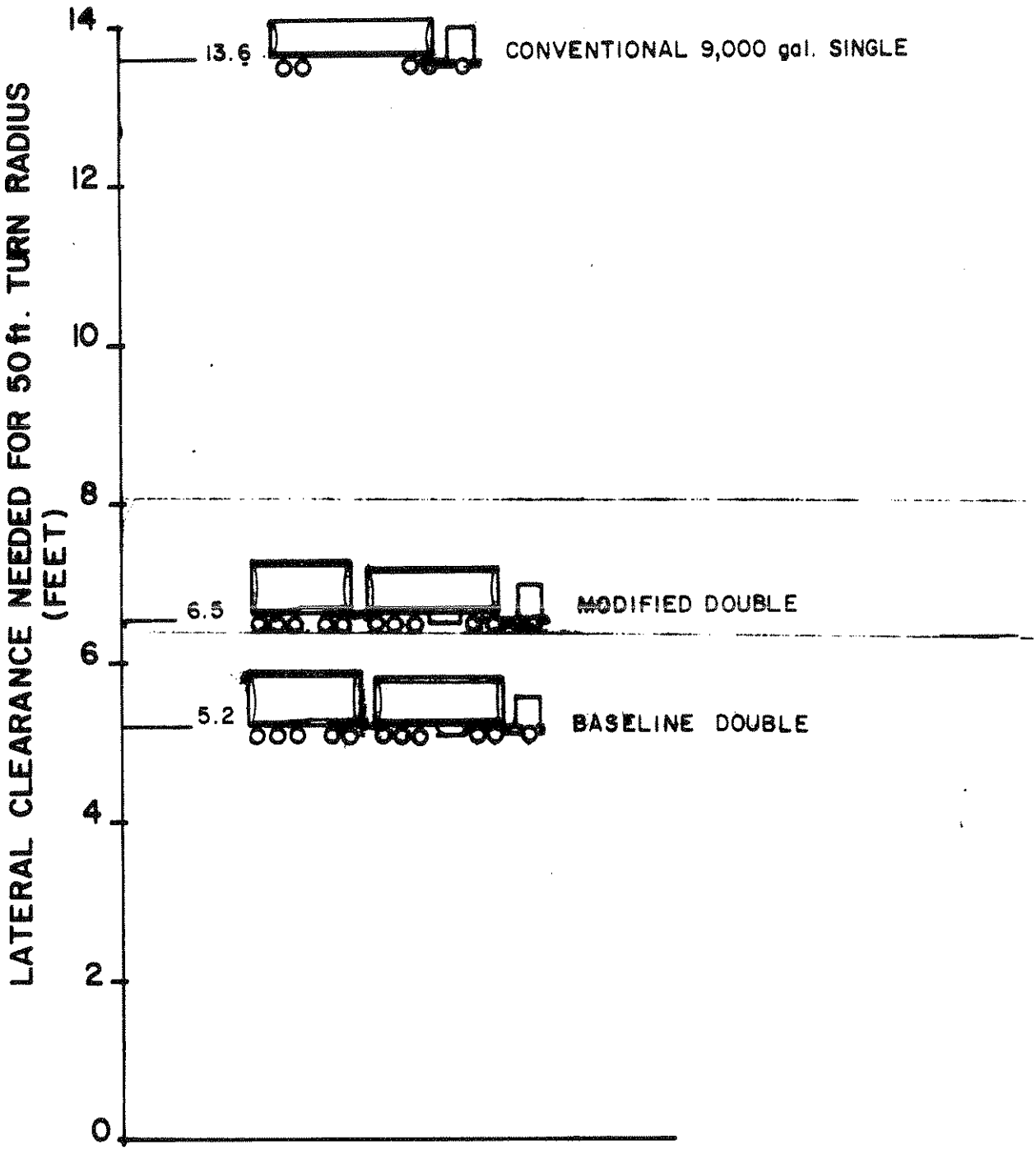

Figure 2.4. Extra lateral clearance needed, outside of the nominal 8-foot width of the vehicle, for maneuvering three different tankers around a 50-foot radius turn. (This dimension is also called "off-tracking.")

rubber bushings would appear to minimize hitch maintenance compared to the case of the original pintle hitch mechanism. On the other hand, tire scrubbing associated with the locked dolly steer motion will increase the rate of tire treadwear, but presumably not to the level experienced now on single-bottom tankers with seven and eight axles in a row (recognizing that tight maneuvering of these vehicles is done with certain axles lifted, leaving typically five axles carrying the total load). Also, although the two trailers of a double tanker are rarely disconnected in normal service, the modified hitch does render the disconnection procedure more time-consuming and, indeed, precludes any convenient separation of the trailers in the field.

Regarding structural issues, the modified hitch imposes new and greater structural loads on the semitrailer frame and the dolly. Certain of these loads can be very large, requiring that the strength of the hitch mechanism itself, as well as the trailer and dolly structures, be carefully evaluated. The Fruehauf Corporation conducted the necessary strength analyses on the large doubles of its manufacture during the time period of this study, determining that no problem exists. Such evaluation of other double trailers, however, seems to be needed before their modification would be carried out.

Finally, regarding retrofitting costs, the Fruehauf Corporation has estimated that the modification of double-bottom tankers of its manufacture will cost approximately $3,000 (May, 1978).

2.3 Other Safety Considerations

The basic findings regarding relative stability limits of vehicles were derived for the case of a fully-loaded vehicle in an emergency lane change—a case which was hypothesized to be the uniquely hazardous problem with the double. The tanker use survey task of this study has confirmed, however, that partial loading (that is, hauling with less than full capacity) of doubles and singles is rather common—though predominantly for the transport of the denser

fluids, diesel fuel and heating oil. Although there appears to be no clear evidence that partial loading has been a causal factor in double-bottom tanker accidents, it must be asserted that certain partial loading practices are patently hazardous. Partial loading occurs in one of two ways. Either selected compartments within the tank are operated full while others are empty, thereby altering the fore/aft location of the center of gravity, or individual compartments are partially full, permitting the free fluid sloshing motions which can promote unstable vehicle responses.

This study has shown that operation with some compartments full and others empty is not generally of great hazard, except that rear-biased loading of pup trailers on double tankers can cause definitely hazardous oscillations at highway speeds (see Appendix A). The dynamic problems associated with sloshing fluid in non-filled compartments were not directly investigated here. Nevertheless, published research on the subject shows that the practice is fundamentally destabilizing. Especially for the 25% to 80% range of compartment filling and for tanks which have no baffles running fore and aft (such as is the case for typical fuel-transport vehicles), fluid slosh can cause a large reduction in the basic stability level of the vehicle (see Appendix B).

Although these considerations reveal that sloshing fluids can be hazardous, it must be noted that rigorous treatment of the issue was beyond the scope of the study. Thus the careful examination of whether, for example, semitrailers with elliptical profile tanks are more or less sensitive to sloshing problems than modified double-bottom tankers with rectangular profile tanks is an item of potential relevance which is not addressed here. Nevertheless, based on the available knowledge, recommended practices for partial loading are given in Section 3.3 of this report.

Looking at the broad picture of the safety of highway tankers in Michigan, given the context of pending legislation which may change the makeup of the tanker fleet, certain additional considerations must be cited. These considerations, developed more in Appendix F,

relate to the accident "exposure" issues associated with fleets of differing candidate vehicles.

To determine a sound basis for examining exposure, we first need to identify the primary hazard to which the traffic system is being exposed. It seems clear that the primary perceived hazard associated with fuel tankers is fire.* In an analysis of truck accidents by the Michigan Department of State Highways and Transportation [4], half of the dangerous cargo accidents resulting in either fire or spill involved rollover. Thus, rollover is the primary incident producing a fire hazard, although all other incidents may, together, contribute a comparable hazard. In this discussion, we will consider only rollover as the fire hazard linking vehicle configuration to the overall number of fire incidents.

Most legislative alternatives can be distinguished by differences in both the tank volumes of the vehicles which would be permitted in operation and in the center of gravity (c.g.) heights of those vehicles. Alternative policies may consider, for example, tanker fleets consisting exclusively of five-axle single tankers carrying approximately 9,000 gallons at a relatively low c.g. height. Other alternatives may include mixed fleets comprised of various high capacity, high c.g. units (such as modified doubles and large singles), as well as low capacity, low c.g. units like the five-axle single tanker. To evaluate the safety significance of these alternatives requires that accident "exposure," which is related to the total number of fuel-hauling units, be traded off against the likelihood that high c.g. vehicles will have a higher rollover percentage in their accidents.

It can be generally said that if we increase, by a factor n, the number of a certain type of vehicle in the traffic system, we

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*Whether fires are truly the greatest hazard which tanker vehicles pose to life, limb, and property or whether our primary concern with fire is psychological, is both unknown and probably moot.

should expect an n-fold increase in the number of accidents involving such vehicles. On the other hand, not all vehicles exhibit the same propensity for rollover, in the event of an accident. Thus, for example, if vehicles A and B are alike in all their basic dynamic properties except that A is 10% lower in rollover stability level, we will expect that, while both will experience roughly comparable accident rates, a higher fraction of accidents will involve rollover for that vehicle which has the lower rollover stability. The total rollover involvement of a given tanker fleet, then, will depend upon the overall accident rate, given the number of vehicles needed to meet the fuel delivery demand, and the percentage of rollovers per accident given the rollover propensity of the vehicles making up the fleet.

An approximation of these relationships is developed in Appendix F, suggesting that:

1) A fleet of five-axle, 9,000-gallon singles may experience a total number of rollovers which are roughly comparable to the total produced by a fleet of modified 17,000-gallon double tankers meeting the same fuel delivery demand. Since non-rollover accidents will be greater with the 9,000-gallon vehicle, which must exist in greater numbers, however, the overall fire incidence rate with this vehicle would seem clearly higher.

2) The 9,300-gallon "short Michigan single" is a conspicuously poor choice from a safety point of view as a fuel delivery vehicle. The tank volume and high c.g. of this vehicle makes it both a high exposure element in the fleet and a vehicle with higher probability of rollovers per accident.

Moreover, our judgment concerning the likely safety repercussions to alteration of the tanker fleet is that changes in accident exposure resulting from changes in the typical tank volume are highly important and have equally serious fire hazard implications as changes in percent rollover involvement resulting from changes in the typical c.g. height.

Of course, given the findings cited earlier concerning the stability of the baseline double-bottom tanker, we see that this vehicle does not belong as a candidate in the above discussion. The baseline double was seen to be especially capable of overinvolvement in fires due to the "self-induced" type of rollover accidents. Further, the double's low stability level has derived not simply as a consequence of the high center of gravity associated with large capacity tanks. Rather, the baseline double has "overexposed" the traffic system to a special hazard due to its particularly low rollover stability.

As a final note to this discussion, the question can arise as to whether a large tanker threatens a greater hazard in the event of a fire than a smaller tanker. For example, "would a fire involving 17,000 gallons of gasoline be significantly more of a threat to life and property than a fire involving 9,000 gallons of gasoline?" While certain circumstances may exaggerate the importance of the volume of fuel involved, it appears that gasoline fires even in the one thousand gallon range pose a very large emergency. Accordingly, it is our understanding that the perils imposed by a tanker fire cannot be viewed as proportional to fluid volume involved in the fire. Further, our review of a sample of tanker fire reports from the State Fire Marshall's Office reveals that consumption of a tanker's full load in a fire is rare. Typically, however, more than half of the fluid load may be burned.

3.0 TASKS OF THE STUDY

In this section, each of the study's tasks will be explained in a summary fashion. The intent of this presentation is to give a general understanding of the means which were used to obtain the findings of the study. Three categories of effort were pursued:

1) Engineering analysis, leading to findings regarding the basic character of the double's instability and pointing the way toward effective vehicle modifications.

2) Full-scale tests which showed the range of validity of the analyses and which established the stability limits of various baseline and modified vehicle configurations.

3) Field survey of tanker operations, examining the manner in which tanker vehicles are employed to transport fuels in Michigan.

In the first category, two analysis tasks were conducted. A yaw stability analysis was done to examine the basic character of the "swaying" motions which occur during steering maneuvers. The yaw stability analysis also provided measures of those particular aspects of the "swaying" motion which promote rollover. These measures were then used in another analysis to investigate the rollover phenomenon, itself. Candidate modifications to the double-bottom tanker were examined by changing the mathematics describing the way vehicle elements interact in each of the two analyses. The double-bottom tanker was then re-analyzed to assess the relative merits of the various modifications.

Before either analysis could be conducted, it was necessary to obtain numbers actually describing the design of the vehicles of interest. Thus, the first task of all, undertaken to support analytical work, was the effort to measure, calculate, and otherwise estimate values for the vehicle design parameters.

The analysis tasks served not only to evaluate the stability of doubles as compared to other types of articulated vehicles, but also to guide the full-scale testing of doubles. The test maneuver conditions were based on an hypothesis that an emergency swerving (lane-change) maneuver with a fully-loaded double-bottom tanker was both: (1) a scenario of major concern to traffic safety* and (2) a dynamic condition in which the double would be peculiarly unstable. Further, it was hypothesized that the improvement of vehicle stability in this type of maneuver would correspond to improvement in other driving situations which also tend to make special demands on the double.

Accordingly, the full-scale test program focused upon vehicle response in an emergency lane-change maneuver as its primary measure of stability. Findings concerning stability of the baseline and modified vehicles are based upon results of these tests.

The final task, involving a field survey of tanker operations from loading terminals to delivery points, provides insight into the typical application of the vehicles in question. This effort, conducted in parallel with the stability investigations, resulted in a data set characterizing tanker trips by vehicle, road type, speeds, tank fill status, and other factors describing Michigan's fuel transport system.

3.1 Parameter Determination

The analytical methods which have been employed in this study, and which will be described in the following two sections of this report, are mathematical in nature, and thus require a precise mathematical description of any subject vehicle to which they are to be applied. Such a description is composed of a set of numbers, each

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*Although this study has not provided for detailed analysis of accident data, the sketchy reports which were available made it apparent that the common incident of double-bottom rollover involves (a) fully-loaded compartments (no fluid sloshing) and (b) a loss of control while attempting to avoid an obstacle, most commonly resulting in rollover of the pup trailer alone.

one representing the numerical value of one vehicle parameter. Simple examples of vehicle parameters include the vehicle weight, wheelbase (distance from front to rear axle), and track widths (the right-to-left spread between tires on a given axle).

The parameters used to describe the vehicle in this study can be conveniently grouped as follows:

1) Geometric Parameters. The spacing (longitudinal, lateral, and vertical) between various significant elements about the vehicle.

2) Mass and Inertial Parameters. The weights and moments of inertia of the sprung mass (chassis, body, and load) and unsprung masses (axles and wheels) as well as the location of the center of gravity of these elements.

3) Suspension Parameters. Deflection, lash, and frictional properties of the suspension springs.

4) Tire Parameters. Tire spring rates, rolling radius, and traction properties.

Geometric properties were easily obtained by direct measurement of the test vehicle or from engineering drawings provided by the manufacturer.

Mass and inertia properties can be determined by laboratory measurement methods, or they can be estimated through calculations based on data taken from engineering drawings. Both methods were used in this project.

Empty vehicle weights were obtained by direct measurements using vehicle scales. Loaded vehicle weights were found by adding to these figures the weight of the known volumes of fluid used as load.

Since the vehicle's center of gravity position is very important to determining rollover limits, it was felt that this parameter should be measured rather than estimated. Experiments were conducted

in which both the semitrailer and pup trailer from a double tanker combination were suspended from a crane. (See Figure 3.1.) In these experiments, each trailer was lifted twice so that it hung at two substantially different angles. Photographs were made of both "hangs" using a precisely located camera. The center of gravity of the suspended mass was then found using the photographs. The process is demonstrated in Figure 3.2. By this method, using the graphical process shown in Figure 3.2, the c.g. position of the empty doubles trailers were found. Since the full liquid load is easily described mathematically, its additional effect was then calculated.

