Strategies for Reducing Truck Accidents on Wet Pavements

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ABSTRACT

The discovery that heavy truck tires do hydroplane at vehicle speeds from 50 to 70 mph is explored in depth. Horne's prediction of this phenomenon is described in detail. The Texas Transportation Institute's testing program to verify this prediction is described and the results are compared with Horne's theory. An analysis of the Bureau of Motor Carrier Safety files on truck accidents for the years 1979 through 1981 shows the extreme overrepresentation of unloaded tractor semitrailers in wet weather accidents, supporting the thesis that tire hydroplaning of large unloaded vehicles is a major contributor to wet weather accidents. Finally, other elements of the problem are explored such as vehicle stability, braking system effects, low tire-pavement friction, and the speed increases associated with unloaded vehicles.

The recent prediction by Horne (1) and verification (2) that truck tires are subject to dynamic hydroplaning at highway speeds has dictated a reassessment of the causes of tractor semitrailer accidents in wet weather. Those concerned with highway safety have long noted the high frequency of single vehicle losses of control in wet weather. Although many reports have been published documenting this phenomenon and discussing low tire-pavement friction (3,4), reduced visibility (5), and hydroplaning (6) as influential factors, almost all this work has dealt primarily with automobiles. Large trucks have been considered an especially puzzling case. For example, some engineers have noted what appeared to be a comparatively frequent occurrence--unloaded trucks' loss of control during wet weather. Because it was understood that large truck hydroplaning at highway speeds did not occur, these losses of control were usually attributed to low tire-pavement friction, brake balance problems, and possibly excessive speed by lightly loaded trucks. This common understanding has now been shown to be in error and another influential factor must be added to the list--truck tire hydroplaning.

The addition of this new factor does not negate any of those previously known but it does complicate the loss of control phenomenon because there is now a new level of interactions between (a) visibility, (b) speed, (c) loading condition, (d) pavement surface properties, (e) brake system characteristics, and (f) hydroplaning.

The reduction of visibility during wet weather has been described in several reports (5,7) and is generally associated with a reduction in the time required for traction performance, at the time the availability of traction for either cornering or braking may be greatly reduced. Figures 1 and 2 show the influence of rainfall on visibility. Figure 3 shows how available tire-pavement friction is reduced on wet pavement (3). This reduction is maximum at high speed.

Although it remains to be proven, it appears probable that an inverse relationship exists between tractor semitrailer speed and load carried. The obvious capability of some rigs to run faster under lightly loaded conditions points to this probability. It will be demonstrated in other sections of this paper that it is the lightly loaded truck tire that is susceptible to hydroplaning. Thus the likelihood of higher speeds under reduced load condition in-

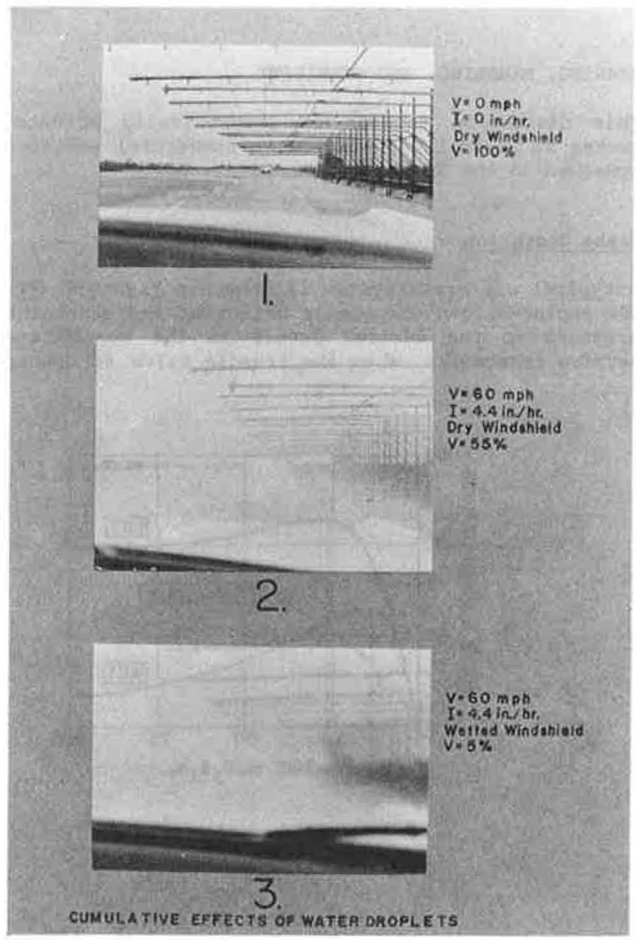

FIGURE 1 Progressive influence of rainfall on visibility as the intensity increases and as the windshield surface becomes covered with water.

