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EFFECTS OF TIRE PROPERTIES ON TRUCK AND BUS HANDLING

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16. Abstract

The principal thrust of this project was to identify the importance of the traction properties of truck tires in determining the steering and braking response of light and heavy commercial vehicles. The study generated a large quantity of parametric data describing the commercial vehicle and, especially, its tires. Tests on a large sample of light and heavy truck tires were conducted using two laboratory and one over-the-road tire test device. A computerized simulation study, providing a mechanistic understanding of the response sensitivity of the open-loop vehicle to tire properties was conducted. Full-scale vehicle tests permitted validation of the simulation and reinforcement to the basic findings obtained through computerized analysis.

Findings of this study include the illumination of significant differences in the qualitative performance characteristics of truck tires relative to passenger car tires, and the manner in which these unique truck tire properties may affect the yaw stability of the commercial vehicle. Potential problems of vehicle stability were dramatically illustrated by a rollover incident which occurred during testing of a heavy truck.

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1.0 INTRODUCTION

This document constitutes the summary final report on a research study entitled "Effects of Tire Properties on Truck and Bus Handling" which was conducted by the Highway Safety Research Institute of The University of Michigan. The study was supported by the National Highway Traffic Safety Administration of the U.S. Department of Transportation under contract DOT-HS-4-00943.

This research is based upon the application of the fundamentals of tire and vehicle mechanics to specific considerations of the control behavior of light and heavy commercial vehicles. In this regard, the tire properties of interest are those which determine shear forces and moments such as are generated during steering and braking maneuvers.

Shear force and moment properties, hereinafter referred to as "traction properties," are confined in definition, here, to highway operating conditions—specifically involving nondeformable pavement-type surfaces. Vehicle maneuvering conditions are not limited in their treatment and cover the full range from low-level path-keeping tasks to severe accident-avoidance maneuvers.

To the extent that this study examines vehicle maneuvering only in reference to the physical characteristics of the (open loop) tire/vehicle system, the term "handling" in the project title may be judged a misnomer since, to many, "handling" implies the closed-loop control performance of the driver/vehicle system. For the commercial vehicle very little, if indeed any, research has ever been reported describing examination of closed-loop behavior. This contrasts with a substantial, though by no means comprehensive, body of literature pertaining to passenger car handling.

Examination of the open-loop behavior of heavy commercial vehicles preceded the study reported here, particularly in the form of a DOT-sponsored study entitled "Truck and Bus Handling" [1]* in which "handling" again was employed to title an investigation of open-loop properties. The "Truck and Bus Handling" study developed a set of heavy-vehicle test procedures which were employed in full-scale experiments conducted during the project reported here. The unplanned rollover of a large truck during application of these test procedures during this study led to subsequent findings on truck yaw stability which are not known to have been reported previously.

The principal thrust of this project was to identify the importance of tire traction properties in determining the steering and braking responses of trucks and buses. To that extent, this study can be viewed as the extension, for commercial vehicles, of another recently completed DOT-sponsored project entitled "Effects of Tire Properties on Passenger Car Handling" [2]. The contrast between cars and trucks is indeed significant, however, despite a commonality in the basic physics involved. Since the commercial vehicle's mission implies that payload constitutes the raison d'etre for such vehicles, we find loaded-to-unloaded weight ratios for heavy trucks, for example, to be on the order of 2:1 to 5:1 as compared to a 1.3:1 value of the same measure for a typical mid-sized passenger sedan. It was found that commercial vehicle payloads profoundly influence basic vehicle properties and impose severe demands on the performance of the commercial vehicle tire. Additionally, suspension and axle configuration differences between cars and trucks provide a number of contrasting mechanisms and levels of sensitivity which render the tire's role in the performance of the respective vehicle classes to be worthy of independent study.

In further contrast between passenger and commercial vehicle systems, it should be noted that the published data base describing the traction properties of car tires is immensely greater than

*Numbers in brackets refer to References listed at the end of this report.

that describing truck tires. Accordingly, it was necessary, in this study, to conduct a large number of truck tire measurements thereby establishing a data base for use in computerized simulations of truck and bus response. Thus, this study has generated a body of findings pertaining to the traction properties of commercial vehicle tires, themselves, as well as findings pertaining to the control behavior of the overall tire/vehicle system.

