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Problems of Combination Trucks on Wet Pavements: An Accident Analysis

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ABSTRACT

A study of wet-pavement truck accidents was carried out for over-the-road trucks authorized by the Interstate Commerce Commission (ICC). The study was based on accident data from the Bureau of Motor Carriers Safety (BMCS) for 1979 through 1981. The analysis was limited to truck accident involvements on four-or-more-lane highways in Texas. Discrete-multivariate methods were used for the analysis. The analysis indicates that empty trucks show up to three times higher propensity for single-truck accident involvements (run-off-road, jack-knife, overturn, and separation of units) on wet pavements than do loaded trucks. The ratios of wet-pavement to dry-pavement accident involvements were found to be influenced by the following factors: empty/loaded, truck type, and accident type, but not by day/night. The ratio of single-truck accident involvements on wet pavements to those on dry pavements was found to be much higher for empty trucks than for loaded trucks, after adjusting for truck type. Heavy-truck involvements in multivehicle collisions were used as a comparison group. These findings appear to strongly support the prediction by Horne and the laboratory study conducted by Ivey, that truck tires can hydroplane at highway speeds when the trucks are empty or lightly loaded.

The purpose of this paper is to identify possible causes of combination-truck accidents that result from loss of control. In particular, an in-depth analysis of past accident experience of empty combination trucks in wet conditions will be carried out. The data source for this investigation is the Bureau of Motor Carriers Safety (BMCS) file for the Interstate Commerce Commission [(ICC) authorized)] carriers.

INTRODUCTION

Combination truck accidents that result from loss of control are complex phenomena. They are usually the result of failures in the system comprising vehicle, roadway, driver, visibility, and environmental characteristics, as well as chance. Although theoretical

work on vehicle dynamics, laboratory simulation, and vehicle testing have greatly enhanced the knowledge about the factors that lead to lack of stability of trucks in wet conditions, past accident records of these heavy trucks have not been thoroughly analyzed to provide evidence in support of these theories.

Ivey et al. (1) reported that the following elements, independently or interactively, had been identified in past studies as possible causes of combination trucks losing control in wet conditions:

1. Low tire pavement friction,
2. Brake system characteristics,
3. Speed,
4. Reduced visibility, and
5. Hydroplaning.

Loss of control of combination trucks may result in reported accidents such as jackknife, overturn, run-off-road, and separation of units. These four

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types of accidents are collectively referred to in this paper as single-truck accidents.

It was not until recently that dynamic hydroplaning was believed to contribute to loss of control of lightly loaded combination trucks (2). The accident analysis presented here will systematically identify factors that affect the probability of single-truck accidents in general first. Then an in-depth analysis of truck accident records will be performed to determine and to compare single-truck accident propensity on wet pavements for empty trucks and for loaded trucks. In this way, past accident experience of these trucks may be used to provide supporting evidence (or otherwise) for the hydroplaning hypothesis of Horne (2).

LITERATURE REVIEW

Horne (2) was the first to predict that, contrary to conventional wisdom, truck tires were subject to dynamic hydroplaning at highway speeds when empty or lightly loaded. A verification of Horne's prediction was carried out by Ivey (1), who used a test trailer in simulated highway environments and recorded the speeds at which the tires began to spin down. In reporting these results in support of Horne's prediction, Ivey also explained the following:

> In the early 1960s, Horne and his fellow engineers in 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 (that portion of the tire actually in contact with the ground) remains much the same for a fairly wide variation of tire load. The NASA group found that one could predict hydroplaning speed as a simple function of tire pressure. This relationship predicted hydroplaning speeds of tires with 60 to 100 psi inflation pressure well above what could be achieved by highway vehicles. Since truck tires normally required pressures in this range, it was felt that they would not be subjected to speeds high enough to hydroplane. Further work in the late 1960s on automobile tires confirmed that hydroplaning speeds would be extremely high at high levels of tire pressure. These studies of automobile tires, including testing by A.J. Stocker, B.M. Gallaway, and D.L. Ivey at TTI, pointed to tire loads as being an unimportant variable. The following was not appreciated. While 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 lbs. With this extremely wide load variation, the aspect ratio of a truck tire surface contact zones varies spectacularly, leading to hydroplaning conditions for a lightly loaded, albeit normally inflated, truck tire at speeds common to highway vehicles. The aspect ratio is the ratio of the surface contact zone width to length.