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FIGURE 2 Spray generated by tractor semi-trailer reduces visibility for drivers of following vehicles.

creases the probability of hydroplaning and makes the appropriate balance in the brake system more critical to vehicle control.

BRAKING, HANDLING, AND STABILITY

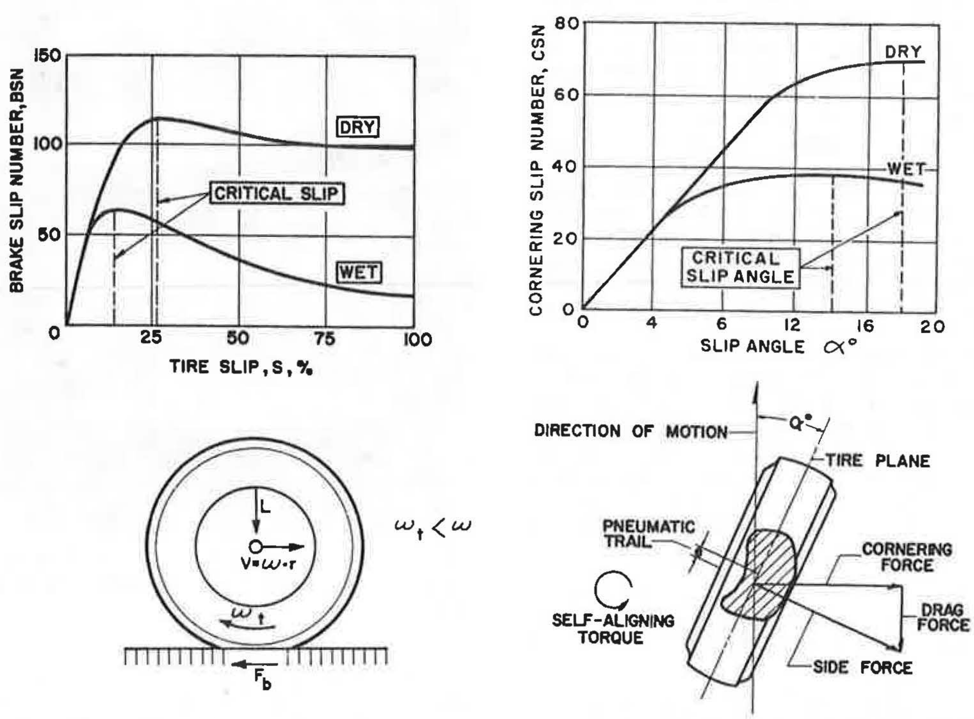
This discussion focuses on pneumatically actuated brakes as typically installed on commercial vehicles operated in the United States.

Brake Operation

A typical air brake system is shown in Figure 4 (8). The engine-driven compressor builds up and maintains pressure to the desired levels in the supply and service reservoirs. When the treadle valve is opened by the driver's foot (under normal operation), it takes a certain length of time for the supply pressure to be achieved in the brake chambers. This response time depends on the system's arrangement, which can be fairly complicated as demonstrated in Figure 4. The volumes of each system component, orifice and valve sizes, and line lengths strongly influence the response time. In Figure 5, MacAdam et al. (9) shows time histories of trailer brake chamber pressure of three combination vehicles. The application times are measured from the instant of pressure increase at the treadle valve. This figure shows that, in an accident environment in which a great deal can occur in a few milliseconds, the response time of the trailer brakes may have a significant effect.

The air pressure in the system is converted into an actuation force on the brake by the brake chamber. Typically, the air pressure displaces a piston/diaphragm assembly through a distance called the stroke. This displacement actually produces the force necessary for brake application, which force can be ideally computed by the product of the pressure times the piston/diaphragm area. In practice, however, this ideal result is not obtained. Figure 6 shows the results of processing typical test data and plotting effective area as a function of stroke and pressure. This graph illustrates dramatically how significant shortfalls in design force can be experienced in maladjusted brakes. As the brakes are used (if they are not properly adjusted for the current state of lining wear) the chamber can run out of stroke. Also, as brakes are heated through use, drum expansion may increase the influence of marginally adjusted links so that a loss of torque capacity is realized.

In order to draw reasonable conclusions about the expected performance of a brake system, the components described earlier must be analyzed as a system. A detailed analysis is beyond the scope of this paper; however, excellent developments have been



Operating in the Brake Slip Mode (After Kummer and Meyer (3))

Operating in the Cornering Slip Mode (After Kummer and Meyer (3))

FIGURE 3 Frictional characteristics of tires operating on typical wet and dry pavements.