2.0 RESEARCH METHODOLOGY

2.1 Introduction to the Methodology

The study was designed so as to generate a large quantity of parametric data describing commercial vehicles and, especially, their tires. The parameter measurements were obtained to permit a computerized simulation study which provided a mechanistic understanding of the response sensitivity of the open-loop vehicle to tire properties. Full-scale vehicle tests were also conducted to permit validation of the simulation and to provide a reinforcement, wherever possible, to the basic findings obtained through computerized analysis.

The focus of the study was on the commercial vehicle tire as a force and moment producing mechanism. Thus the relevant parametric characterizations derived from the use of traction testing apparatuses especially suited to measurement of the shear force and moment response of heavy tires. These test machines are comparable to apparatuses employed in the traction measurement of passenger car tires, but are appropriately scaled up in load capacities. Since machinery for measuring truck tire traction has only been available recently, the literature documenting such measurements is relatively scarce, thus the need in this study to obtain, through direct experiment, data exemplifying even the more fundamental truck tire properties.

Similarly, the mathematical modeling of a specific truck or bus requires that a large array of generally unavailable design parameters be obtained through direct measurement. Thus, various laboratory apparatuses were employed to directly measure inertial properties of the sprung and unsprung masses as well as the kinematic and compliance characteristics of steering and suspension systems.

Prediction of the nonlinear behavior of truck and bus vehicles is a sufficiently complex analytical task that only computerized calculations are feasible. Accordingly, two "state-of-the-art" simulations were employed to permit a general study of vehicle response sensitivities to tire properties and to provide a means for more specific investigation of truck directional stability.

In this section, the various methodologies employed in the study will be summarized.

2.2 Methods Employed to Measure Tire Traction Properties

Direct measurements of the traction characteristics of light and heavy commercial vehicle tires were obtained using three different test systems. Data obtained with each machine pertain to the shear force and moment response of the specimen tires under conditions of dry, uncontaminated, non-deformable surfaces.

Firstly, a low-speed laboratory device, the HSRI flat-bed machine, was used in the tire test program. This apparatus applies the specimen tire to a flat plank which traverses at a rate of 1.4 mph. The test tire is sustained at selected conditions of vertical load, F_z, slip angle, α, and inclination angle, γ, for both right-going and left-going passes of the bed. Insofar as the bed velocity is very low, the data obtained through flat-bed measurement is most suitable for that operating regime in which slip velocities are low.

Thus, flat-bed measurement can be looked upon as primarily addressed to the examination of structural compliances such as are manifested in force and moment response at small values of angular slip.

A total of 40 tires were tested on the flat-bed machine during this study. Each tire was subjected to a matrix of vertical load and slip angle conditions covering the full operating regime.

The Calspan Corporation's Tire Research Facility (TIRF) was employed in this study to provide measures of traction sensitivity to velocity and to examine combined slip properties. The TIRF machine employs a flat steel belt as the test surface while exposing the test tire to the desired conditions of slip, load, and velocity.

Two tire types were tested on the TIRF facility—providing a view of light and heavy tire velocity sensitivities as well as an indication of the extent to which such tires alter their traction behavior as a consequence of test-induced wear.

The tire test apparatus employed to measure traction properties "over-the-road" was the HSRI Mobile Truck Tire Dynamometer. This tractor-trailer device permits measurement of longitudinal behavior by way of the trailer-mounted fixture while lateral properties are obtained using an assembly mounted as an undercarriage to the tractor. As with laboratory machines, the mobile apparatus exposes the tire specimen to controlled conditions of load, slip, and velocity, but with the added realism of representative road surfaces. Thus the device is particularly suited to the characterization of traction performance at elevated levels of slip—for which the frictional coupling between tire and pavement determines the level of developed shear forces.