Other inertial parameters, particularly moments of inertia, were calculated using engineering drawings. Inertial properties of the tractor were estimated based on previous measurements made at the Institute.

Another laboratory measurement process was used to determine significant properties of the double tanker's suspension. Since the trailer manufacturer uses the same basic suspension assembly at each of the several axle positions on the two trailers, representative measurements needed to be made on only one axle. With the axle loaded near the full load condition, the trailer body was exercised in roll while deflection and frictional characteristics of the suspension related to roll motion were being measured.

Tire parameters are among the most important vehicle properties necessary for predicting and understanding vehicle performance. Tire parameters are difficult to determine in that highly specialized equipment is required to perform the necessary measurements. In this study, HSRI identified an appropriate set of tire parameters using data obtained from previous experiments performed with our truck tire test apparatus.

For purposes of comparison, vehicles other than the Michigan double tanker were also examined in this study. Parameters for these vehicles were gathered either from previous measurements made at the Institute or through calculations based on engineering drawings.

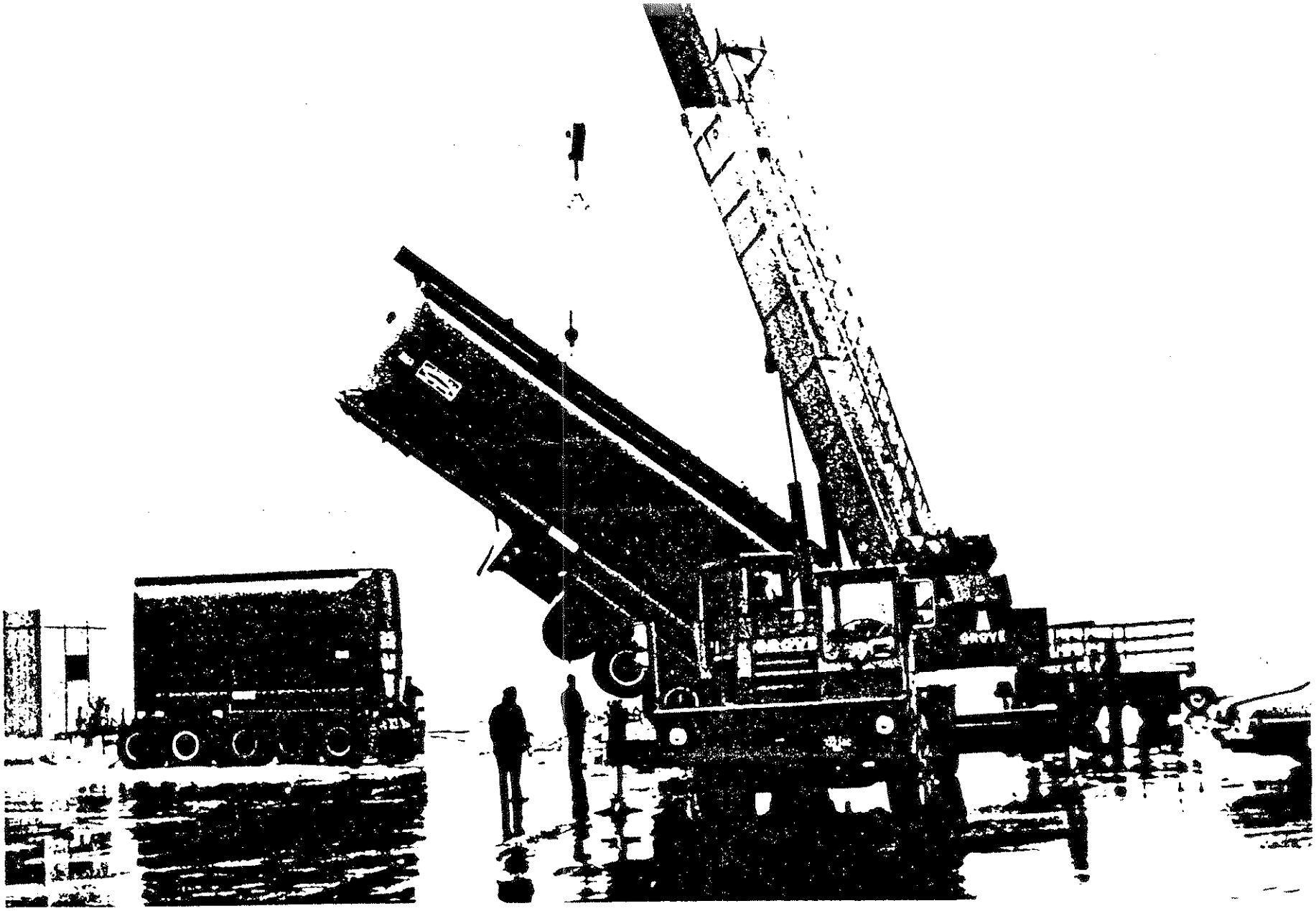

Figure 3.1. Center of gravity testing of the baseline Michigan double tanker.

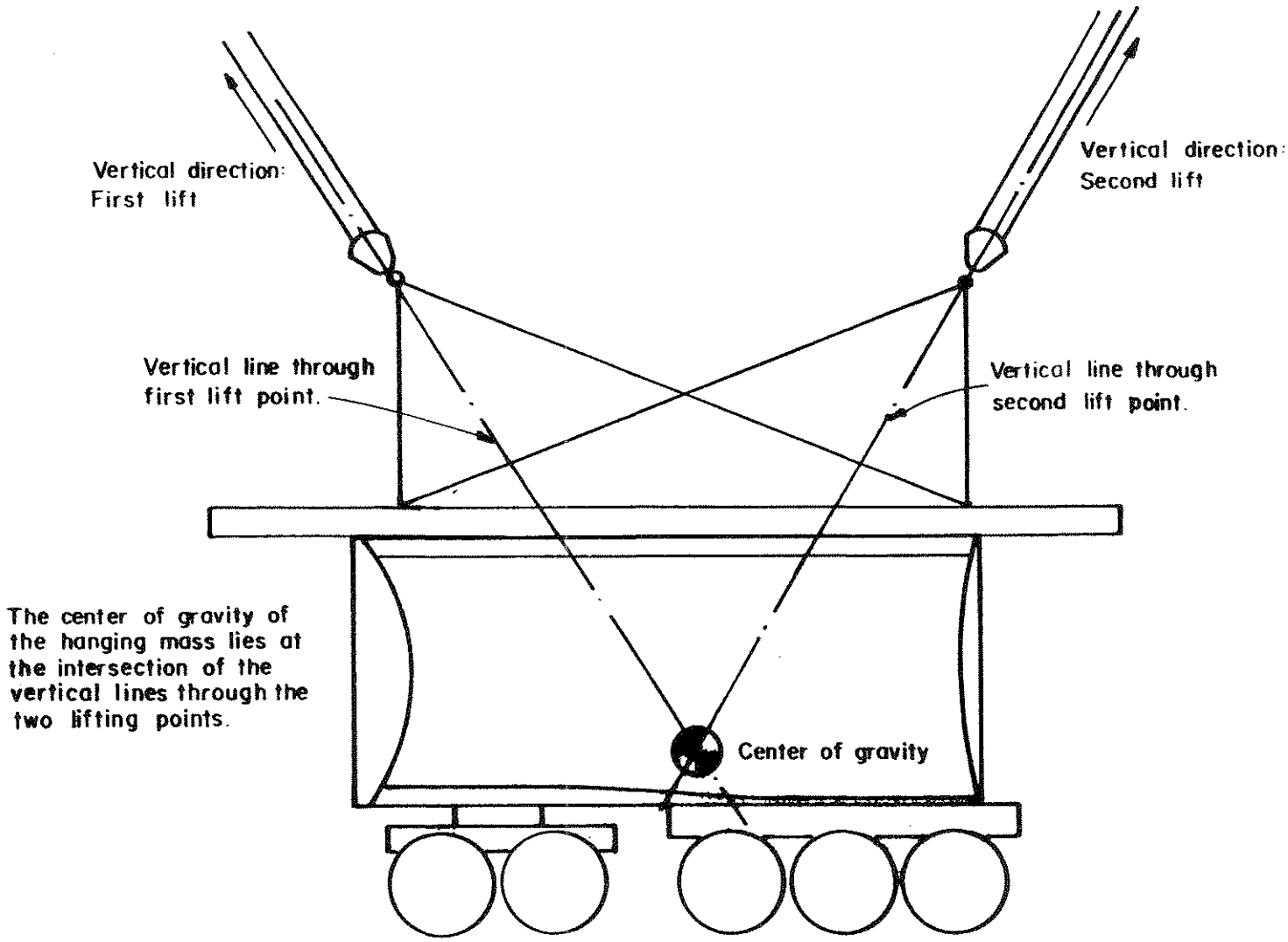

Figure 3.2. Method for determining center of gravity position.

3.2 Yaw Stability and Response Analysis

Introduction

Mathematical models* of articulated (jointed) vehicles have been used in this study to aid in understanding the motions which take place during maneuvering on the highway. In order to simplify the investigation, two sets of models have been developed for studying different types of vehicle motions. One set of models, treating rolling motions, is used to estimate the level of turning maneuver which will cause the vehicle or one of its trailers to rollover. Another set of models, addressing those motions which are parallel to the ground, is used to evaluate the directional, or yaw behavior of articulated vehicles (including trailer "swaying"). The "rollover" models are discussed in Section 3.3, while features of the "yaw" models and the findings (understanding) developed using the yaw models are summarized in this section.

Purposes

The purposes of investigating yaw stability and the directional response to steering are to: (1) understand in a fundamental manner the rotational and translational motions parallel to the ground of the standard 55-foot Michigan double-bottom tanker during steering maneuvers at highway speeds, (2) compare the directional behavior of other commercial vehicles which are in use with the behavior of the Michigan double-bottom tanker, and (3) examine practicable design changes which could improve the directional behavior and thus increase the rollover threshold of the baseline (standard) 55-foot double tanker which is currently being used in the State of Michigan.

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*These "mathematical models" are simply technical descriptions obtained by writing equations describing various types of vehicle motions.

Features of the Models

The mathematical models which have been developed for addressing the purposes of this study consist of (1) equations describing the time rate of change of basic motion variables (e.g., the lateral velocity of the tractor, the rotational (yaw) rates of the trailers, the articulation angle between the tractor and first semitrailer, etc.) and (2) numerical values (parameters) which quantify specific properties of a selected vehicle (e.g., weight of the tractor, locations of the axles, locations of the hitches, tire properties, etc.).

The mathematical models used to study lateral and yaw motions contain the following distinctive features: (1) the vehicle is subdivided into individual units separated by articulation joints (pivot points), for example, the double-tanker model consists of a tractor, a first semitrailer, a dolly, and a pup semitrailer connected by (a) a fifth wheel between the tractor and the semitrailer, (b) a pintle hook between the semitrailer and the dolly, and (c) a turntable between the dolly and the pup semitrailer (see Figure 3.3); (2) the laws of physics (Newton's laws) are used to obtain equations of motion whose solutions describe the turning and maneuvering behavior of each of the units of the entire vehicle as it proceeds at nearly constant forward velocity; (3) vehicle motions parallel to the ground plane are included while roll, pitch, and bounce motions which are not parallel to the ground plane are eliminated; (4) the lateral (sideways) forces and moments from the tires, which accelerate and turn the vehicle, are approximated by linear functions of the velocities of appropriate axles; and (5) small angle approximations (i.e., for a small angle, α, $\sin \alpha \doteq \alpha$ and $\cos \alpha \doteq 1$) are employed. Models with these features provide a valid treatment of vehicle behavior up to lateral accelerations of approximately 0.2 g. For more severe maneuvers up to conditions at which wheels start lifting off the ground, comparisons with experimental results indicate that these models predict maximum lateral

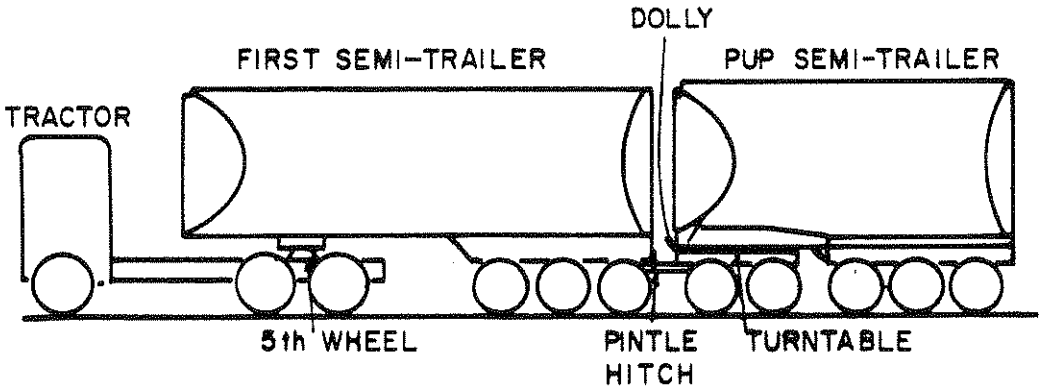


FIGURE 3.3 MICHIGAN DOUBLE TANKER, ITS UNITS AND HITCHES

acceleration and yaw rate levels reasonably well, but the timing and duration of predicted motions will exhibit discrepancies of considerable magnitude.

It should be noted that the models used in this study represent revisions and extensions of prior work performed by other research investigators (for example, see Jindra [5], Hazemoto [6], and Hales [7]). In particular, the double-bottom tanker models used in this study are unique in that they consider multiple tandem axles, changes in tire cornering stiffnesses as a function of the static loads on the axles, and tire aligning moment effects.

A detailed, technical discussion of the mathematical models used for predicting directional response is presented in Appendix A. In addition, Appendix A contains numerical results pertaining to the yaw behavior of a variety of articulated vehicle configurations and operating conditions. The analytical work performed in developing the models and the numerical results given in Appendix A provide the foundation for the discussion presented hereafter.

Methods of Analysis and Simulation

Because the model of yaw behavior possesses a mathematical property called "linearity," it is feasible using well-known techniques to study the yaw (directional) stability of the vehicle system without solving the equations of motion for specific operating conditions. In this type of analysis, calculations are made to determine the "roots of the characteristic equation." (These roots are sometimes referred to as "eigenvalues.") The values of these roots contain a great deal of general information concerning the system they apply to. In this study the eigenvalues are employed to evaluate (1) vehicle stability (or the lack of stability), (2) the amount of damping in oscillatory modes of motion, and (3) the frequencies at which the system will oscillate if it is disturbed.

In contrast to eigenvalue analysis, simulation involves numerically solving the equations of motion to obtain time histories of pertinent vehicle-motion variables during simulated tests. Thus,

simulation provides the means for "experimenting with models" as a substitute for difficult, hazardous, costly, and time-consuming tests.

Nevertheless, it should be emphasized that vehicle testing (or on-highway experience) is needed to confirm significant findings and to obtain results at maneuvering levels beyond the range of validity of the mathematical models.

Characteristics of the "Baseline" Michigan Double Tanker

During the modeling of the directional response to steering of the Michigan double-bottom tanker it was observed that in most turning maneuvers relatively small lateral forces (less than approximately 200 pounds) occur at the pintle hook connection between the first semitrailer and the drawbar of the dolly of the pup trailer. This observation can be used to understand many of the numerical results which have been obtained in the study of yaw response.