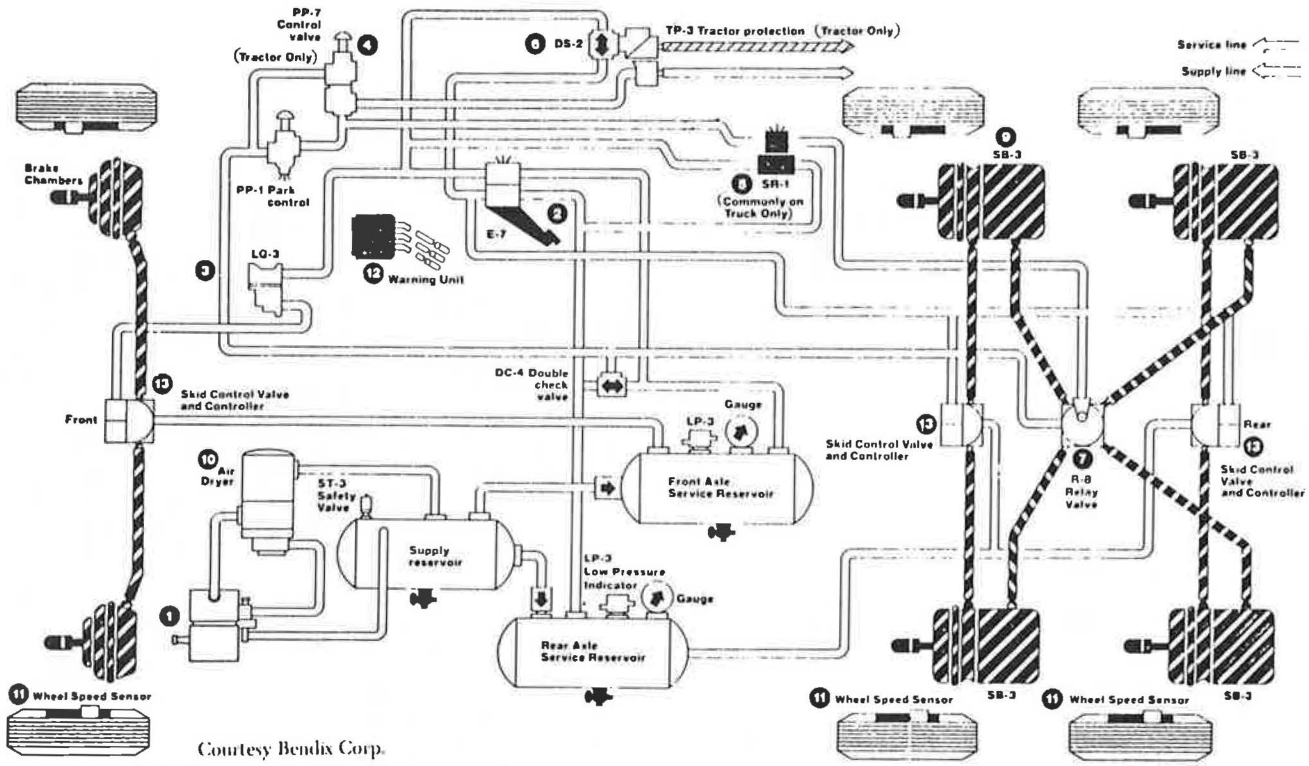


FIGURE 4 Air brake system.

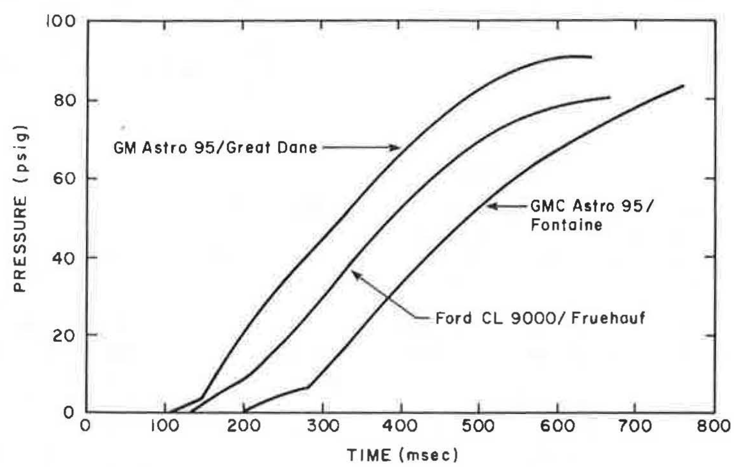


FIGURE 5 Response time histories, trailer brake chamber pressure.

reported (10,11) with a more general, less technical presentation (8).

The essential facts about truck brake operation as it relates to the current subject follow.

Proper brake diaphragm adjustment is essential to proper system operation. This effect, varying as described earlier, is at least as significant as the load variation on the assembly.

The S-cam and wedge-type brake mechanisms, although inherently self-energizing and hence potentially more appealing in normal operation, are more prone to fade, less consistent, and more susceptible to wear and adjustment malfunctions than their disc counterparts.