A total of sixteen light and heavy truck tires were tested on the lateral traction machine and eight heavy tires were also examined in mobile longitudinal tests. All of these tires were mobile tested on the Portland cement concrete track at the Dana Truck Test Center in southeastern Michigan. Additionally, certain mobile tests were conducted at the Texas Transportation Institute (TTI) in order to characterize the surface on which vehicle tests were performed.

2.3 Methods Employed to Conduct Vehicle Tests

2.3.1 Vehicle Sample. A sample consisting of two light and two heavy vehicles was selected for full-scale test measurement. These vehicles were chosen to represent light truck and bus (van) classes and heavy truck and bus classes. In addition to being employed in a program of full-scale tests, the sample was also applied in a set of laboratory measurements which provided the design parameters needed to simulate the four vehicle selections.

The light vehicle selections were chosen with sufficiently high gvw ratings that "LT Series," rather than passenger car series tires (as defined by the Tire & Rim Association) were provided as original equipment.

The selected heavy truck was chosen in the two-axle configuration to provide a simplified system which was more compatible with a program concentrating upon tire properties. The test truck was obtained by loan from the White Motor Corporation and was incorporated in the program as a "straight truck" rather than as a tractor, although vehicles of this type are commonly employed in either role. An "original equipment" tire for the heavy truck was selected, rather than specified by the manufacturer, since most of such vehicles are custom-assembled according to the purchaser's request (including tire designation) rather than according to a standard design.

The selected heavy bus was of the "intercity" variety and was leased from the Greyhound Corporation. This was, likewise, obtained in a two-axle configuration to permit simplified isolations of the tire's role in vehicle behavior. Again, as with the heavy truck, the "original equipment" tire was actually a baseline selection made somewhat arbitrarily given that the vehicle user, rather than the original manufacturer, determines which tires shall be employed.

2.3.2 Vehicle Test Methods - Apparatus. Light and heavy test vehicles were subjected to a common set of open-loop test procedures involving steering and braking inputs which were applied through the action of precision servomechanisms. Thus, each test vehicle was outfitted with a complement of test apparatus which applied control displacements to the steering shaft and brake pedal automatically. Additionally, input and response data were gathered using various on-board transducers whose output signals were telemetered for recording at a ground station.

2.3.3 Vehicle Test Methods. Vehicle tests were conducted at the facilities of the Texas Transportation Institute (TTI) in College Station, Texas, according to open-loop test procedures developed under the research contract of Reference [1]. Test procedures encompassed three basic maneuvers: braking in a turn, lane changing, and severe, or J-turn, steering. (Straight-line braking tests were also conducted as a means of meauring brake system parameters.) Each test was performed through the application of precision steering and braking inputs whose functional form renders a maneuver of one of the three described types.

In this study, as in the preceding work [1], steering input levels and test velocities were chosen so as to avoid maneuvering severities in the vicinity of each vehicle's rollover limit. Thus the data deriving from full-scale tests represents, in general, the sublimit behavior of the vehicles examined.

The sensitivity of vehicle response to tire properties was examined in a limited way using tire sets which were selected from flat-bed traction test results on the basis of their atypical cornering behavior.

The light van test vehicle was tested using its "OE" tire selection and an "extreme variation" selection comprised of the OE tire on the front axle and a selected snow tire on the rear. Tests were run both loaded and empty on both dry and wet asphalt.

The heavy truck was tested in its OE tire configuration on a wet surface but suffered a demolishing rollover while attempting certain setup runs in preparation for braking in a turn on dry asphalt.

The pickup truck was subjected to tests with four tire arrangements. In addition to vehicle tests involving the OE tire, the vehicle was operated with three other tire arrangements covering construction variations as well as a rib tread/snow tread mix.

2.4 The Simulation of Tire/Vehicle Behavior

Two mathematical simulations of tire/vehicle systems were employed in this study. A major parametric sensitivity study was conducted using the hybrid simulation at the Applied Physics Laboratory of Johns Hopkins University. This computerized tool, based upon a fifteen-degree-of-freedom model, was applied in the simulation of all four selected test vehicles. Simulations representing a large variety of tire installations were performed, following modifications to the APL program permitting the entry of tire-descriptive data in tabular form.