A recent study by Chira-Chavala (3), based on analyses of accident data for combination trucks, revealed that for empty trucks on rural highways the proportion of total truck accident involvements that were single-truck (as opposed to collisions with at least another vehicle) substantially increased in wet conditions (up to three times of that on dry pavements). However, the single-truck accident proportion for loaded van, flatbed, and tanker semi-

trailers in wet conditions was only 1.5 times or less of that in dry conditions.

CONCEPTUAL BASIS FOR ACCIDENT ANALYSIS

The analysis of accident data consists of two parts: (a) a preliminary analysis of factors influencing the types of truck accident involvements (i.e., single-truck or multivehicle accidents) in general and (b) an in-depth analysis of single-truck accident propensity on wet pavements for empty trucks and for loaded trucks. The preliminary analysis is required for the following reasons:

1. It provides a quick screening to determine whether the subsequent in-depth analysis is warranted. To be warranted, the preliminary analysis should indicate that pavement condition (wet or dry) and empty/loaded, were among the significant variables influencing the probability of single-truck accidents.

2. The propensity for single-truck accidents on wet pavements may be influenced by a number of other factors. The preliminary analysis will serve as a variable selection step to determine which significant variables, out of a large number of potential variables, are to be included in the in-depth analysis. In this way, a multivariate analysis can be effectively conducted without serious sample size problems, which may have arisen otherwise.

PRELIMINARY DATA ANALYSIS OF ACCIDENT TYPES

Truck accident involvements can be categorized as one of the following accident types:

1. Noncollision,
2. Collision with fixed object,
3. Collision with passenger vehicle, and
4. Collision with large commercial vehicle.

According to the BMCS, about 25 percent of the truck accident involvements reported annually were noncollisions, 10 percent were collisions with fixed objects, 45 percent were collisions with passenger vehicles, 15 percent were collisions with large commercial vehicles, and 5 percent were other accident types. For the noncollisions, about 90 percent were reported as run-off-road, jackknife, overturn, or separation of units.

Given that a combination truck is involved in an accident, the probability that it will be a noncollision accident, a fixed-object collision, or a multivehicle collision is likely to be influenced by factors such as vehicle, operational, driver, roadway, and environmental characteristics. Such a probability can be expressed as

P [A specific accident type|An involvement] = f (vehicle, operation, driver, road, environment)

To identify those significant variables that influence this probability, and to discard those nonsignificant variables, the 1981 BMCS data for all ICC-authorized truck accident involvements were analyzed. Sixteen potential variables were initially examined. These variables and their levels are given in Table 1.

The procedure to determine the significant variables of accident types was based on the tests developed by Landis et al. (4) using two measures of association for contingency-table analyses: Q_{CMH} and Q_T. This procedure had been applied in a re-

TABLE 1 Potential Variables for Analysis of Accident Types

Variable	Level
Vehicle configuration	Single-unit, single, double
Trailer style	Van, flatbed, tanker
Number of axles of power unit	Two- or three-(tandem) axle
Load status	Empty, loaded
Gross vehicle weight	
Trip length	Over-the-road, local
Cargo type	General cargo, other
Road class	Undivided rural, divided rural, urban roads
Road surface condition	Dry, wet
Ramps	Yes, no
Day/night	Day, night
Weather	Clear, rain or snow
Driver experience	$\leqslant 1$ year, 2-4 years, 4+ years
Driver age	18-30, 31-45, 45+
Hours on duty	<2 hours, 2-5 hours, 5+ hours
Region of the country	Northeast, north, south

cent study concerning accident severity of combination-truck accidents (5). Only the result of the variable-selection analysis is reported here.

Of the 16 variables considered, those found to be significant were

1. Trip length
2. Road class
3. Dry/wet pavements
4. Ramps
5. Empty/loaded
6. Day/night
7. Driver experience
8. Driver age
9. Vehicle configuration
10. Trailer body style

As expected, wet/dry pavements and empty/loaded were among the significant variables identified by the variable-selection analysis. The subsequent in-depth analyses will determine single-truck accident propensity on wet pavements and the factors that affect this propensity.