Conventional (nonlock control logic) brake systems must be designed for best compromise between fully loaded (high-temperature rise/drum expansion) and empty conditions. This can promote systems that either tend to lock at light loads (better heavily loaded system) or systems that are marginal under full load (better brake stability and control when empty). In any event, brake adjustment is critical and must be accomplished on a regular basis or the system should incorporate automatic slack adjusters.

It is virtually impossible to adjust a brake system so that it is ideal for all conditions of load. If brake systems are adjusted for the full-load condition, they may be poorly adjusted during the light-load condition. This is why antilock brake systems are potentially so important.

Further complicating the problem is the fact that optimum braking would require a different balance for each level of tire-pavement available friction. Brake systems are not optimized for the occasional low friction levels that occur in wet weather.

The ideal combination of an antilock control logic and disc brake mechanism can exploit all the advantages of each, plus be adaptable to extremes in load

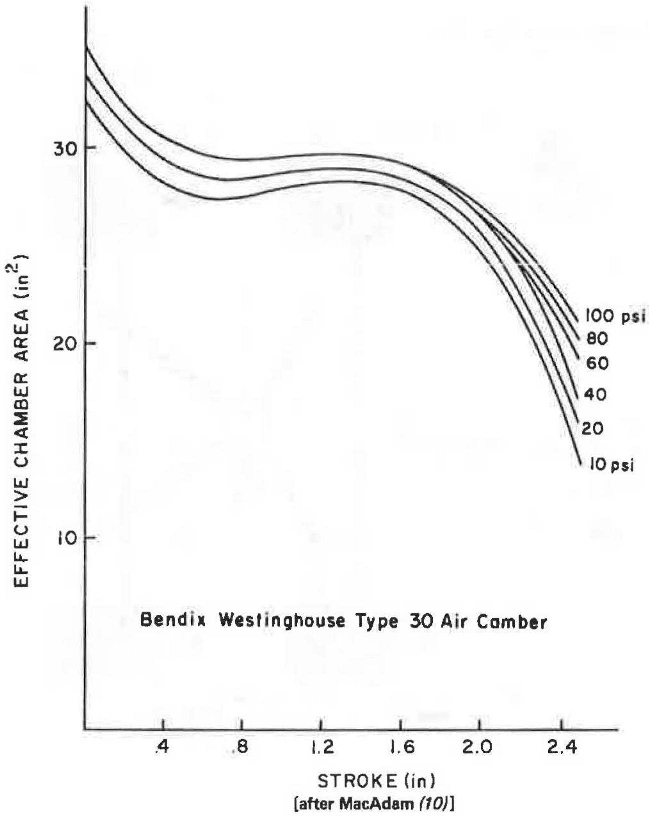


FIGURE 6 Brake chamber effective area versus stroke.

conditions much more readily than nonantilock systems.

Control Loss During Emergency or Extreme Maneuvers

Many reports have been written on how braking systems can be improved in order to achieve shorter stopping distances. Whether or not shortening truck stopping distances will increase highway safety is a question that has not been definitively answered. It does appear apparent that preventing wheels from locking during extreme braking maneuvers would prevent many losses of control.

Many of the emergency maneuver conditions that can lead to losses of control are defined in Table 1. Factors that initiate a loss of control during braking and cornering, or a combination of both, are described in the second column. The possible result of these attempted maneuvers is given in the third column, and possible ways of recovering from the developing loss of control situation are given in the final column. It is with reservation that this final column has been prepared. The instinct and reactions of an experienced and skilled driver cannot be put in tabular form by researchers. In many cases emergency maneuvers and reaction to the resultant dynamic conditions must take place in a time period that allows only instinctive reaction rather than adherence to appropriate learned responses.

The best judgment of the authors has been exercised in developing these possible methods of recovery, along with the counsel of Robert D. Ervin, Research Scientist at the University of Michigan Transportation Research Institute.

Many of the recovery methods are obvious. There are, a few that may warrant some discussion. Possible results of losses of control are tractor jack-knifing, trailer jack-knifing, and rollover. These conditions are shown in Figure 7. For example, when tractor drive wheels break traction and skid laterally during an excessive cornering maneuver, it would appear helpful to disengage the clutch. This reduces circumferential braking due either to drive torque or to engine drag and gives the tire more cornering capacity. The time factor may make this reaction impractical in most cases.

Some consideration has been given to the idea that activating the trailer brakes in a condition of excessive body roll or lateral acceleration could destroy or at least reduce the cornering capacity of the trailer tires and reduce the roll moment. Although this may be true it would also undoubtedly cause trailer swing. Thus one loss of control situation would be traded for another. In view of this, and a growing belief in the industry that individually activated trailer brakes (hand-lever trailer brakes) are an anachronism, the authors have declined to recommend the use of trailer brakes for any situation. Although there may be some specific situations when they could be of value, there appear to be many more situations in which their use would be counterproductive.