For example, the directional behavior of the tractor-semitrailer portion of the Michigan double-bottom tanker is nearly identical to the directional behavior of the vehicle obtained by dropping the pup trailer from the Michigan double. Furthermore, parameters describing parts of the pup trailer (tires, wheel locations, dolly tongue length, etc.) have no significant influence on the motion of the tractor-semitrailer portion of the double. Along this same line of reasoning, for maneuvers in which the tractor-semitrailer is steered to achieve a desired tractor-semitrailer motion, changes in tractor or semitrailer parameters cause only small changes in pup trailer response. In summary, if the response of the pup trailer is to be altered, changes in the pup trailer (not in the tractor-semitrailer) will be most influential.

Further evidence of the feasibility of studying pup trailer motion independently of the properties of the tractor-semitrailer

can be obtained by examining Figure 3.4. This figure shows the locus (as a function of velocity) of the roots of the characteristic equation for the eighth-order linear system of differential equations describing the directional motion of the fully-loaded 11-axle double-bottom tanker. The broken lines labelled "R1" and "R2" are roots determined by the properties of the tractor-semitrailer portion of the double. (Incidentally, these roots also describe the properties of the principal modes of motion of the tractor-semitrailer vehicle which is obtained by dropping the pup trailer from the Michigan double.) The solid lines labelled "R3" and "R4" are roots determined primarily by properties of the pup trailer.

Superimposed on Figure 3.4 are lines of constant natural frequency and damping ratio. As indicated in Figure 3.4, the observed frequencies of the pup trailer modes R3 and R4 are significantly higher than the observed frequencies of the tractor-semitrailer modes. It should be emphasized that the damping ratio of root R4 is small indicating a very oscillatory mode of motion approaching instability of the pup trailer at velocities of 50 mph or above.

In this regard, calculations made for a situation in which the rear compartment of the pup trailer is loaded and the other compartments of the pup trailer are empty show that the pup trailer will become completely unstable at speeds of 50 mph and above.

In addition to studying the roots of the characteristic equation, calculations have been made to predict vehicle performance in obstacle-avoidance maneuvers. Descriptions of Michigan double-bottom tanker accidents have sometimes portrayed a situation in which the vehicle is steered to avoid a suddenly appearing obstacle and, although avoiding the obstacle, the vehicle becomes uncontrollable leading to rollover of the pup trailer. This type of situation has been examined by using the yaw model to simulate the directional behavior of the Michigan double-bottom tanker in obstacle-avoidance maneuvers which take the form of a very rapid lane change.

55 ft. MICHIGAN DOUBLE BOTTOM TANKER FULLY LOADED

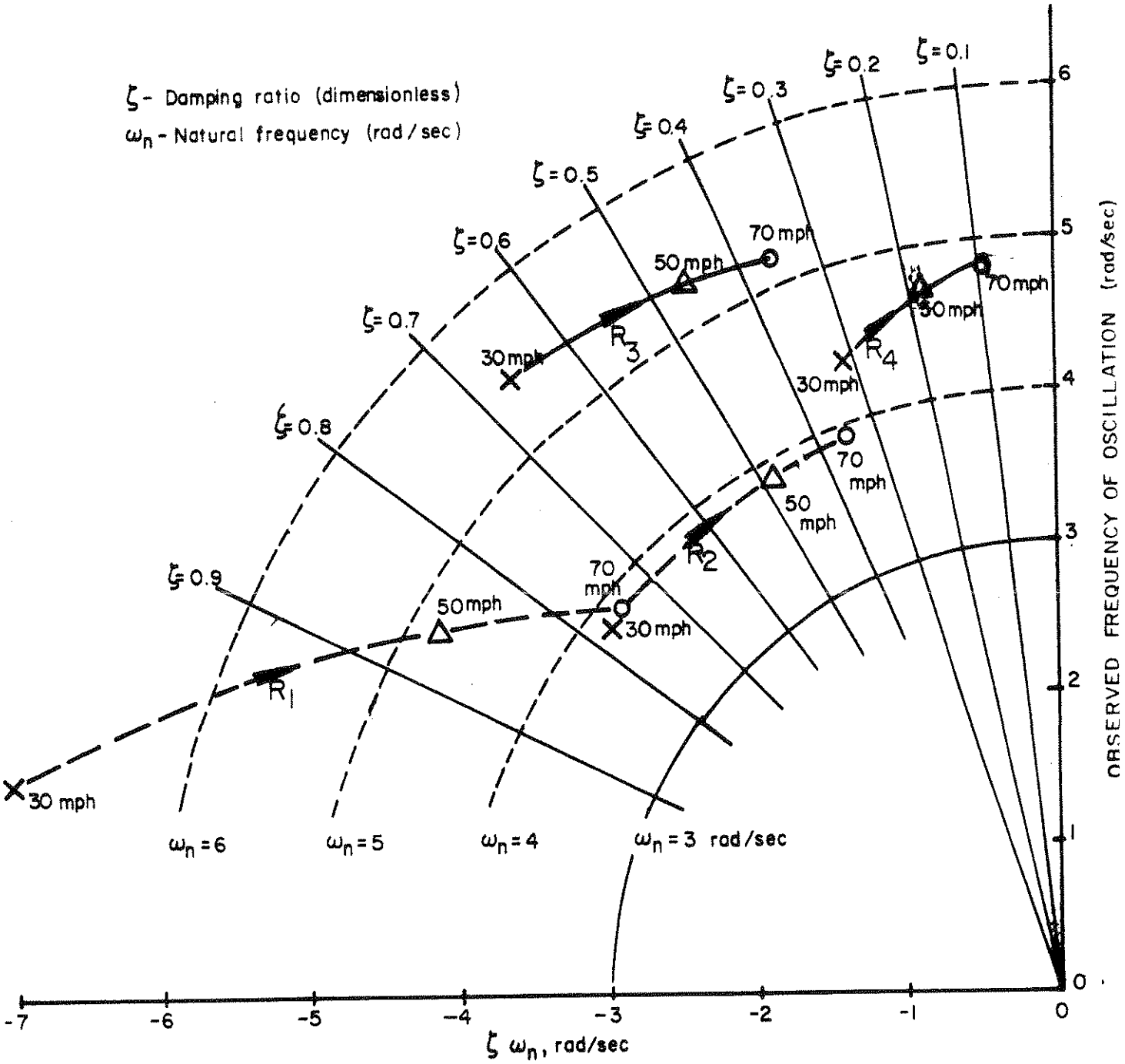


Figure 3.4. EFFECT OF FORWARD SPEED ON CHARACTERISTIC ROOTS

The principal finding from these simulations is that there exists a very large amplification factor between the lateral acceleration of the tractor and the lateral acceleration of the pup semitrailer in a rapid obstacle-avoidance steering maneuver. That is, if the tractor is steered sufficiently to avoid an obstacle, the pup semitrailer will undergo a considerably more violent motion than the tractor. Intuitively, this motion is akin to "cracking the whip."

To complete the analysis of a potential rollover of the pup trailer, the mathematical models described in the next section of this report have been used. Nevertheless, the predicted magnitude of the lateral acceleration of the pup trailer is a strong indicator of the likelihood of rollover.

Figure 3.5 shows calculated time histories of lateral acceleration levels predicted for a "two-second lane change." This is a rapid maneuver in which a symmetric steering input of two seconds duration causes the vehicle to end up traveling in approximately the original direction of motion with an amount of lateral translation dependent upon the amplitude of the steering input. Examination of the results shown in Figure 3.5 indicates that the ratio of the maximum lateral acceleration of the pup semitrailer to the maximum lateral acceleration of the tractor is 2.5 at 50 mph. This magnitude of amplification factor means that in traffic conflicts which could be resolved with relatively low levels of lateral acceleration of the tractor, the lateral acceleration of the pup semitrailer could be large enough to rollover the pup semitrailer.

Directional Response Comparisons Between the Michigan Double Tanker and Various Commercial Vehicles In Use

Mathematical models of various vehicle configurations have been developed to compare the directional (yaw) characteristics of the Michigan double-bottom tanker with other tanker and van-type commercial vehicles. These models are suitable for analyzing vehicle behavior at low levels of maneuver severity. Computer programs for determining (1) the roots of the characteristic equation

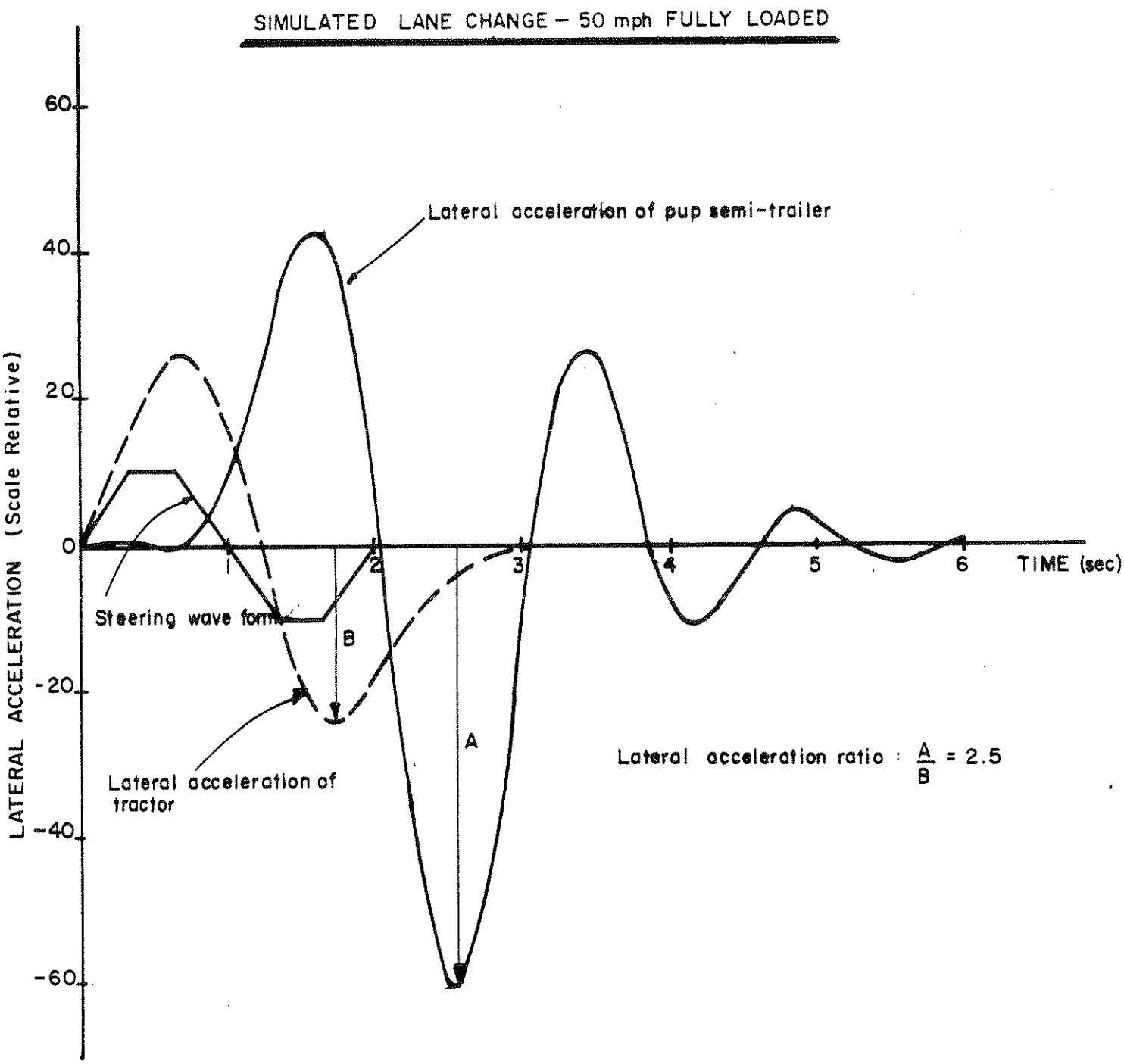


FIGURE 3.5 ACCELERATION TIME HISTORIES DURING OBSTACLE AVOIDANCE

(the damping and frequency of the principal modes of oscillation) and (2) the response to steering inputs (the maximum acceleration levels attained in lane-change maneuvers) have been constructed and exercised in this study.

The vehicles modeled include:

(1) The baseline 11-axle Michigan double-bottom tanker

(2) The single tanker obtained by removing the pup from (1)

(3) A conventional 5-axle single tanker

(4) A conventional tractor with van semitrailer

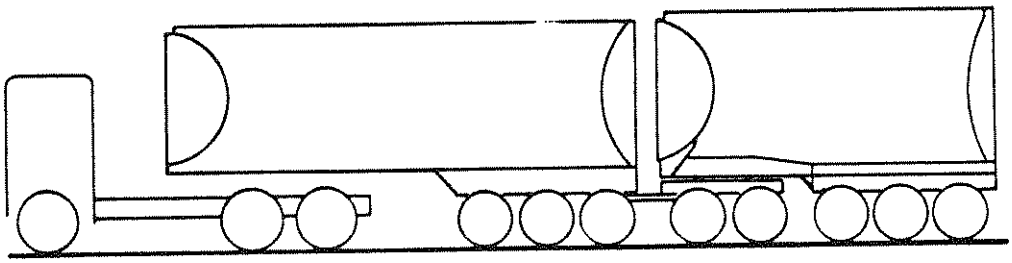
(5) The 11-axle Michigan single tanker

(6) A 65-foot version of (1)

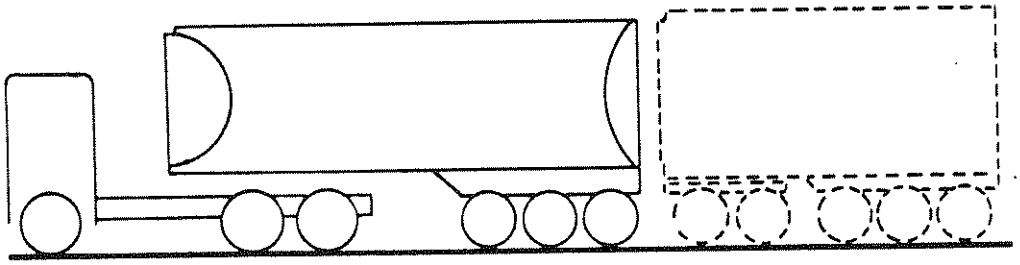
Diagrams illustrating the forms of these vehicle configurations are shown in Figure 3.6.

For purposes of quantitatively comparing the Michigan double tanker to other vehicles, three measures have been selected. Two of these measures are (1) the damping ratio corresponding to the least damped mode of motion of the vehicle and (2) the ratio of the lateral acceleration of the rearmost unit of the vehicle to the acceleration of the tractor in a two-second lane change. These measures have been selected because, as discussed previously, they are indicators of directional response shortcomings which have an applied, pragmatic basis in explaining accidents involving the Michigan double tanker.

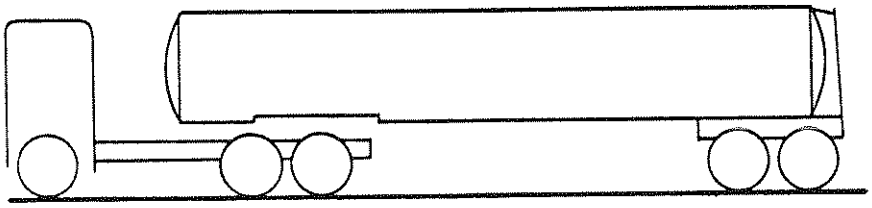
It should be emphasized that these response measures are evaluated at 50 mph in the results which follow. At speeds approaching 70 mph, the damping values are significantly reduced and the amplification factors are substantially increased. Operation of the Michigan double tanker at 70 mph appears to be a very demanding situation requiring delicate, precise control of the vehicle.