ANALYSIS OF SINGLE-TRUCK ACCIDENT PROPENSITY ON WET PAVEMENTS

This analysis is aimed at determining single-truck accident propensity on wet pavements, particularly that which may be attributable to dynamic hydroplaning of truck tires. Specifically, single-truck accident propensity on wet pavements for empty trucks and for loaded trucks will be determined and compared. To this end, the BMCS-reported accidents involving at least one combination truck on four-or-more-lane highways in Texas were analyzed. The analysis was also restricted to the reported accidents involving ICC-authorized trucks in over-the-road service. This restriction was a result of the relatively high undercoverage of the BMCS-reported accidents involving private carriers.

For the accident data to be supportive of the hydroplaning theory by Horne (2), one would expect to see a significantly higher ratio of single-truck accidents (i.e., run-off-road, jackknife, overturn, and separation of units) on wet pavements to those on dry pavements for empty trucks than for loaded trucks. To ensure that this higher ratio was not an artifact of the truck exposure (e.g., empty trucks happened to travel more in wet weather than did loaded trucks, or empty trucks tended to travel faster than did loaded trucks), heavy-truck involvements in multivehicle collisions were used as a comparison group.

All of the significant variables that were iden-

tified in the preliminary data analysis were closely examined here. Trip length, road class, and ramps were incorporated into the analysis by considering only the accident involvements of over-the-road carriers and on four-or-more-lane highways. Driver age and experience were not included because their effect on the proportion of truck accident involvements that were single-truck was relatively small (3). Furthermore, within the same truck type, their effect on single-truck accident probability was found to be similar between wet and dry pavements, as well as between empty and loaded trucks (3).

Data Source

The BMCS file contains information on accidents involving interstate motor carriers that are subject to the U.S. Department of Transportation Act of 1966 (49 U.S.C. 1655). With few exceptions, these carriers are required to report to the BMCS any accident involving their vehicles that resulted in death, injury, or property damage exceeding $2,000. Exempted are occurrences that involve any boardings and alightings from stationary vehicles, loading and unloading of cargo, or farm-to-market agricultural transportation. The accident information is reported to the BMCS by the carriers themselves on standard forms.

There are a total of 74 variables that describe the place and time of accident, events leading to the accident, accident consequences, driver and occupant characteristics, vehicle characteristics, road, and environment. More than 30,000 accident involvements are reported to the BMCS each year. Of this total, about 80 percent involve ICC-authorized carriers and the remaining 20 percent involve private or other non-ICC-authorized carriers.

Data Input

Table 2 is a contingency table of the BMCS-reported truck accident involvements for Texas between 1979 and 1981, cross-classified by wet or dry pavements (V1), empty or loaded trucks (V2), truck type (V3), day/night (V4), and accident type (V5). Five truck types were defined: (a) single-unit trucks (also included tractor-only), (b) combination trucks pulling van trailers, (c) combination trucks pulling flatbed trailers, (d) combination trucks pulling tankers, and (e) combination trucks pulling other types of trailers. The day/night variable was defined so that night included dawn, dusk, dark, and artificial light conditions. Accident type was a dichotomous variable: single-truck accidents (run-off-road, jackknife, overturn, separation of units) or multivehicle collisions involving at least one heavy truck.

Table 2 also gives two useful descriptive statistics: the cross-product ratios (τ) between wet/dry and empty/loaded and the standardized cross-product ratios (Z).

A cross-product ratio expresses the odds of wet-pavement accident involvements for empty trucks to the odds of wet-pavement accident involvements for loaded trucks, or

$$\tau = X_{11}X_{22}/X_{12}X_{21}$$

where

X_{11} = the number of wet-pavement accident involvements for empty trucks,

X_{12} = the number of dry-pavement accident involvements for empty trucks,

X_{21} = the number of wet-pavement accident involvements for loaded trucks, and

X_{22} = the number of dry-pavement accident involvements for loaded trucks.