A few of the terms used in Table 1 may be unfamiliar; for example, "modulating" service brakes and "feeling" for the steering limit. Modulating brakes means simply the driver getting on and off the foot treadle valve in such a way as to prevent any wheels from locking and at the same time braking effectively. Feeling for the limit of cornering is probably not practical. Under a few conditions of almost steady-state cornering, a driver may be able to sense when the truck tires start to skid laterally and reduce and then add steering to approach the cornering limit.

It may remain for detailed dynamic handling and stability testing of a variety of rigs to determine the practicality of many of the suggested methods of recovery.

HYDROPLANING

It has been understood in the highway engineering community that large truck tires do not hydroplane at highway speeds. There were several reasons why this myth developed. In the early 1960s, Horne and his fellow engineers in the National Aeronautics and Space Administration (NASA) discovered and studied the phenomenon of hydroplaning as it related to aircraft tires. Because of the way aircraft tires are constructed, the shape of the contact patch remains much the same for a fairly wide variation of tire loads. The NASA group found that hydroplaning speed could be predicted as a simple function of tire pressure. This relationship predicted hydroplaning speed of tires with 60 to 100 psi inflation pressure well above that which could be achieved by highway vehicles. Because truck tires normally required pressures in this range, it was believed that they would not be subjected to speeds high enough to hydroplane.

Further work on automobile tires in the late 1960s confirmed that hydroplaning speeds would be extremely high at high levels of tire pressure. These studies of automobile tires, including research by Stocker and Gallaway at Texas Transportation Institute, suggested that tire loads were an unimportant variable. Those who interpreted this work to mean that truck tires could not hydroplane did not appreciate the following. Although an automobile tire for a 4,000-lb vehicle may have a normal range of loads from 800 to 1,200 lb, a truck tire may be operated with loads varying from 600 to 6,000 lb. With extremely wide

TABLE 1 Types of Control Loss During Emergency or Extreme Maneuvers and Possible Solutions

Maneuver	Factor Initiating Control Loss	Result	Possible Methods[a] of Recovery
Straight-line braking	Front tractor wheel lockup	Steering control is lost and vehicle may stay on a straight path in a stable condition.	Modulate[b] service brakes to regain steering.
	Tractor drive wheels lockup	Excessive tractor yaw may occur quickly. (Tractor jack-knifing.)	Modulate service brakes and steer in direction of movement (i.e., if tractor is rotating to left steer to right and vice versa).
	Trailer wheels lockup	Trailer swing may occur. (Trailer jack-knifing.)	Modulate service brakes and if reasonable, accelerate modestly.
	Tractor front wheels skid[c] laterally	Steering control is lost. Reduction in cornering capacity and probable drift of tractor front end outside of intended curve path.	Reduce steering and "feel" for steering limit of tire-cornering capacity.
	Tractor drive wheels skid[c] laterally	Reduction in cornering and probable drift of tractor drive wheels outside of intended curve path. Excessive tractor yaw may occur quickly. (Tractor jack-knifing.)	Reduce steering; steer in direction of movement and depress clutch.
Cornering	Trailer wheels skid[c] laterally	Drift of trailer wheels outside of intended curve path. Trailer swing may occur. (Trailer jack-knifing.)	Reduce steering.
	Excessive body, roll, or lateral acceleration	Rollover	Reduce steering.
	Tractor front wheels lockup and/or skid[c] laterally	Steering control is lost. Reduction in cornering capacity and probable drift of tractor front end outside of intended curve path.	Reduce steering and modulate service brakes.
Combined braking cornering	Tractor drive wheels lockup and/or skid[c] laterally	Reduction in cornering and probable drift of tractor drive wheels outside of intended curve path. Excessive tractor yaw may occur quickly. (Tractor jack-knifing.)	Reduce steering and modulate service brakes. Steer in direction of movement and depress clutch.
	Trailer drive wheels lockup and/or skid[c] laterally	Drift of trailer wheels outside of intended curve path. Trailer swing may occur. (Trailer jack-knifing.)	Release trailer brakes if they have been activated. Reduce steering and modulate service brakes.
	Excessive body roll or lateral acceleration	Rollover	Reduce steering.

[a]In some cases on pavements having low values of available friction, the result of attempted emergency maneuvers will occur so quickly the driver will not have time to provide other than an instinctive reaction. The time necessary for the theoretically best countermeasures will not be available or effective.
[b]Modulating the service brake means successively activating and releasing the foot treadle to prevent lockup while braking effectively.
[c]Lateral skidding means the cornering capacity of the tire is saturated, the tire may start to skid laterally and the cornering force may be greatly reduced.