Another portion of the study involved computerized simulations employed in the HSRI "Phase II" digital simulation of heavy trucks and tractor-trailers. This thirty-two-degree-of-freedom model was applied in a set of steering-only calculations aimed at examining the sensitivity of truck yaw stability to a variety of vehicle design and loading parameters. The limited study of yaw stability was prompted by the observation that a mild yaw divergency had resulted in the inadvertent rollover of the heavy truck during testing.

The HSRI simulation, validated during previous efforts, was exercised first to examine the extent to which the test incident may have been merely an isolated anomaly, and, secondly, to identify the primary vehicle configuration parameters which influence the directional limits of heavy trucks. These calculations were not restricted to variations in tire characteristics, alone, but rather included the major elements of heavy truck design which might be hypothesized to impinge upon the balancing of the directional moment during a J-turn type of maneuver.

Insofar as the test truck was of the type commonly applied as the tractor of a combination vehicle, additional calculations were run with this truck coupled to a suitably matched semi-trailer to determine the generality of the observed yaw response anomalies. Results of this simulation effort clarify the observations of marginal truck yaw stability and form a basis for the conclusion that a finding of potential significance to traffic safety has been discovered.

3.0 CONCLUSIONS AND RECOMMENDATIONS

This study has endeavored to apply the principles of engineering mechanics in a concentrated examination of the heavy truck and bus tire and its influence on the control behavior of commercial vehicles. A primary output of this study has been the expansion of the data base defining the traction properties of the commercial vehicle tire. An equally important output, however, is the extension of the state of knowledge concerning the mechanical properties of commercial vehicles themselves—with this extension putting into focus numerous features for which an analogy with the passenger car fails. The failure of various "rules of thumb" concerning control relationships based upon passenger car experience and technology appears to be a significant general finding. Insofar as the great preponderance of literature treating the mechanics of motor vehicles is based upon passenger cars and upon tires suited to passenger cars, it is relevant to be concerned about the validity of applying the state of the art in passenger vehicle dynamics to trucks. Although there should be no "surprises" in applying the basics of passenger car analysis to trucks, the application appears to become increasingly tenuous as one endeavors to simplify a commercial tire-vehicle system according to generalizations that arise out of passenger car experience.

A number of specific findings and observations have derived from this study in support of the foregoing general conclusion. Although certain of these findings are believed to constitute new discoveries, others have been cited in the text as confirming previously published results. The following conclusions summarize specific observations of the study and serve to elucidate the mechanical behavior of commercial vehicles and their tires.

3.1 Conclusions—Concerning the (dry) longitudinal traction properties of commercial tires:

1) The commercial vehicle tire exhibits a large falloff in longitudinal shear force capability at values of longitudinal slip beyond which peak traction prevails. This behavior contrasts markedly with passenger car tires which typically yield a small falloff, if any, on dry pavements.

2) The various tread and carcass constructions currently used in commercial vehicle tires exhibit a broad range of longitudinal stiffness (namely, longitudinal force per unit slip in the domain of normal braking).

3) Peak braking traction afforded by commercial vehicle tires is comparable to that obtained with passenger cars, although "slide" values are markedly lower.

4) Both peak and slide values of the braking traction of commercial tires normalized with respect to the vertical load are significantly sensitive to the imposed value of vertical load, invariably reducing their traction potential as load increases.

5) Slide values of braking traction reduce markedly with vehicle velocity, especially in the range from 0 to 30 mph, whereas peak traction is only slightly influenced by velocity.

6) The lug or cross-bar type truck tire typically exhibits lower levels of braking traction than tires configured with the rib-type tread pattern. This characteristic of lug tires particularly influences the braking performance of heavy trucks and tractors because of the widespread, year-around use of these tires on the drive axles of these vehicles.

7) The braking traction of tires employed on heavy commercial vehicles is observed to be remarkably stable throughout extended test sequences whereas limited measurements have shown light truck tires to be rather sensitive to test-induced wear.