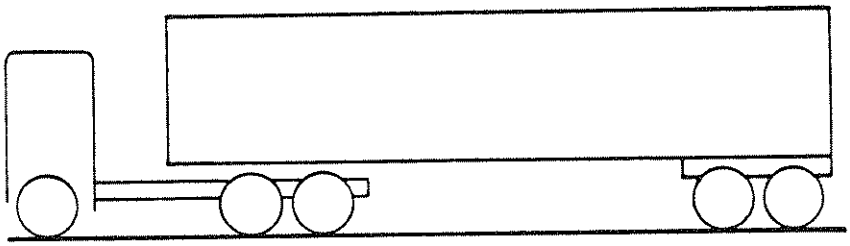
MICHIGAN 11 AXLE DOUBLE TANKER



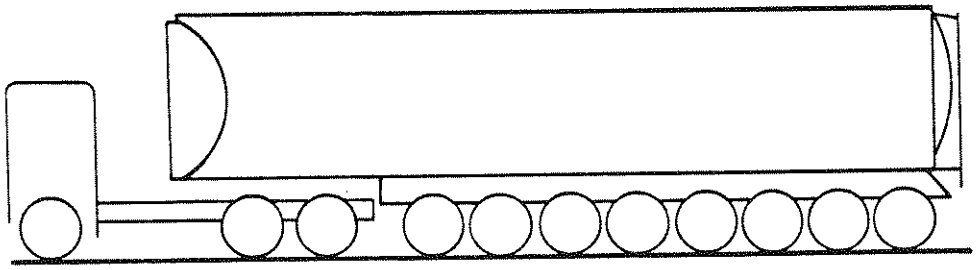
MICHIGAN DOUBLE TANKER WITH PUP REMOVED



5 AXLE SINGLE TANKER



CONVENTIONAL TRACTOR WITH VAN SEMI-TRAILER



11 AXLE SINGLE TANKER

FIGURE 3.6. DIAGRAMS OF VARIOUS VEHICLE CONFIGURATIONS

The third directional response measure, called the "rise time," has been chosen to provide an indication of the quickness of response attainable from various vehicle configurations. (Specifically, as used in this study, the "rise time" is defined as the time for the lateral acceleration of a unit of the vehicle to go from 10% to 90% of its final value in response to a step function steering input (i.e., a sudden turn) at 50 mph.)

Calculated values of the three selected response measures for various in-use commercial vehicle configurations are given in Table 3.1. These results clearly indicate that the small damping ratio and large lateral acceleration ratio shortcomings are unique to the Michigan double tanker. It is interesting to note that the larger 65-foot version of the standard 55-foot Michigan double tanker is an improved vehicle with respect to damping and lateral acceleration ratios. However, the results in Table 3.1 also show that the conventional five-axle single tanker and the tractor/van-semitrailer have slower rise times than the double tanker indicating a different type of obstacle-avoidance problem. These slowly responding vehicles may not be able to move quickly enough to successfully resolve sudden traffic conflicts.

Examination of Modifications to Improve the Directional Response of the Michigan Double Tanker

As part of the analytical study of yaw behavior, modified versions of the Michigan double tanker were examined. The types of modifications considered for retrofitting were those which could be accomplished without significantly redesigning the existing pup and semitrailer. Examples of "retrofits" which were investigated but did not cause a major improvement in the performance of the fully-loaded Michigan doulbe are increasing or decreasing the dolly tongue length, using a longer wheelbase tractor, and using radial tires instead of bias tires on the pup trailer.

Table 3.1. Comparison of Commercial Vehicles In Use.

Vehicle Configuration	Damping Ratio of the Least Damped Root	Lateral Acceleration Ratio in a 2-Second Lane Change	Lateral Acceleration Rise Time for the Slowest Unit of the Vehicle (seconds)
1. Michigan 11-Axle Double			
Fully Loaded	0.19	2.5	0.8
Empty	0.12		
2. 1. Above Without the Pup (Michigan Short Single)			
Fully Loaded	0.48	1.1	0.8
Empty	0.56		
3. Conventional 5-Axle Single Tanker			
Fully Loaded	0.84	0.8	1.6
Empty	0.52		
4. Conventional Tractor with Van Semitrailer			
Fully Loaded	0.64	1.0	1.6
Empty	0.73		
5. 11-Axle Single Tanker			
Fully Loaded	0.63	0.8	1.1
Empty	0.70		
6. 65-Foot Version of 1.			
Fully Loaded	0.35	2.3	0.8
Empty	0.23		

The type of retrofit that did show a major improvement in directional performance was to rigidize the connection at the pintle hook, thereby causing the yaw and roll motions of the dolly to be rigidly coupled to the first semitrailer. The predicted results for this retrofit indicated an improvement in the damping ratio measure from 0.19 to 0.32 and in the lateral acceleration amplification factor from 2.5 to 1.7. In practice, the vehicle test results described in Section 3.4 show that in extreme maneuvers the retrofitted vehicle is a considerable improvement over the standard Michigan double.

It should be noted that it was beyond the scope of this study to make a comprehensive investigation of thoroughly redesigning the Michigan double to produce the best possible double. Nonetheless, the predictions which were made show that significant improvements can be made using longer wheelbase trailers, relocating or removing axles, and relocating hitches. The possibility of designing a double which performs as well as or better than the conventional five-axle semitrailer (while carrying considerably more payload) appears promising.

3.3 Analysis of Rollover Threshold

The objective of the project task on rollover was to determine the rollover threshold for double-bottom tanker vehicles and to compare that threshold level against the corresponding level for other commonly used tractor-semitrailer combinations. While a static analysis was originally planned, a dynamic analysis became necessary in order to take into account the differing lateral behavior of the combination vehicles under consideration. The dynamic rollover model, illustrated in Figure 3.7, consists of a sprung mass (tank, cargo, and chassis) supported by a suspension incorporating spring, damping, and roll geometry characteristics. The suspension rests on an unsprung mass (axles and wheels) which in turn are supported by four

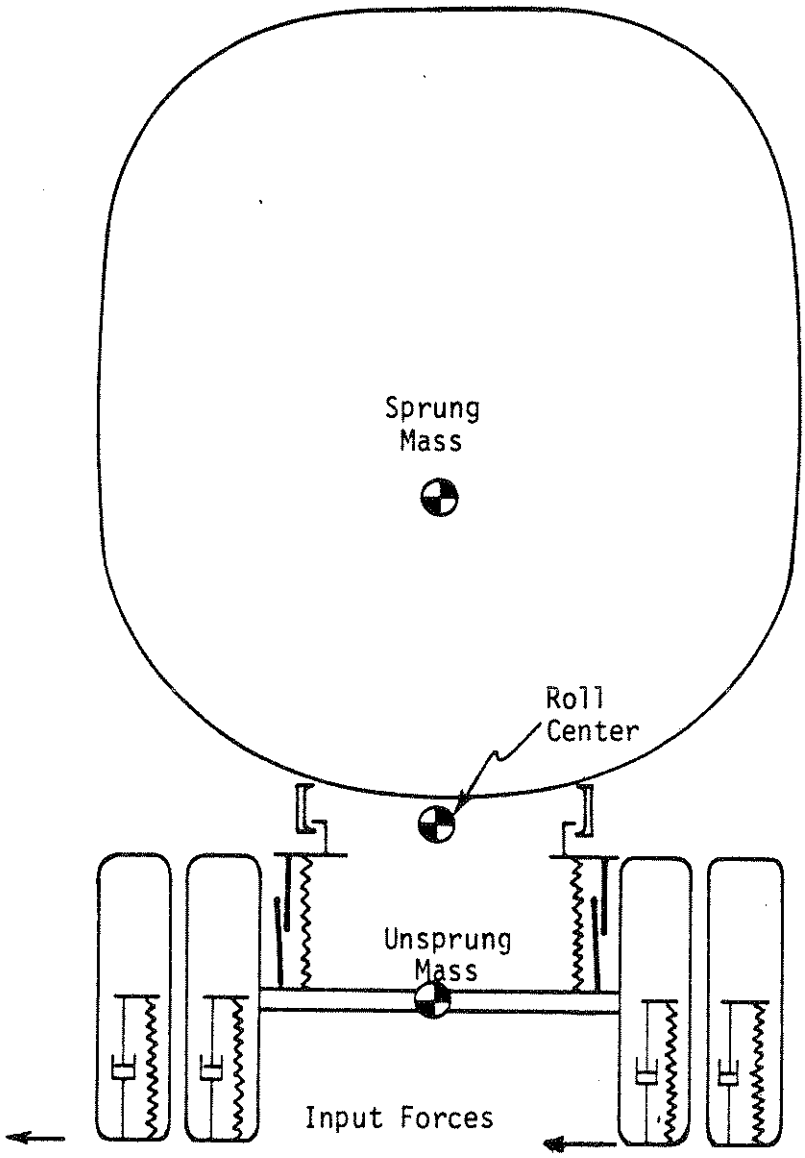


Figure 3.7. The dynamic rollover model.

spring-dampers representing the tires. Such a model, when subject to a lateral force, duplicates the roll dynamics of an automotive vehicle.

The model was used to investigate the rollover threshold for vehicles in a two-second lane-change-type maneuver (see Appendix B). The lateral force time history for the vehicle of interest was determined from the combination of experimental tests and yaw simulations, and was then used as input to the roll model. The amplitude of the lateral force input was varied (simulating steer inputs of varying magnitude) to determine the level at which a rollover threshold was reached. The rollover threshold was defined as the roll condition equivalent to outrigger touch-down in the experimental tests. The lateral force amplitude in each case is reported in terms of the peak lateral acceleration which the tractor can experience without rollover of any element of the vehicle train.

Six vehicle configurations, as illustrated in Figure 3.8, were studied. For multiple vehicles which are coupled in roll, such as a tractor-semitrailer, parameters for the composite vehicle combination were determined for use in the roll model, and the lateral forces to all axles of the roll coupled combination were summed together at each instant of time. In the case of the baseline double-bottom tanker, the pup trailer is independent in roll from the rest of the train, so that the rollover of the pup trailer was investigated separately from that of the leading tractor-semitrailer vehicle.

The results of the roll analysis are presented in Table 3.2. The baseline double-bottom tanker was observed to reach the rollover threshold at a low tractor maneuver level (~ 0.17 g's peak lateral acceleration) due to the combination of a high center of gravity and the amplification of the lateral acceleration level at the pup trailer. For the doubles modified with a rigidized dolly hitch and reduced suspension backlash, the rollover threshold was

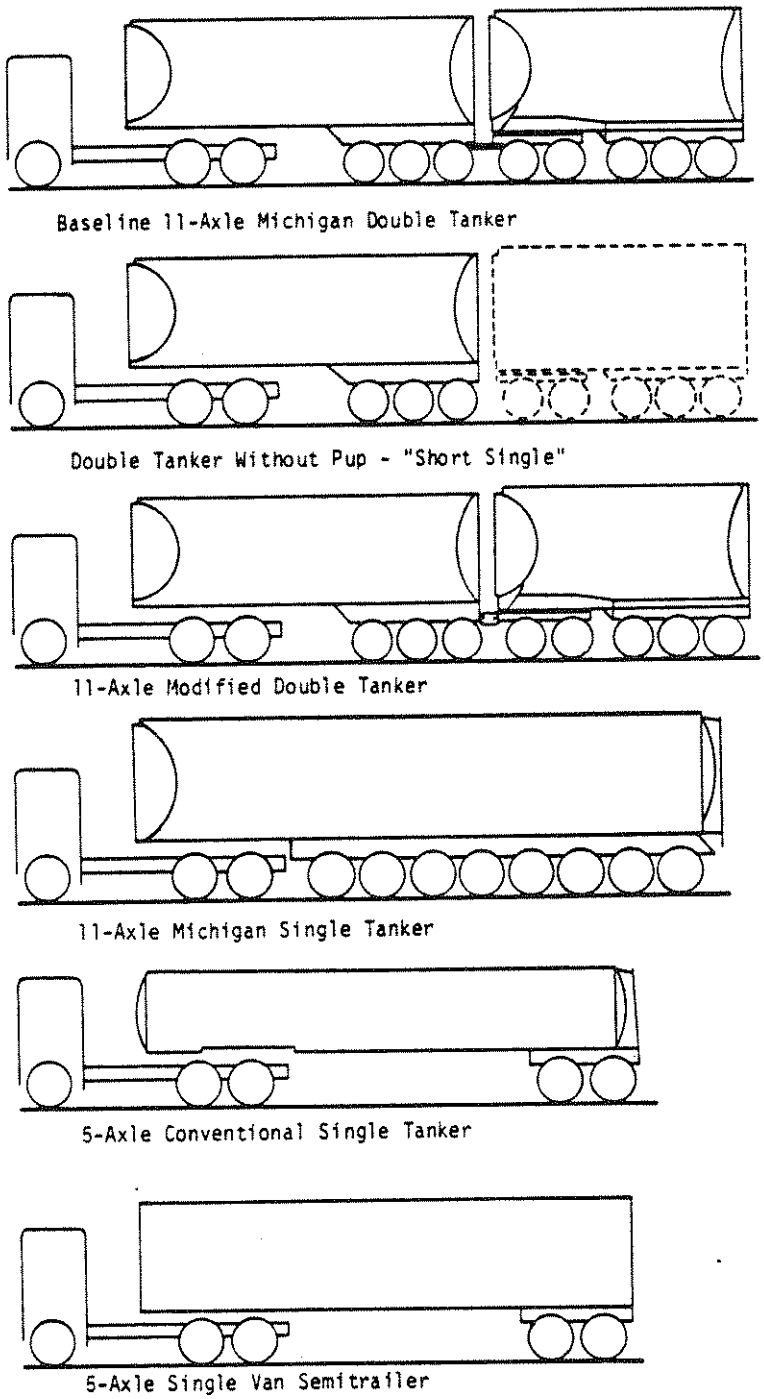


Figure 3.8. Michigan double-bottom tanker and five comparison vehicles.

Table 3.2. Rollover Threshold for Six Vehicle Configurations.

Vehicle	Tractor Peak Lateral Acceleration Measured	Calculated
Baseline Double-Bottom Tanker	0.17 g's	0.17 g's
Short Single	0.36	0.37
Modified Double-Bottom	0.36	0.37
11-Axle Single Tanker		0.41
5-Axle Single Tanker		0.49
5-Axle Van Semitrailer		0.40

improved to 0.36 g's tractor lateral acceleration. Three of the other tractor-semitrailer combinations (the short single, the eleven-axle single tanker, and the van trailer, loaded to a typical high center of gravity) exhibited comparable performance, falling in the range of 0.36 to 0.41 g's tractor lateral acceleration. Finally, the five-axle single tanker, because of its relatively low center of gravity and long wheelbase, exhibited the highest rollover threshold of 0.49 g's tractor lateral acceleration.

The influence on the rollover threshold of suspension characteristics, as described by the spring rate, backlash, and damping, were examined. Though damping had little effect, the spring rate and backlash influenced the threshold, as evident in Table 3.3. From the baseline condition, elimination of the backlash increased the rollover threshold by 18 percent, with a similar effect at a lower spring rate. A reduction of the spring rate below its normal value of 35,000 lb/in reduced the rollover threshold as shown, but an increase in spring rate was observed to have negligible effect. This observation of the potential improvement achieved by reduction of the backlash is evident with the data shown for the modified vehicle as well, and is the primary basis for recommending reduction or elimination of the backlash in the suspensions of these vehicles.