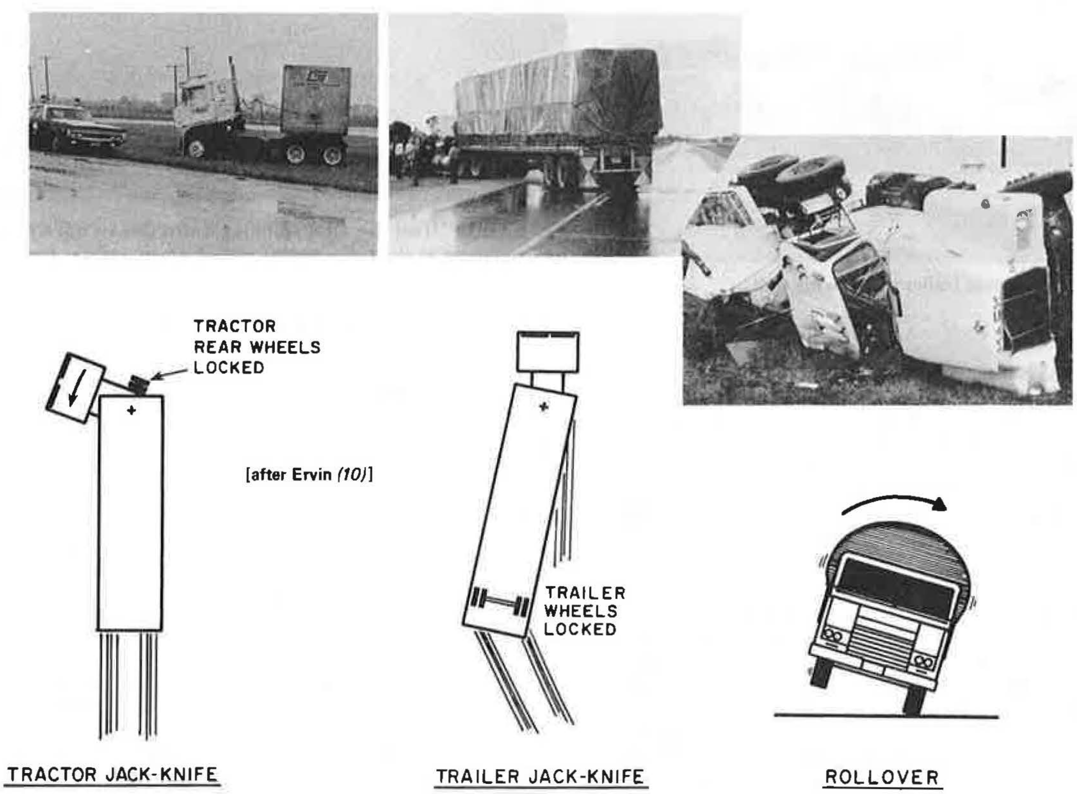


FIGURE 7 Loss of control responses of tractor semi-trailers.

load variation, the aspect ratio of a truck tire surface contact zone varies spectacularly, leading to hydroplaning conditions for a lightly loaded, albeit normally inflated, truck tire at speeds common to highway vehicles. This footprint aspect ratio is the ratio of the surface contact zone width to length.

At the meeting of the Committee on Surface Properties--Vehicle Interaction during the Transportation Research Board's Annual Meeting in January 1984, it was suggested that a task group be set up to look into the special problems of tractor-trailer loss of control. During the course of committee discussion, Horne disclosed that he had written a paper predicting that truck tires, in an extremely low load condition, will hydroplane at highway speeds and explained why this would occur. Horne was asked if this theory had been experimentally verified, as it was definitely contrary to conventional wisdom. Horne responded that it had not been so verified. Shortly after the meeting, Horne sent the Texas Transportation Institute (TTI) a copy of his forthcoming paper, scheduled for presentation at the meeting of ASTM E-17 in April 1984 (1). Horne's arguments, explanations, and predictions were compelling. Intrigued by the possibility of explaining why unloaded tractor-trailers are so prone to loss of control during wet weather, engineers at TTI constructed the test trailer shown in Figure 8. The hydroplaning trough used in this testing is shown in Figure 9, and the trailer used during testing in the trough is shown in Figure 10. The test data are summarized in Table 2.

FIGURE 8 Hydroplaning test trailer and towing unit.

At this time, only four data points have been determined. The lightest load available on the test tire was 940 lb. By imprinting the tire footprint (contact area on pavement surface) using carbon paper, it was determined that the aspect ratio (the nominal ratio of the footprint width to length) was 1.4 for tire pressure varying between 20 and 100 psi. This footprint is shown in Figure 11 at an inflation pressure of 75 psi.