Concerning (dry) lateral traction properties:

8) A large range in values of cornering stiffness, C_α, is available among the various tread and carcass constructions represented in the commercial tire market.

9) The C_α sensitivity to vertical load is perhaps the most significant lateral traction characteristic distinguishing the truck tire from the passenger car tire. In particular, the truck tire exhibits a steep slope in its C_α versus F_z relationship in the vicinity of rated load thereby providing a significant first-order adjustment in cornering stiffness to compensate for the placement of payload. Some light truck tires were found to be so nearly linear in their C_α versus F_z behavior (over the operating range) that the linear directional properties of light trucks outfitted with common tires on all wheels would be virtually insensitive to changes in payload.

10) Normalized lateral forces (F_y/F_z) generated at high slip angles (above $\alpha = 8°$) decrease significantly with increased vertical load.

11) The sensitivity of lateral traction to velocity has been observed to be virtually insignificant for all tires examined in this program.

12) Lateral force saturation of commercial tires has been observed to occur at normalized traction levels comparable to that obtained with passenger car tires. Since most heavy trucks and buses will roll over prior to tire side force saturation, however, this property is of little significance.

13) The basic features distinguishing the lateral traction properties of radial versus bias and rib versus lug constructions are, in general, common to both truck and car tires. For example, characteristics typifying radial tires used on motor cars are also generally seen in lateral traction measurements of heavy truck radials. The relatively lower values of cornering stiffness possessed by lug-type tires is, probably, of greater significance to the heavy truck because of the tendency to use them almost exclusively on driving (rear) axles.

14) Test-induced shoulder wear significantly influences the lateral traction generated by commercial tires and thus poses a significant confounding influence in the interpretation of experimental data.

15) The dependency of cornering stiffness on inflation pressure is a property distinguishing commercial tires from passenger car tires. Whereas decreased inflation pressure typically reduces the cornering stiffness of the passenger car tire, the commercial tire (most significantly, the light truck tire) does not exhibit a comparable systematic behavior. Thus, manufacturer's recommendations for inflation pressure differentials between axles hold the potential for randomly influencing vehicle directional properties depending upon the polarity and the strength of the sensitivity of installed-tire cornering stiffness to changes in inflation pressure.

Concerning the mechanics of commercial vehicles:

16) The "typical" heavy truck has been found to be capable of eliciting a yaw instability while initiating a turn whose severity is much lower than that

needed to achieve limit response of passenger cars. Further, it is significant that a marked degradation in directional controllability can accrue well in advance of the maneuver severity required for commercial vehicle rollover. A corollary to these observations is that truck yaw instability can be precipitated while tires are operating at relatively low slip angles. In contrast, passenger cars (which are spinout-limited) generally destabilize as a consequence of side force saturation (large slip angles) occurring at the rear tires.

17) A primary mechanism serving to aggravate truck yaw stability is the rear-biased distribution of suspension roll stiffness. Further, typical truck and tractor frames are quite compliant in their transmission of roll moments. Thus, the high roll stiffness incorporated into rear suspensions is seen as a design necessity given the need to react the rear-biased roll moments imposed by straight-truck payloads and by semitrailers.

18) The use of tandem rear axles tends to markedly improve the directional stability of fully-loaded trucks and tractors.

19) The installation of differing tire constructions at front and rear axles has been seen to provide a powerful mechanism for influencing the directional behavior of light and heavy trucks. The classically-degrading mixes (radial front/bias rear, and/or rib-tread front/lug rear) can serve to destabilize vehicles which, by dint of unfavorable payload placement and roll stiffness distribution, tend to be otherwise marginally stable in the small disturbance regime. This (perhaps unsurprising) finding is particularly noteworthy since it is the practice of heavy truck manufacturers to

provide vehicles with a great variety of tire combinations as requested by the purchaser.

20) The directional behavior of heavy trucks and tractors is markedly sensitive to the longitudinal as well as vertical placement of payload (or fifth wheel kingpin). Insofar as many road tractors are outfitted with so-called "slider" (movable) fifth wheels, the significance of kingpin location to tractor yaw stability deserves special consideration.