Table 3.3. Influence of Suspension Spring Rate and Backlash on the Rollover Threshold

Vehicle	Spring Rate Per Spring	Backlash	Peak Lateral Acceleration Tractor	Peak Lateral Acceleration Pup
Baseline	35,000 lb/in	1.5* in.	0.17 g's	0.38 g's
	35,000	0.0	0.20	0.45
	16,000	1.5	0.15	0.34
	16,000	0.0	0.18	0.40
Modified	35,000	1.5	0.33	0.52
	35,000	0.75*	0.37	0.58
	35,000	0.25	0.38	0.60

*Nominal values

The dynamic roll model was also used to investigate certain minimum performance requirements for the "roll rigid" dolly hitch proposed as a retrofit. This investigation was prompted by the practical concern that some degree of flexibility in the hitch is inevitable, and in fact, is desirable to ensure its durability. To evaluate the significance of this flexibility, two models (one representing the tractor-semitrailer and one the pup trailer) were linked together by a torsional spring with backlash and a variable spring rate. The backlash and rate were varied to determine the limits on hitch flexibility at which detrimental influence on rollover threshold occurred. The study concluded that hitch properties were not critical at roll angles of a few degrees (i.e., some rubber mounting is acceptable) as long as the hitch develops at least three million inch-pounds of roll torque at a five degree difference in roll angle between the semitrailer and dolly frames.

Lastly, the effects on the rollover threshold due to liquid slosh in partially loaded tanks was investigated to determine the extent to which slosh may compromise the roll stability of the double-bottom tanker. Figure 3.9, taken from Strandberg [8], illustrates the influence of slosh on the rollover threshold of a tanker with an unbaffled cylindrical tank. For a solid load, the threshold decreases

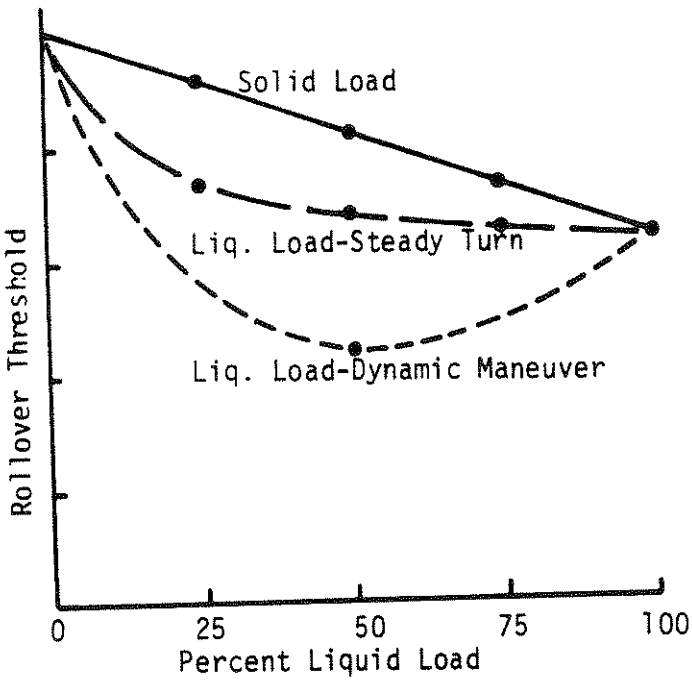


Figure 3.9. Influence of liquid slosh on rollover threshold, from Strandberg [8].

with increasing load in proportion to the increase in center of gravity height. Liquid loads in steady-state turns decrease the threshold in a nonlinear fashion due to lateral shift of the center of gravity. The most detrimental influence, however, occurs with dynamic maneuvers such as the lane change in which liquid oscillations occur and substantially reduce the rollover threshold to values even less than that of the fully-loaded vehicle. Assigning quantitative values to the influence of partial load sloshing on the performance limits of the typical Michigan double-bottom tanker is difficult without an extensive research program because of the strong dependence on the specifics of tank shape, liquid level, vehicle, and maneuver. Nevertheless, such a program would likely result in similar observations of a range of load conditions at which rollover threshold was even less than that of the fully-loaded vehicle. In light of this fact, it is clear that partial loading practices should be

discouraged until such time that appropriate loading limits can be established or effective baffling systems can be developed.

3.4 The Vehicle Test Program

A full-scale vehicle test program was conducted as part of this study. The test program extended over a two-and-one-half-week period, and took place at the Chrysler Corporation Proving Grounds in Chelsea, Michigan. Testing was directed and performed entirely by Institute personnel.

The test vehicle which was used was typical of the largest variety of the Michigan double-bottom tanker. The power unit was a short wheelbase, three-axle, GMC, cab-over-engine highway tractor. This unit pulled a three-axle semitanker and a five-axle (two on the dolly and three on the trailer) pup, both produced by Fruehauf Corporation. Both trailers were constructed with three tank compartments in each trailer providing for total capacities of 9,300 gallons on the semitrailer and 7,700 gallons on the pup trailer.

The vehicle underwent extensive preparation prior to testing. Most obviously, the outrigger assemblies seen attached to the trailers in Figure 3.10 were constructed and installed. These devices permitted tests to be conducted at maneuvering levels which would normally have resulted in rollover. With the outriggers in place, however, the vehicle remains upright and the safety of test personnel and equipment is not threatened. As an additional precaution, four-point shoulder harnesses were installed for driver and passenger protection.

Special modifications were made within the tanks to allow for proper loading. As noted above, the semi- and pup trailers have capacities of 9,300 and 7,700 gallons. When these tanks are loaded with gasoline, the resulting total vehicle weight is 152,000 pounds, distributed among the various axles, as shown in Figure 3.11. For

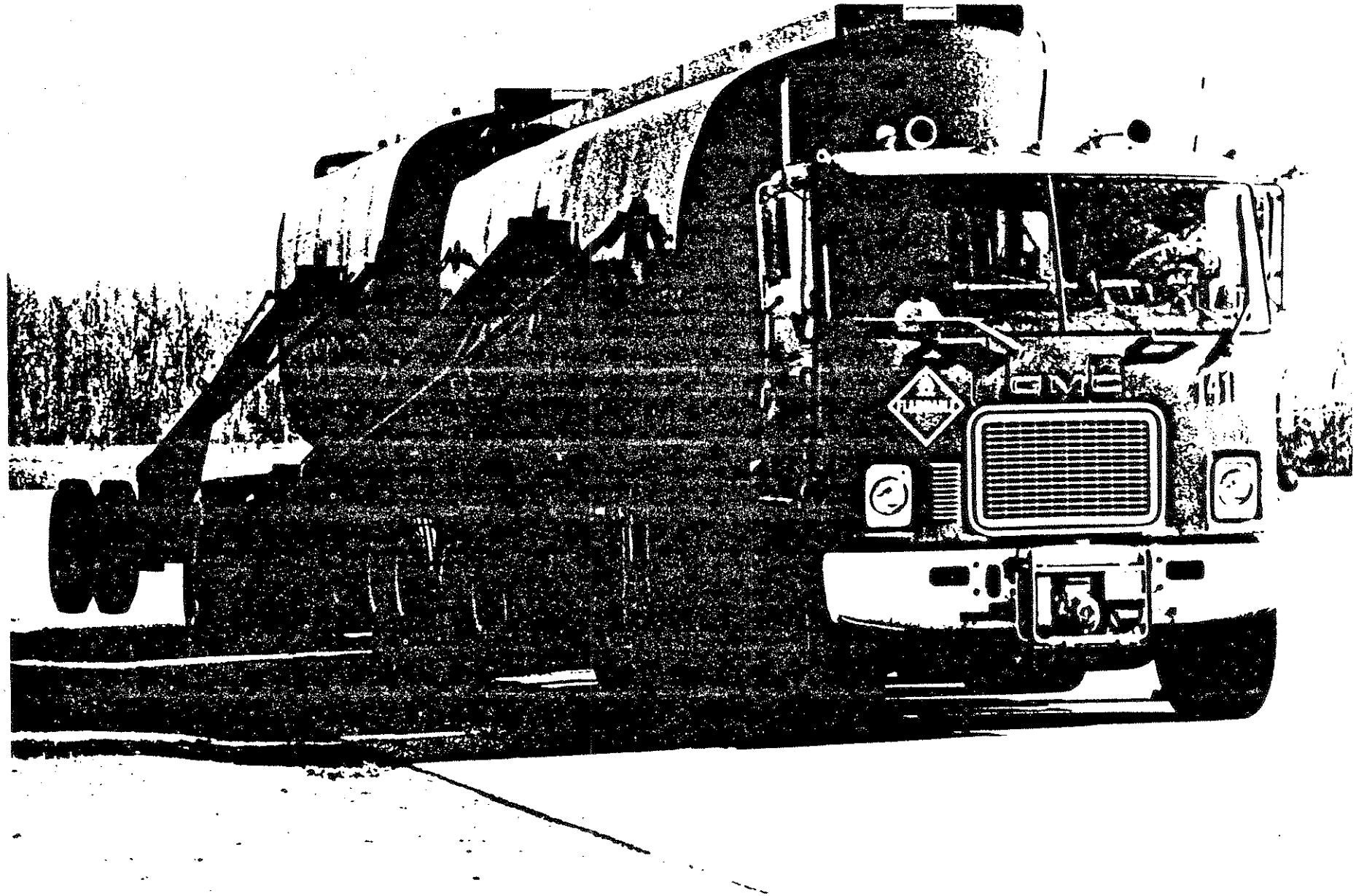
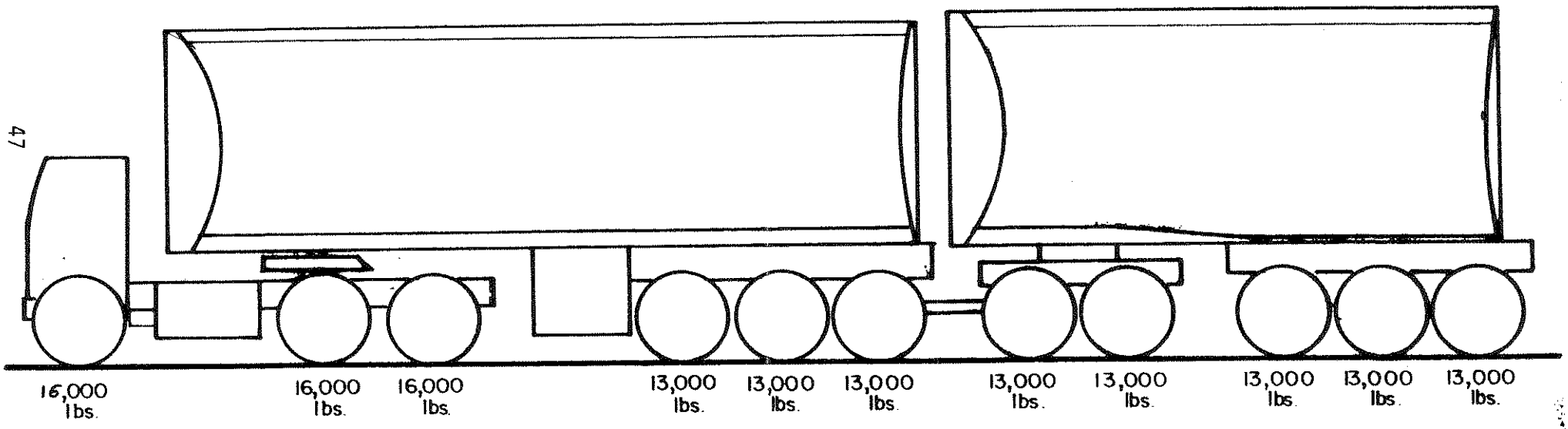


Figure 3.10. The test vehicle with outriggers installed.



Total Gross Vehicle Weight : 152,000 lbs.

Figure 3.11. Axle load distribution of the test vehicle.

obvious reasons of safety, it was desirable to use water rather than gasoline in these tests. Since water is about 34% denser than gasoline, however, the use of water as a test load required that tank capacity be altered by installing several sealed air chambers inside the trailer tanks. These chambers were located so that with the small center compartment in each trailer left empty, the other compartments of each tank could be filled with water, thus satisfying the following conditions:

a) The proper total weight and axle weight distribution would be achieved

b) Center of gravity height would be like that of a full load of gasoline

c) No excess free space would be present in any compartment, thereby preventing fluid sloshing.

The vehicle was also equipped with a special steering wheel. This wheel was fitted with two adjustable stops which could limit steering wheel motion to the desired amount in either direction. The mechanical stops were helpful in assisting the test driver in accomplishing the desired steering input.

The vehicle was also equipped with instruments providing measurements of ten different variables, viz.:

1) steering wheel angle
2) forward speed
3) tractor lateral acceleration
4) trailer* lateral acceleration
5) tractor yaw rate
6) trailer* yaw rate
7) trailer* roll angle
8) fifth-wheel (tractor/semitrailer) yaw articulation angle
9) pintle hook (semitrailer/dolly) yaw articulation angle
10) turn-table (dolly/pup trailer) yaw articulation angle

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*In the majority of tests the "trailer" was the pup trailer. In some tests, particularly those of the single trailer vehicle, these instruments were moved to the semitrailer.

During testing, recordings of the behavior of all these variables were made using pen chart recorders located in the cab of the tractor, as shown in Figure 3.12. Later, these recordings could be closely examined in the data reduction process.

One test vehicle was used in this program. This vehicle, however, was tested in differing configurations in order to gain test data on several classes of vehicles. The vehicle was tested in three basic configurations, viz.:

1) The baseline 11-axle Michigan double tanker.

2) The short Michigan single. The tractor-semitrailer which results when the pup trailer is removed from the 11-axle Michigan double.

3) The modified (or retrofitted) Michigan double bottom.

These three vehicles represent the present Michigan double-bottom tanker and its two primary replacement candidates for the near term.

The modifications included in the third vehicle above were threefold. They were:

1) a modified hitch mechanism between the semitrailer and the dolly of the pup trailer,

2) reduction of lash, or free play, in the spring elements of the trailer suspension, and

3) removal of the center axle of the pup trailer.

The standard hitch between the semitrailer and dolly is the three-point type shown in Figure 3.13. As illustrated in Figure 3.14, this hitch allows rotational freedom in all three directions, i.e., yaw (steering), pitch, and roll.

The modified hitch, shown in Figure 3.15, is a four-point hitch. This hitch is rigid, rather than free, in yaw and roll.

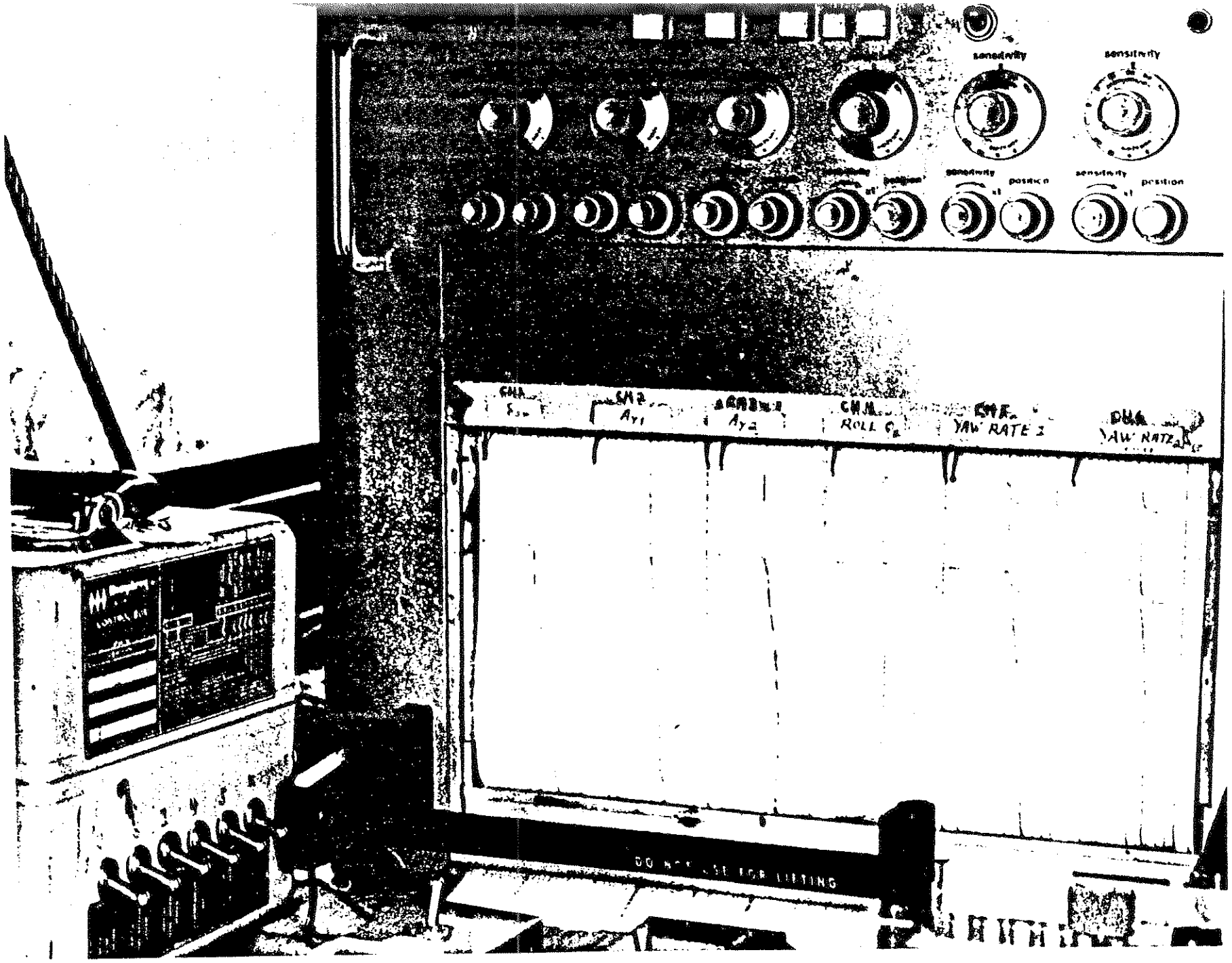

Figure 3.12. Data recorder in the cab of the test vehicle.