By gradually increasing speed, the speed was determined (for a particular load and pressure condition) at which the tire began to spin down. That point selected was a reduction of apparent tire speed of 2 mph. By increasing speed beyond that value, large values of spin down could be achieved.

Figure 12 shows how the four data points compare to Horne's predictions. Within the range of practical truck tire pressures (60 to 120 psi) the comparison appears quite good. Horne's prediction is about 4 mph low (8 percent) at 60 psi, correct at 75 psi, and about 6 mph high (10 percent) at 100 psi. Because there was no replication of the data achieved, this is probably within the range of experimental variation if such factors as tire construction, tire tread depth, water depth, and pavement texture are considered.

FIGURE 9 Hydroplaning trough.

FIGURE 10 Test tire after spinning down due to full dynamic hydroplaning as the test wheel is pulled down a water trough.

TABLE 2 Tabulation of Test Conditions

Truck Tire	Wear Condition	Pressure (psi)	Load (lb)	w/ℓ	Hydroplaning Speed (mph)
10.00.20	New	20	940	1.40	43
10.00.20	Worn[a]	40	940	1.40	51
10.00.20	Worn[a]	75	940	1.43	58
10.00.20	Worn[a]	100	940	1.41	62
10.00.20	Worn[a]	70	3,600	0.95	Over 62[b]
10.00.20	Worn[a]	100	3,600	1.10	Over 62[b]

Note: Water depth about 1/4 in. ± 0.1 in.

[a]Worn to approximately 2/32 in. tread remaining.

[b]The top speed achievable was 62 mph. No spin down was detected at this speed.

Horne's equation is

$$VEL = 7.95\ (P)^{0.5}\ (1/w/\ell)^{0.5} \tag{1}$$

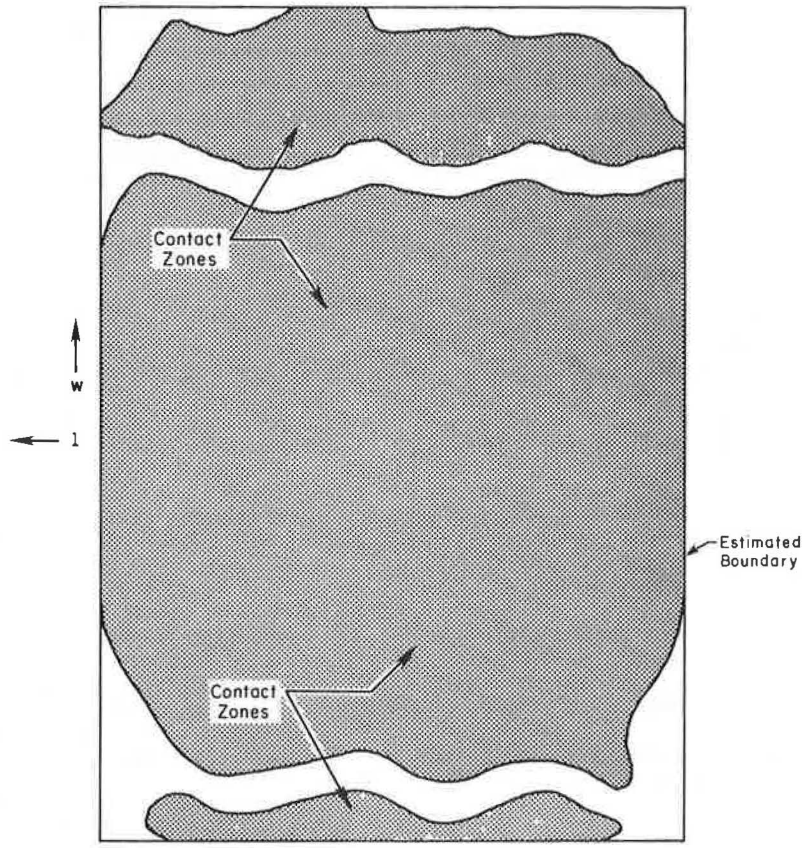


FIGURE 11 Footprint of test tire.

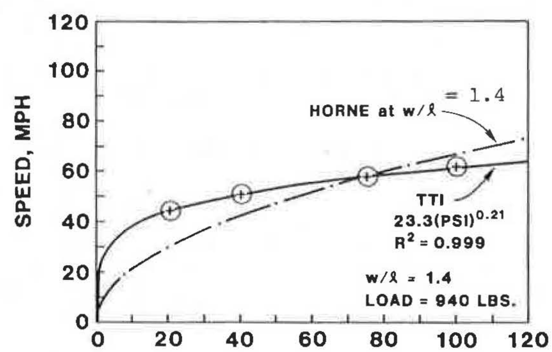


FIGURE 12 Comparison of TTI data points and Horne's predictions.