21) The addition of payload to an intercity bus, although clearly more constrained in placement than truck payloads, generally increases the understeer of the bus because of the typically rearward mass center location of an unloaded bus with its engine located at the rear.

Overall, the commercial tire by dint of its tread compounding, carcass construction, unit loading, and operating load range has been found to exhibit a number of unique characteristics which impact directly upon truck and bus control behavior. The commercial vehicle, and most notably, the heavy truck and tractor, have been found to exhibit certain unusual control characteristics which derive, in large part, from various features unique to the construction and usage of such vehicles.

3.2 Recommendations

It would appear that the first item of follow-up to this study should be an investigation of the significance of the finding concerning the marginal yaw stability of heavy trucks and tractor-trailers. Significance should be evaluated along two fronts, one scientific—utilizing the engineering and psychophysical disciplines to study the vehicle control problem directly—and the other empirical—studying the evidence afforded by the accident record. Primary questions to be asked in the scientific pursuit are:

a) To what extent can the professional truck driver control a directionally unstable truck or tractor-trailer, given that the positive exponentials defining the divergencies are likely to be rather small?

b) Are there specific maneuvering conditions, such as encountering circular freeway exit ramps at elevated velocities, which render the driver's stabilization task virtually insurmountable?

c) What level of improvement in the directional stability of trucks will be significant with respect to driver ability to control vehicle motions?

An empirical study of truck accident data may well prove unenlightening until such time as accident evidence can be gathered to include the relevant information. In particular, since loss of control in a yaw divergency implies vehicle rollover in the case of a straight truck, and jackknife, possibly followed by rollover, in the case of a tractor-trailer, the divergency incident may well be masked by the distracting evidence associated with the rollover of a heavy vehicle. Further, since heavy vehicle spinout can be precipitated without tires encountering high values of lateral slip, tire marks may not be evident or visible.

It would seem that the accident investigation community would be well advised, nevertheless, to begin considering truck and tractor-trailer loss of control accidents with the recognition that yaw divergency can, indeed, precede rollover. It should be further emphasized that the traditional notion that jackknifing accrues only during heavy braking is not a comprehensive rule. From a causality point of view, it should be made clear that a heavy vehicle operator may have encountered the challenge of yaw stabilization prior to any variety of final impact, rollover, or ran-off-road consequences.

Going beyond the matter of further yaw stability investigations, it appears that much remains to be learned about the mechanics of motor trucks. A broad study of the implications of frame compliance would serve to establish the extent to which rigid body models of heavy vehicles may be inadequate. There also remain numerous kinematic and compliance properties of truck steering and suspension systems which have not been adequately examined. In addition, the inertial properties associated with many of the common truck body configurations have not been formally evaluated. Overall, there is a need to obtain, for heavy trucks, a level of understanding of common control properties such as obtains for passenger cars, thereby providing a solid and comprehensive basis upon which to found investigations of specific interest.

With regard to articulated vehicles, one specific item seems relevant to the foregoing discussions. By way of extension to the recommended study of frame compliance effects, the torsional compliance of semi-trailers is a similarly crucial item insofar as it determines the distribution of trailer roll moment reaction between tractor suspensions and trailer suspensions (and thus between the respective tire sets). An associated inventory of roll stiffnesses afforded by common trailer suspensions should accompany any study of the effects of trailer frame compliance. Additionally, the articulated commercial vehicle is seen as a configuration tending, in general, to further exacerbate whatever control anomalies exist in straight trucks. Accordingly, studies of articulated vehicle control behavior are recommended as logical extensions to research programs which have effectively addressed and resolved the mysteries of the unit truck.

In the specific area of tire mechanics, the most significant unresolved item involves the combined slip behavior of commercial vehicle tires. This complex regime of traction behavior remains virtually unexplored. In the authors' view, no serious analyses and predictions of braking-in-a-turn response of commercial vehicles can be entertained until these data are available.