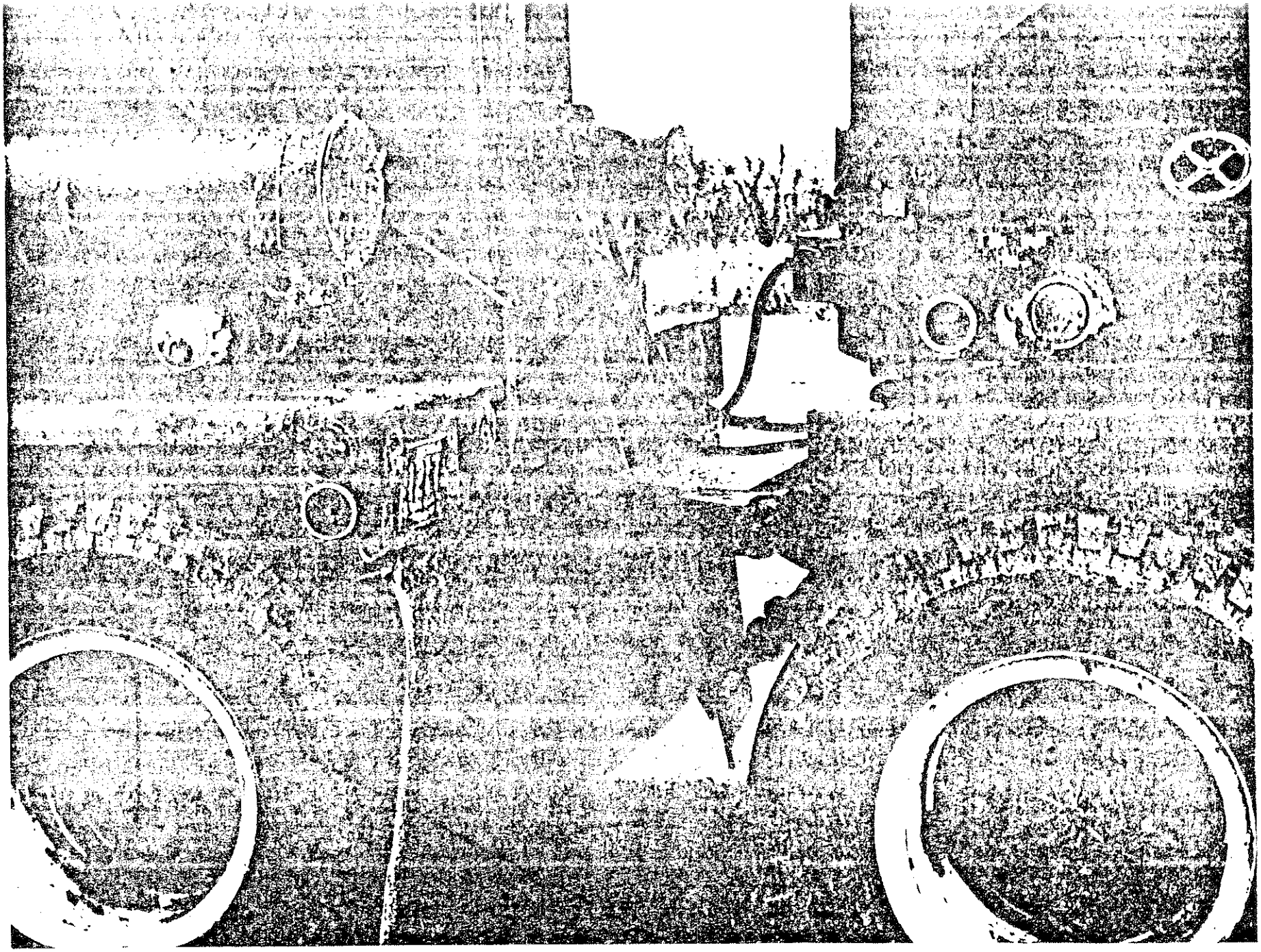

Figure 3.13. The standard, 3-point hitch in place between the semitrailer and the pup trailer dolly.

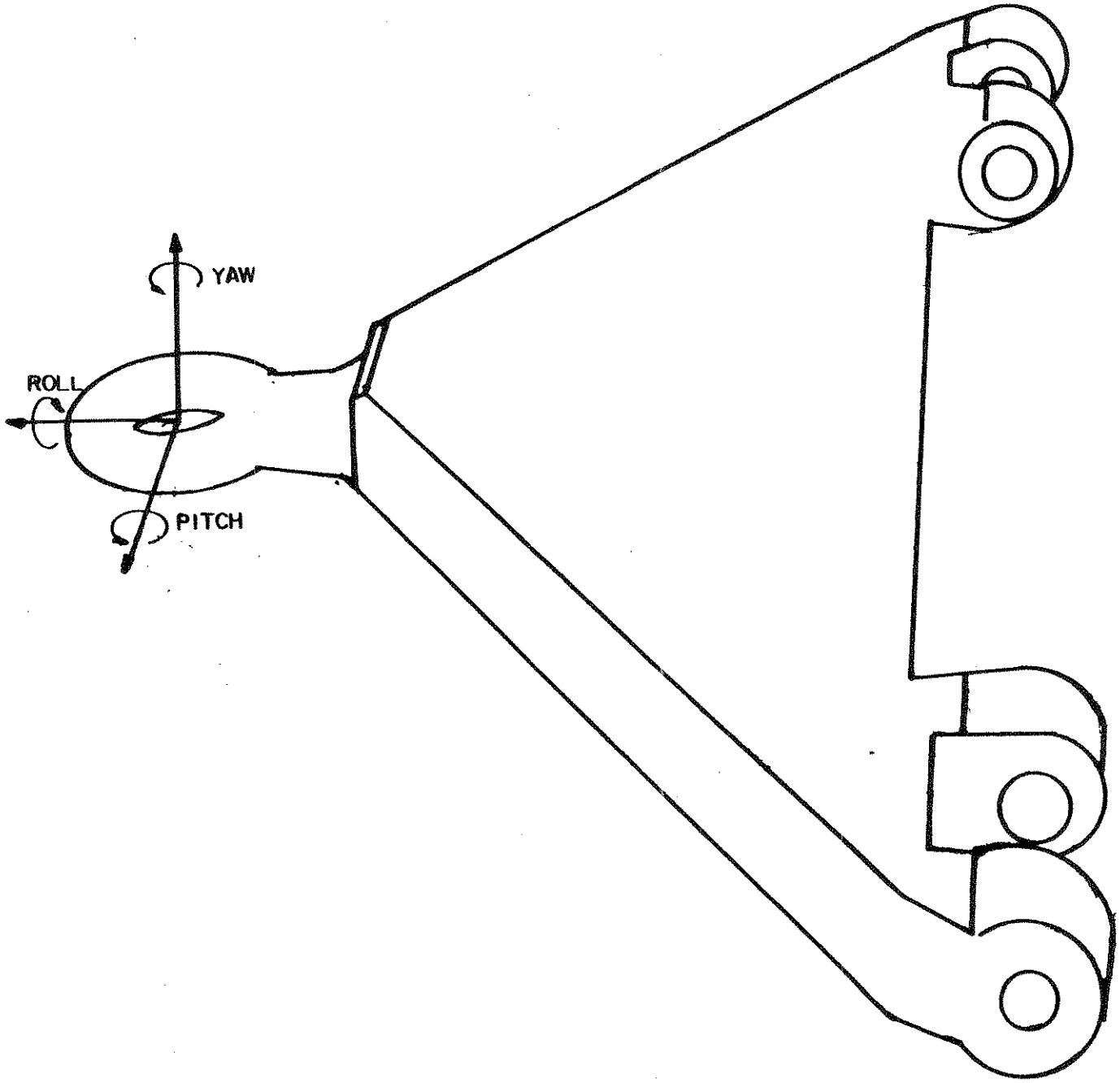

Figure 3.14. The standard hitch provides three degrees of rotational freedom.

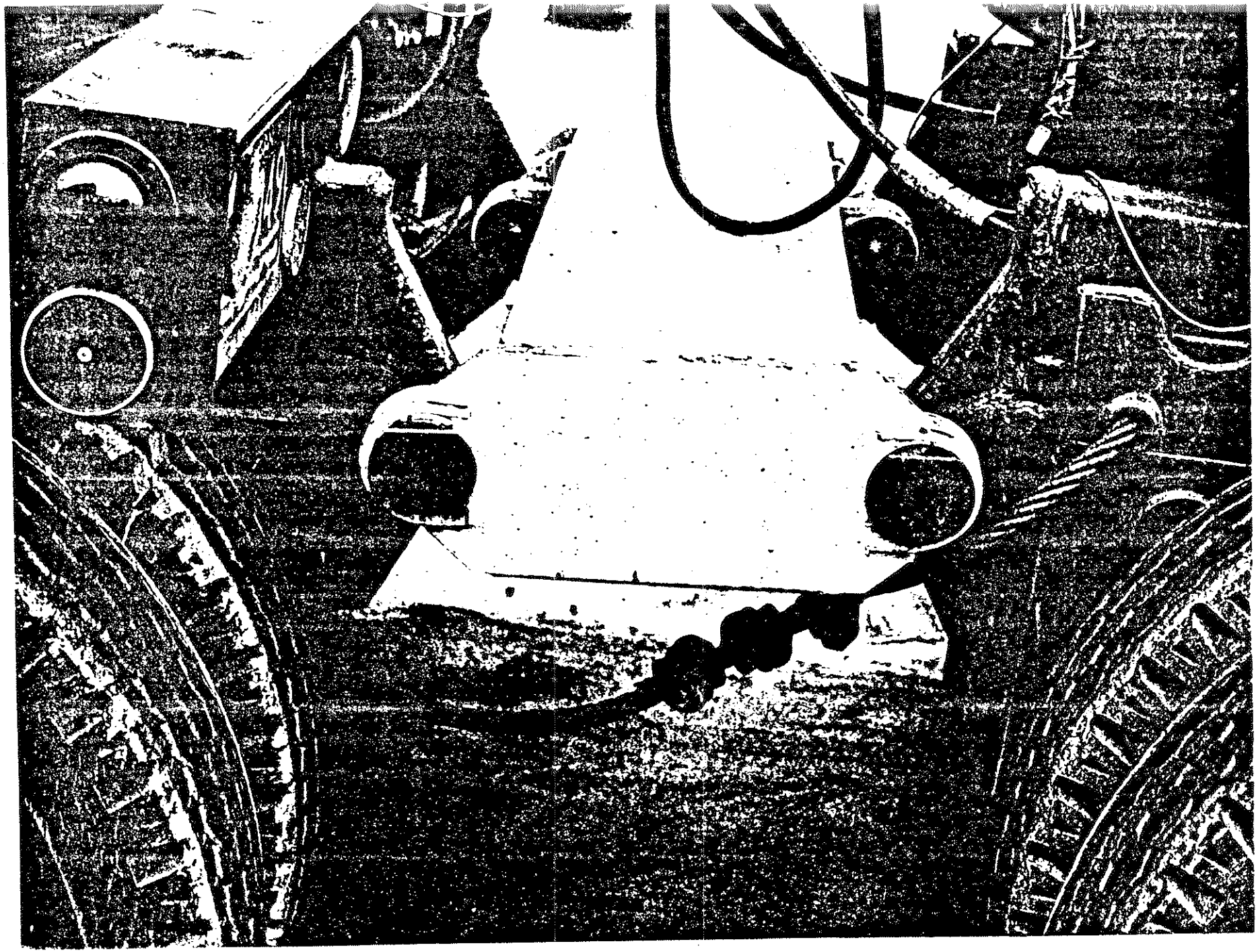

Figure 3.15. The modified, 4-point hitch in place between the semitrailer and pup trailer dolly.

With this hitch, the dolly tires remain aligned with those of the semitrailer (Figure 3.16), and the roll action of both trailers is coupled together.

In practice, the modified hitch is connected to both the semitrailer and dolly in much the same way that the standard hitch is presently connected to the dolly. That is, conical rubber bushings and steel pins are used to make the connection, as shown in Figure 3.17.

The second modification reduced the lash, or free play, in the trailer suspensions. As shown in Figure 3.18, the ends of the leaf springs used in the trailer suspensions rest in brackets fixed to the vehicle's frame. These brackets allow a great deal of free play* (about 1 1/2 in.) when the spring passes from tension to compression. To reduce this free play, holes were drilled and bolts were added to the spring hangers, as shown in the figure.

As the third modification, the center axle of the pup trailer (i.e., the forward axle of the rearmost three-axle set) was "removed." For test purposes, the whole axle was not actually removed; rather, the tires and wheels were taken off, and the inter-axle load leveler was blocked as necessary.

These three vehicles were tested, in both empty and loaded conditions, using three primary test maneuvers. These were

1) steady-state, constant radius turn
2) "pulse" steer
3) lane change, or sinusoidal steer.

The nature of the steering input and resulting vehicle path for each of these tests is shown in Figure 3.19. The steering inputs were accomplished manually by the driver with the aid of the mechanical stops on the steering wheel.

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*This free play is completely insignificant during virtually all operation of the vehicle except during the brief time interval of an unstable roll motion.