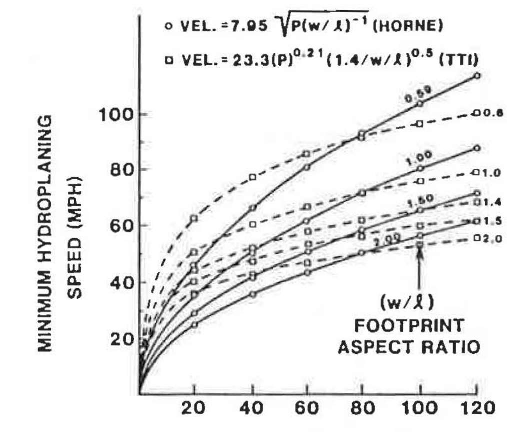


FIGURE 13 Comparison of Horne's and TTI's curves.

compared to an equation based on TTI's curve fit, normalized at the test aspect ratio of 1.4

$$VEL = 23.3\ (P)^{0.21}\ (1.4/w/\ell)^{0.5} \quad (2)$$

A comparison of the curves achieved using the two equations is shown in Figure 13. It must be considered highly presumptious to base an equation on four data points. In the future, TTI engineers expect to acquire more data at lower and higher tire loads. These data should allow the formation of a more reliable predictive equation. It is conclusive, however, that Horne's theoretical predictions are reasonably accurate at commonly used truck tire inflation pressures and that lightly loaded truck tires do hydroplane.

ACCIDENT DATA

Further support of the thesis that lightly loaded trucks are subject to loss of control due to hydroplaning was provided by Chira-Chavala (12). Using 1979 through 1981 Bureau of Motor Carrier Safety data for all Interstate Commerce Commission (ICC)-authorized truck accidents, Chira-Chavala determined that empty combination trucks were overrepresented in wet weather by a factor of 3 when compared to loaded rigs.

Demonstration of the hydroplaning phenomenon for lightly loaded tires and the overrepresentation of unloaded combination trucks during wet weather fit together to strongly indicate that truck tire hydroplaning has a significant influence on vehicle handling and stability.

CONCLUSION

Controlling commercial tractor semitrailers on pavements that provide limited tire-pavement friction are a major problem during periods of wet weather. The characteristics of large truck tires contribute to this problem in that they also provide lower tire-pavement friction levels when compared with automobile tires. Complicating this already severe situation is the fact that truck tires on vehicles in a lightly loaded condition can undergo full dynamic hydroplaning when a significant layer of water covers the pavement surface. This can occur at speeds easily reached by many commercial rigs.

Commercial tractor semitrailers possess unique braking and handling characteristics. These characteristics, in combination with the wide range of load conditions experienced by these vehicles, especially the unloaded configuration, provide situations in which there is a significant probability that one or more of the following will occur:

1. Tractor jack-knifing under combinations of emergency or extreme braking or cornering, or both;
2. Trailer jack-knifing (trailer swing) under combinations of emergency or extreme braking or cornering, or both;
3. Tractor or trailer initiated rolling under conditions of emergency or extreme cornering (development of high values of lateral acceleration).

There are ways to avoid most of these situations by driving defensively, and possible ways to recover as critical dynamic conditions begin to develop that are described here. Reducing speed to 50 mph in wet weather should preclude hydroplaning of tires inflated to 80 psi or more.

Another complication is the problem of brake system design and maintenance. Without careful attention to brake maintenance, including adjustment, loss of braking effort between wheels can contribute to unstable braking. Although some authors believe there is a best sequence of wheel lockups in a severe braking maneuver, others remain unconvinced. Some believe that insufficient evidence currently exists to establish such a preferred sequence. The problem of brake system design under major load variations has traditionally dictated compromise. If the system is designed for the fully loaded condition, it will not be optimum when the rig is unloaded. This is a compelling argument for antilock systems--the one system all authorities appear to agree is preferable to any sequence of wheel lockup.

Because of the wide variation in the loading conditions of tractor semitrailer combinations, the peculiar handling characteristics of these articulated vehicles and the manner in which the braking characteristics and the loading variations affect those handling characteristics, the authors are convinced that reliable, effective antilock brake systems will become the norm in all such vehicles in the near future. The advent of low-cost microprocessor technology with its companion sensor and actuator development, leaves little doubt of the viability of this concept. The mid-1980s is witnessing the application of this technology to high-end passenger cars in both Europe and the United States. Its use in the vehicles discussed in this paper is more compelling for safety reasons and far more easily justified on a benefit-cost basis.

DEDICATION

This paper is dedicated to Louis Homer Hart, trucker, who died in the iron arms of an 18 wheeler trying to avoid a jack-knifed rig on a rain-slick south Texas highway, November 22, 1947.

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