Additionally, there is a need to expand the dry surface measures of longitudinal and lateral traction of commercial tires to include measurements on wetted and snow-covered pavements. Although some limited measurements of heavy truck tires have been made on wet pavements [3], these experiments should be extended to constitute a general inventory of wet traction produced by commercial tires employed in the U.S.

Also, the prevalent usage of wheel slip control systems on heavy trucks since promulgation of FMVSS 121 suggests a need to examine the influence of dynamically varying longitudinal slip on traction behavior. While such investigation might concentrate initially upon the relationship between slip dynamics and longitudinal traction, the influence of slip dynamics on traction response in combined braking and cornering seems also pertinent for study.

Observations of the non-classical sensitivity of cornering stiffness to inflation pressure on many light and heavy truck tires suggests that follow-up investigations are in order to evaluate the control significance of manufacturer recommendations for an inflation pressure bias. While current recommendations of inflation pressure bias may be prompted by considerations of load-carrying capacity rather than vehicle directional response to steering, the destabilizing effect of commonly recommended biases suggests that the recommended practices deserve serious scrutiny.

With respect to the test practices which may be employed in future full-scale experiments conducted with commercial vehicles, certain recommendations are prompted by the experience obtained in this study. Firstly, it would appear wise that no full-scale test of a heavy vehicle proceed without adequate roll-protective structures deployed. Further, in tests conducted to examine directional behavior at lateral acceleration levels which even slightly exceed the normal maneuvering range, it is recommended that experiments be conducted either in an unmanned (remotely controlled) mode or in a manual mode with a human operator who is suitably protected using rollover preventing hardware. Reflecting upon passenger car experience, the anti-rollover outrigger is an indispensible component in severe maneuvering studies—but only when the outrigger design can be confidently demonstrated to provide a conservative level of protection. While such devices have been reported in studies investigating the dynamics of heavy trucks [4], the adequate fastening of such hardware to heavy truck frame rails is not altogether straightforward.

An overall assessment of the technology of truck dynamic prediction would suggest that full-scale testing should proceed cautiously when tests are in order at all. The general familiarization of the researcher with a new regime or mode of maneuvering, however, should be initiated (before testing) using computerized simulation and laboratory measurement of mechanical parameters.

A truly general view of the foregoing study's potential for impacting programs in truck and bus safety suggests that we recognize the user-dominated character of the commercial vehicle system. To the extent that heavy vehicles, especially trucks and tractors, are largely specified by their purchaser, it would appear that certain safety advisory information must ultimately be directed at "the trucker." Accordingly, recommended practices concerning tire installation, payload placement, fifth wheel location, etc., must be effectively presented to the professional driving community and to the associated fleet owners. Correspondingly, it would appear that the results of broadened research into the mechanical behavior of trucks as derives from vehicle design features (i.e., suspensions, frames, steering systems, etc.) should be effectively disseminated to the truck engineering community. The truck manufacturer could then be expected to rationally constrain the availability of those assembly options (or combinations of options) which are found to yield undesirable control quality.

While rulemaking in the area of commercial vehicle handling may be a facet of NHTSA's overall charter, it is recommended that near-term improvements in heavy vehicle safety may well be effected through information initiatives that build upon recent research findings such as those developed in this particular study.

4.0 REFERENCES

1. Weir, D.H., et al., Analysis of Truck and Bus Handling, Final Report, Contract DOT-HS-242-2-421, June 1974.

2. Roland, R.D., Rice, R.S., and Dell'Amico, F., The Influence of Tire Properties on Passenger Vehicle Handling, Final Report, Contract DOT-HS-053-3-727, June 1974.

3. Dijks, A., "Wet Skid Resistance of Car and Truck Tires," Tire Science & Technology, TSTCA, Vol. 2, No. 2, May 1974, pp. 102-116.

4. Strandberg, L., Nordstrom, O., and Nordmark, S., "Safety Problems in Commercial Vehicle Handling," Proceedings of a Symposium on Commercial Vehicle Braking and Handling, Univ. of Michigan, May 5-7, 1975, pp. 463-528.