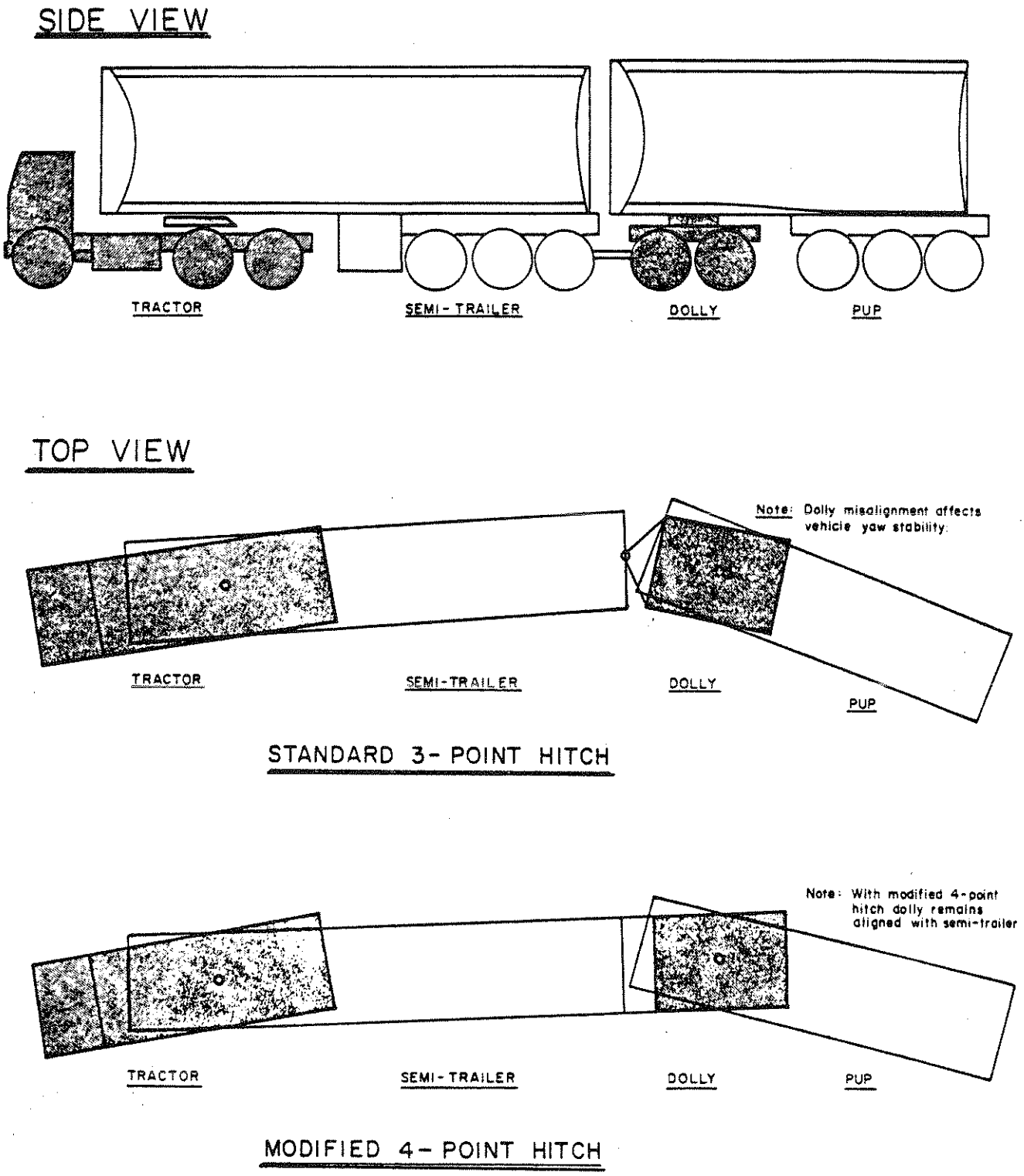

Figure 3.16. The effect of the modified hitch in yaw.

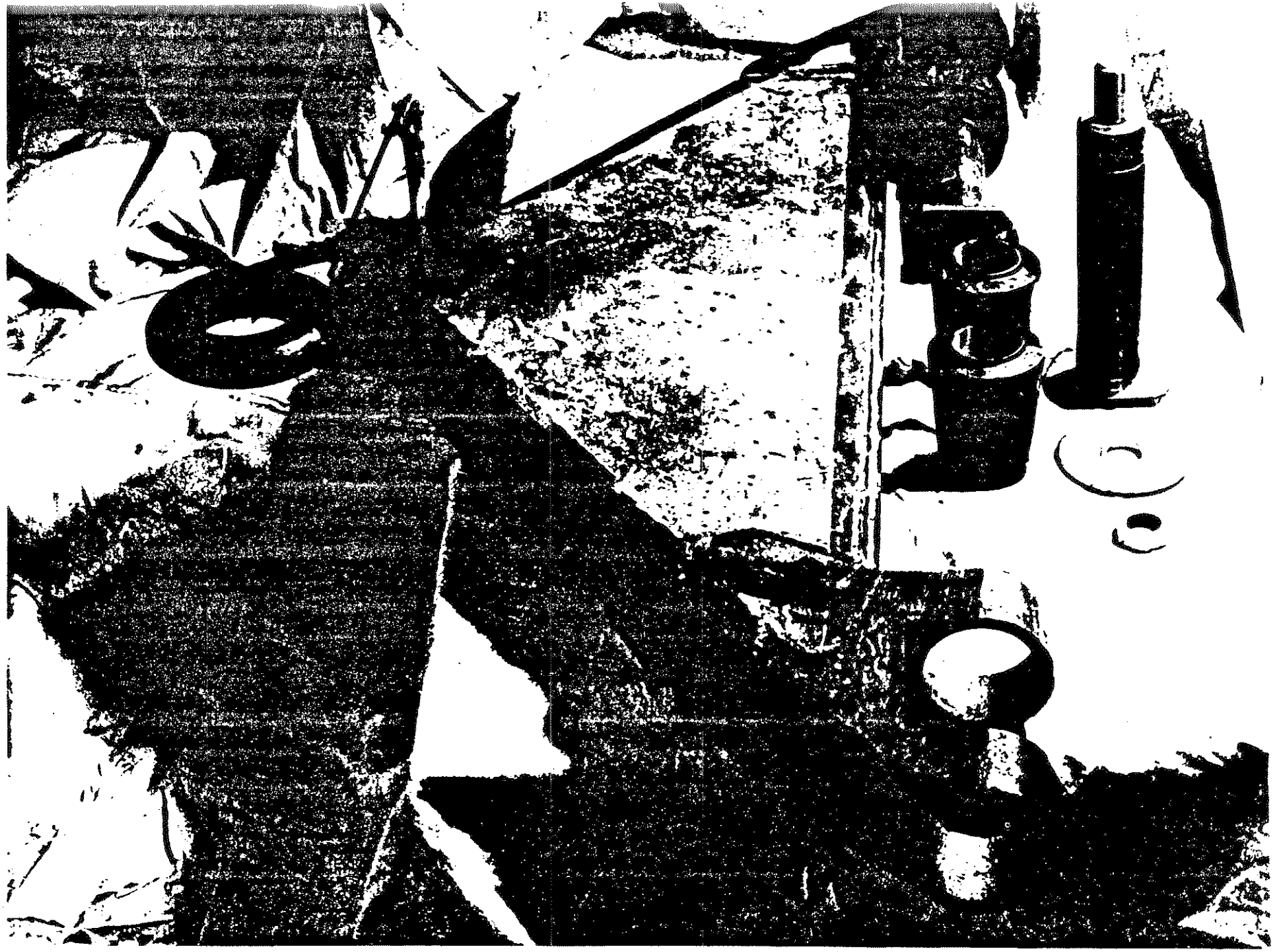

Figure 3.17. The standard hitch with installation hardware.

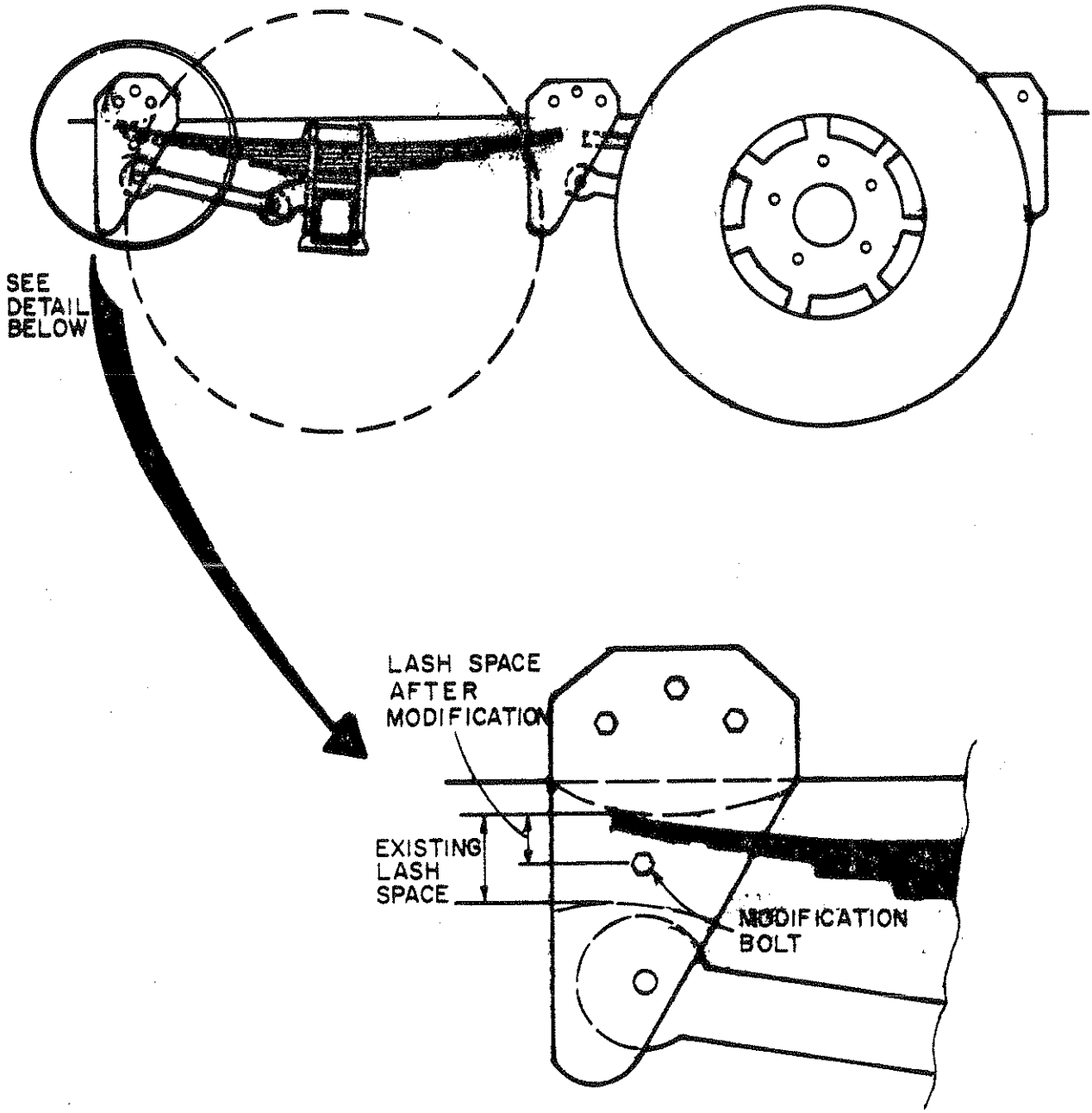

Figure 3.18. The spring lash modification.

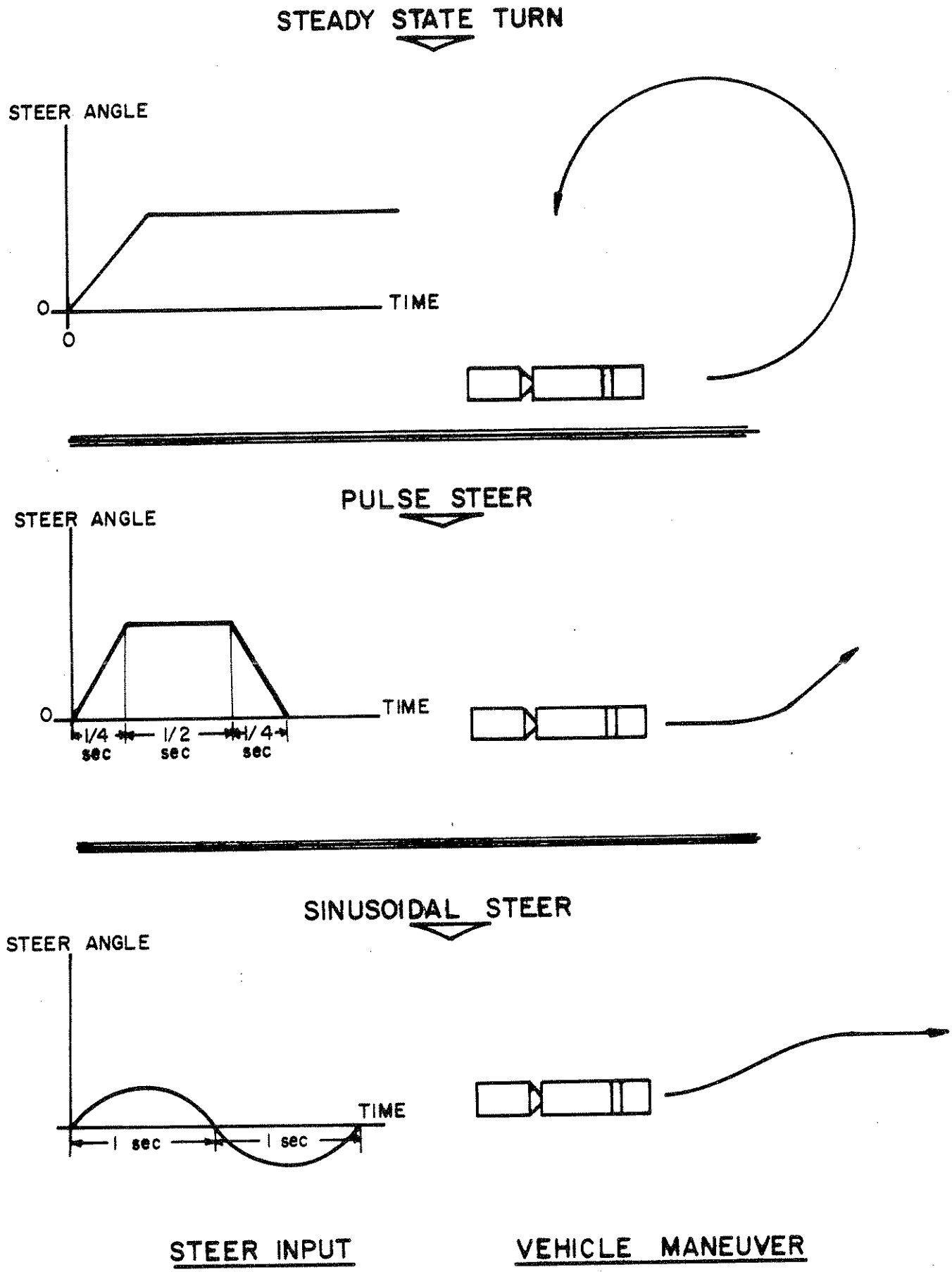

Figure 3.19. The three primary test maneuvers.

The data derived from testing were used for two purposes. The primary purpose was to examine the limit performance capability of the various test vehicles. The second purpose was to compare data gathered near the limit and at lower levels with earlier analytical predictions of vehicle performance in order to validate these predictions.

Limit performance comparisons were based primarily on the lane-change test maneuver. In this case, the "limit" was defined as the occurrence of outrigger touch-down. (With the outriggers properly adjusted for height, this condition virtually corresponds to the rollover limit of the vehicle without outriggers.) In this context, the test program showed the following:

- The baseline 11-axle Michigan double-bottom has an unusually low limit maneuvering capability.
- The short Michigan single tanker has a maneuvering limit of approximately twice that of the baseline double-bottom.
- The modified double tanker also has a maneuvering limit of approximately twice that of the baseline double-bottom. Thus the short single and the modified double are comparable in this respect.

The improvement in the performance limit of the modified double derives from just two (the hitch and spring lash modifications) of the three modifications tested. During the testing, the three modifications were made successively. First, the modified hitch was installed. Tests showed that this change accounted for the bulk of the improvement. Then, with the modified hitch still in place, hardware to reduce spring lash was installed, and an additional improvement on the order of 10% was observed.* When the

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*The original spring lash averaged approximately 1 1/2 inches. Modifications made in this program reduced this lash by about 50%. Presumably, greater reduction will produce more improvement. Lash values of 1/4 inch appear desirable.

center axle of the pup was removed, in addition to the first two modifications, no further improvement was noted.*

A small, additional portion of the test program examined off-tracking and low speed maneuverability. Simple off-tracking tests were accomplished at the test track. More significant tests were accomplished at five service station locations about Ann Arbor, Michigan. In these tests, a contemporary double-bottom tanker, a modified double-bottom tanker, and a conventional single bottom (i.e., the tanker commonly used in other states, not the "Michigan single") were maneuvered through the stations as they would be in delivering fuel. All these trials were made by one professional tanker driver. The results indicated that the two double-bottom units were nearly identical in maneuverability (the contemporary unit being slightly better) and that both were substantially more maneuverable than the conventional single tanker.

3.5 The Field Survey Task

A separate task of this project involved the conduct of a field survey to determine how large gasoline and oil tankers are actually used on Michigan roads. The survey addressed the generalized question, "What kinds of vehicles are carrying what products on what kinds of roads at what times of day?"

With the assistance of data provided by the Michigan Energy Administration, a list of the 65 pipeline, marine, and refinery terminals in Michigan was compiled along with their estimated distribution of gasoline in 1976. Fourteen of these terminals were selected by a controlled probability procedure, eight in Wayne County and six in the outstate areas. These terminals were then visited on one randomly selected day during the period February 6 to March 14, 1978. Up to five drivers were interviewed at each terminal to obtain

*We remain convinced that lengthening the wheelbase of the pup trailer has a stabilizing influence. However, this specific modification not only lengthens wheelbase, but also removes tires from the rear suspension of the vehicle. It appears that nonlinear effects of increasing load on the remaining tires serve to counteract any improvement gained by increasing wheelbase.

information describing the vehicle and all trips made by that vehicle on the sample date. The dates were assigned so that two terminals were contacted on each of the seven days of the week. Information was collected on 68 vehicles which made 245 trips on the sample dates, an average of 3.6 trips per vehicle. The average number of trips per vehicle at the Wayne County terminals was 4.3; a considerably larger number than the 2.7 average at the outstate terminals. This difference is explained by the fact that the Wayne County vehicles tended to travel shorter distances per trip and because they were much more likely to be used on a double shift, with two drivers in one day.

Among the 68 vehicles counted:

1) 15 were double-bottom tankers (only 3 in Wayne County, hauling fuel oil),

2) 21 were short Michigan singles (19 in Wayne County), and

3) 32 were single tankers of other descriptions.

Beyond these three general types, a great variety of configurations were found in terms of numbers of axles on the tractors and trailers and the number and size of the various compartments of the trailers. In all, there were 44 different configurations of these variables among the 68 surveyed vehicles, with the largest number of vehicles in any one configuration being six (that is, the short Michigan single with a three-compartment tank). The capacities of the surveyed vehicles ranged from 5,700 gallons to 17,000 gallons.

In terms of miles, the average round trip from outstate terminals was 74 miles, while the average round trip from Wayne County terminals was 43 miles. As would be expected, these miles were almost equally divided between driving loaded and driving empty. More than three-fifths of the loaded mileage for trips from Wayne County terminals was on urban freeways, and almost one-quarter was on other urban roads. For the loaded mileage on trips from outstate

terminals two-fifths was on rural freeways and more than half was on other rural roads. In regard to time of day, the most common time for tankers to be driving loaded was from 6-9 a.m. followed by the 9-12 a.m. period. Of course, the time of day during which tankers run loaded is spread out more for two-shift vehicles than for one-shift vehicles, and the concentration in the morning hours was therefore greater for trips from the outstate terminals than for trips from the Wayne County terminals. Almost all first-shift and single-shift drivers reported beginning work before 7:00 a.m. and 10-hour or longer days were reported by almost all drivers, many for five or even six days a week.

In regard to products carried, 205 of the 245 trips involved gasoline only, 37 involved fuel or diesel oil only, and there were three trips on which both types of petroleum products were carried. Presumably, fuel oil trips would be even less common during other periods of the year. There were also only 13 trips in which fuel was unloaded at each of two different destinations (all gas stations). There were no trips with more than two destinations. It is clear that single-destination trips are the general rule, even when the trip requires that the tanker be only partially filled because its tank capacity is greater than the quantity of the requested consignment. It was found that about 30% of the trips involved incomplete filling within one or more compartments at the terminal, and four other tankers traveled from a first destination to a second destination with certain compartments partially filled. Most of these partially loaded compartments were between 20% and 90% full, a range with a potential for significant slosh effect on the stability of the tanker. About one-sixth of the trips involved a significant slosh potential in more than one compartment. In addition, there were a number of trips in which one or more compartments were completely empty, a condition which also may affect vehicle stability, depending upon the locations of the empty and full compartments.

A more detailed report on the methods and findings of the field survey is in Appendix D, along with copies of the four survey forms which were used.

4.0 CONCLUSIONS

Based upon the analysis, testing, and survey tasks of this study and upon application of the state of knowledge on the dynamics of heavy vehicles, we conclude the following:

1) The baseline double-bottom tanker is exceptionally low in dynamic rollover stability, particularly in accident-evasion type maneuvers.

2) The specific type of instability which has been identified probably accounts for a preponderance of the accidents in which the pup trailer rolled over alone, leaving the tractor-semitrailer still standing. (Seven out of 13 rollover accidents recorded in the Detroit area were of this type.)

3) The baseline double can be modified to yield a twofold improvement in its rollover stability level. Such an improvement can be attained by installing, between the dolly and semitrailer, a hitch which is rigid in both the steer and roll directions and by installing devices in the suspensions to eliminate excessive clearance in the leaf spring constraints.

4) The modified double-bottom tanker exhibits a rollover stability level which is comparable to that of the short Michigan single tanker. (The "short single" is that tractor-semitrailer unit which remains when the pup trailer is removed from a doubles train.)

5) The modified double has slightly less maneuverability than the baseline double, although still requiring much less space to maneuver than any of the long wheelbase singles.

6) The pup trailer of the baseline double has a lightly-damped mode of yaw oscillation which can become unstable if only the rear compartment of the pup trailer is loaded and the vehicle speed exceeds 50 mph. (One recent rollover accident can be attributed to this instability.)

7) Operation of fuel tankers with any compartments only partially filled risks a reduction in the rollover threshold.

8) Field survey results show that tankers transporting fuel in Michigan frequently operate with partial loading.

9) Virtually all current double and single trailer combinations of any kind, and perhaps many straight trucks as well, incorporate a suspension feature which, though traditionally disregarded as harmless, can reduce the dynamic rollover threshold by as much as 15%. This feature,* involving free play in the vertical location of suspension leaf springs, can be almost eliminated with a minor modification.

10) The delivery of fuel using short Michigan single tankers probably yields the highest exposure of the traffic system to fire hazard of all known fleet options (excluding the unmodified double-bottom tanker).

11) The delivery of fuel using conventional 9,000-gallon single tankers may yield an exposure to fire hazard which is equal to or somewhat greater than that of modified double-bottom tankers and large single tankers.

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*Note that this conclusion attaches a broader significance to one of the mechanisms which contributed to the low rollover stability of double-bottom tankers. The significance is that virtually all heavy road vehicles in the nation are suspected of suffering from this compromising feature.

5.0 RECOMMENDATIONS

1. The type of tankers represented by the baseline double investigated in this project should not be permitted to operate on the Michigan highway system for reasons of public safety.

Discussion

The baseline double used in this project is considered representative of a type of tractor-semitrailer-fulltrailer tanker* which may be characterized by a capacity near 17,000 gallons (approximately 150,000 lbs gross vehicle weight), designed to operate within a nominal 55-foot length law, and consequently having overall trailer heights in the range of 150-160 inches. The findings of this project can be summarized without reservation by the statement that double tankers in this group exhibit a level of stability which is insufficient for safe highway operation. The safety issues relating to stability are of such a serious nature as to merit removal of these vehicles from the highway.

2. In the short term, we recommend that tankers of the baseline double type be modified to improve their stability to the level demonstrated in this project.

Discussion

We see that an interim period will prevail between our current situation, with unmodified doubles still in service, and a future date at which advancements in tanker design may materialize to improve traffic safety. During this interim, it appears that modified double-bottom tankers of the baseline type will offer an overall safety performance which competes well against other existing alternative vehicles.

*The double tanker, as retrofitted in this study, is a type of tractor-semitrailer-semitrailer vehicle.

3. In the short term, we recommend that double tankers, other than the baseline configuration of this study, be modified to achieve at least the stability level of the modified baseline tanker of this study.

Discussion

We recognize that for our recommendations to be useful, they must generalize to include double-bottom tankers other than the specific baseline vehicle of this study. We have separated this recommendation from the above, however, to emphasize that it is made on the basis of our best engineering judgment, rather than on specific, hard findings as obtained in this study.

It would appear that virtually all other double-bottom tankers commonly used to haul fuel in Michigan (i.e., 10-axle versions, etc.) could be rendered at least as stable as the modified double of this study through the direct application of the two cited modifications. This expectation is based on the propositions that: (1) the 11-axle double studied herein probably begins as the least stable of the many varieties of double tankers in common use in Michigan (especially because of its high center of gravity and short effective wheelbase of the pup trailer), and (2) the modification techniques can be expected to have generally the same effect on all these double combinations.

4. We recommend that wide use of the short Michigan single be discouraged, if not prevented.

Discussion

Given other transportation options which have come to light, namely, the modified double, there appears no rational basis, from a safety point of view, for supporting the general use of the short Michigan single. When comparing vehicles on an individual basis, the short single and the modified double represent nearly identical stability limits. However, considerations of accident exposure clearly lead to the conclusion that a fleet of modified doubles is much more favorable than a fleet of short singles.

The baseline modified double has a total product volume capacity which exceeds that of the short single by about 83%. Thus, to accomplish the same product delivery task, a fleet of singles would necessarily have to travel approximately 83% more miles than a fleet of modified doubles. It follows that the general highway safety risk presented by the fleet of short singles would be greater than that of a fleet of modified doubles by approximately the same percentage.

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5. Partial loading of all tankers should be discouraged, especially partial filling of individual compartments or loading of only rearward pup compartments.

Discussion

Partial loading should be considered in two distinct groupings, viz.:

1) loading conditions in which individual compartments are partially filled which allows liquid sloshing to occur, and

2) loading conditions in which some compartments are filled and others are empty which results in fore/aft shifts of the vehicle's center of gravity.

Considering the first condition:

Generally speaking, partial loading of individual compartments downgrades the rollover stability of the tanker relative to its stability at full load because of the liquid sloshing effect. Of course, when the partial load is sufficiently small (say, less than 25%) rollover stability can be better than it is at full load. However, in other load ranges (25%-80%) the degradation in rollover stability can be rather severe. Thus it appears prudent to generally discourage any partial loading of individual compartments.

With regard to the second condition:

As a general rule of thumb, moving a vehicle's center of gravity rearward tends to degrade its directional (steering) stability. In the specific case of the baseline double tanker, the condition in which the rearward compartment(s) of the pup trailer are loaded, while other forward pup compartment(s) are empty, is a severely hazardous condition. In this condition, the pup may demonstrate an unstable, oscillating yaw response at speeds above 50 mph. That is, above 50 mph, the pup may sway back and forth in an ever increasing manner until rollover occurs, even though the tractor is simply traveling on a straight course.

Thus, the unloading of rearward compartments first should be encouraged.

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6. An in-service trial should be conducted for all vehicle modifications before any mass introduction of retrofitted vehicles takes place.

Discussion

We recognize that this recommendation may not be easily implemented through rulemaking action, but rather may be addressed through the initiative and cooperation of the vehicle manufacturing and truck transport industries.

The purpose of an in-service trial is to insure that proposed modifications (1) be placed under the scrutiny of vehicle manufacturers who are skilled in assessing structural integrity of vehicles in actual service, (2) provide the desired braking and handling characteristics under all of the myriad conditions which are encountered, and (3) do not unduly hinder the transportation mission of the vehicle.

Clearly, this recommendation represents a conservative approach toward implementing the vehicle modifications developed in this study.

It is suggested as a wise step, not because of concerns over the general validity of the findings of this study, but in the recognition that the real operating environment offers the final basis of proof—such proof is best established using a few vehicles under close observation rather than a whole fleet running without any constraint.

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7. Any policies which effect a change in the makeup of the tanker fleet transporting fuel in Michigan should account for changes in the total exposure of the traffic system to fire hazard.

Discussion

Tanker fires are known to occur in both rollover and non-rollover accidents. Vehicles are generally expected to be involved in non-rollover accidents simply in proportion to their numbers in service. Thus, tankers existing in greater numbers will be involved in greater numbers of non-rollover related fires. Tanker fires involving rollover can be expected to occur in proportion to the number of vehicles in service, as adjusted by the relative rollover stability of the vehicle types involved. Examination of these relationships indicates that tankers of larger carrying capacities, implying a smaller number needed in service, contribute a benefit which is of comparable importance to the benefits of rollover stability. Accordingly, policies intended to reduce fire hazards need to appropriately consider both the number and rollover stability of tankers in service.

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8. Future research into (1) optimum tanker design, (2) the influence of road use laws on commercial vehicle design, and (3) the dynamic properties of doubles used to transport various non-hazardous cargos should be performed.

Discussion

As implied by the nature of this recommendation, there are a number of topics of pertinent interest which were not addressed

in this ad hoc study. This recommendation selects three areas in which the methods, models, and experience gained in this study provide a foundation for future research.

First, with regard to "optimum" tanker designs, we certainly do not believe that the modified baseline double is necessarily the best vehicle that can be developed in the long term. Indeed, the results of this study indicate that considerable improvement in the directional and rollover performance of tanker vehicles can be made. We see that tanker designs have recently emerged, notably in Canada, offering many of the features which our investigation has shown to be in favor of stability and overall safety performance. In a broad view of the design alternatives that exist, there is strong reason to believe that some type of double trailer vehicle may hold the broadest number of advantages as an optimized configuration for transporting liquid cargo.

In developing new commercial vehicles, road use laws are an important consideration influencing the final design of a vehicle. The existing road use laws in Michigan have undoubtedly contributed to the design of vehicles which are unique to the State of Michigan. Given constraints on the length and width of a vehicle, and the maximum allowable load on various axles, the basic design of a vehicle to provide maximum payload capacity is largely determined. There remains only the number and location of articulation joints to be decided on the basis of the maneuverability needed to deliver the product. Accordingly, the implications of road use laws on vehicle design need to be thoroughly examined.

The study of road use laws should be approached from two directions. Firstly, of course, allowable vehicle loading must be within the practical limits needed to protect roadways and bridges. These concerns have formed the basis for existing road use laws in Michigan and elsewhere.

It now seems imperative, however, that the road use law should effect constraints on vehicle design in the light of the connection between vehicle design and safety, as well. This is a newer approach which acknowledges that not all vehicle designs are equally "safe" even when the hardware is unworn and in "perfect" condition. Moreover, to lay the groundwork for an improved road use law, a number of roadway, vehicle, and other considerations should be addressed in future research investigations.

Finally, the results of this study draw our attention to the fact that double-bottom vehicles are used extensively to haul cargo other than liquid fuels in Michigan. For example, doubles are used to haul dry goods, gravel, milk, and other commodities. It is possible that some of these vehicles have dynamic properties similar to the baseline double tanker investigated in this study. In the interest of highway safety, it seems wise to use and extend the methods developed in this program to study the dynamic characteristics of all currently used double-bottom vehicles.

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