A cross-product ratio of 1 therefore indicates that the wet-pavement-accident propensity is the same for empty trucks and for loaded trucks. A ratio higher than 1 indicates a higher likelihood of wet-pavement accident involvements for empty trucks than for loaded trucks, and vice versa.

The values of cross-product ratios alone are not usually reliable measures for comparison because of their difference in standard errors. These standard errors, in turn, are influenced by the sample size (i.e., $X_{11} + X_{12} + X_{21} + X_{22}$). Standardized cross-product ratios, which take into account the magnitude of standard errors, are usually more useful as descriptive statistics.

A standardized cross-product ratio is defined by Griffin (6) as

$$Z = \ln \tau / [(1/X_{11}) + (1/X_{12}) + (1/X_{21})$$
$$+ (1/X_{22})]^{1/2}$$

A τ value of 1 corresponds to a Z value of zero. A τ value less than 1 corresponds to a negative Z value, and a τ value greater than 1 results in a positive Z value.

To obtain the significant effect of the independent variables on the single-truck accident propensity on wet pavements, the following modeling method is used.

Analysis Method

In order to analyze and compare the ratios of single-truck accidents on wet pavements with those on dry pavements for empty and for loaded trucks, a discrete-multivariate model with a control group was used. The purpose of the modeling was to account for the significant effect of truck type, day/night, and chance variation so that the true effect of empty/loaded on the ratios of wet-to-dry single-truck accident involvements could be obtained. The control group of multivehicle collisions involving at least one heavy truck was also employed in the analysis to further enhance the credibility of the results. In this way, the effect due to confounding variables would be minimized and the estimates of wet-to-dry accident ratios might then be stable.

The model can be expressed as follows:

$$\ln [p/(1 - p)] = w + w_2 + w_3 + w_4 + w_5$$
$$+ w_{23} + w_{24} + \cdots$$

TABLE 2 ICC-Authorized Truck Accident Involvements on Four-or-More-Lane Highways in Texas, 1979-1981

Accident-Type (V5)	Light (V4)	Truck Type (V3)	Empty/ Loaded (V2)	Pavement Condition (V1) Wet	Dry	Cross-Product Ratio (τ)	Standardized CPR (Z)
Single-truck	Day	Single unit	E	2	4	0.25	−0.92
			L	2	1		
		Van	E	42	7	3.95	3.07
			L	76	50		
		Flatbed	E	8	2	7.33	2.29
			L	12	22		
		Tanker	E	16	5	10.67	3.42
			L	6	20		
		Other	E	10	4	3.75	1.51
			L	4	6		
	Night	Single unit	E	3	1	2.00	0.47
			L	3	2		
		Van	E	33	10	3.34	3.06
			L	80	81		
		Flatbed	E	1	3	1.61	0.39
			L	6	29		
		Tanker	E	9	3	7.50	2.26
			L	4	10		
		Other	E	2	1	5.00	1.09
			L	2	5		
Multivehicle collisions	Day	Single unit	E	5	43	0.52	−0.71
			L	2	9		
		Van	E	44	99	1.32	1.30
			L	102	303		
		Flatbed	E	27	86	1.35	1.00
			L	31	133		
		Tanker	E	15	49	1.53	0.96
			L	11	55		
		Other	E	13	22	2.73	1.92
			L	8	37		
	Night	Single unit	E	13	24	1.35	0.34
			L	2	5		
		Van	E	27	59	1.52	1.60
			L	90	299		
		Flatbed	E	9	52	1.23	0.48
			L	21	149		
		Tanker	E	13	23	2.31	1.73
			L	11	45		
		Other	E	8	13	2.98	1.79
			L	7	34		

Source: BMCS 1979, 1980, 1981.

where

p = the proportion of accident involvements
that occurred on wet pavements. Therefore,
(1 - p) is the proportion of accident in-
volvements occurring on dry pavements;

w = the overall mean;

w_2 = the main effect of empty/loaded;

w_3 = the main effect of truck type;

w_4 = the main effect of day/night;

w_5 = the main effect of accident type;

w_{23} = the interaction between empty/loaded
and truck type, and so on.

Analysis Result

The model estimation was carried out using the
FUNCAT program (7). The "best" model was found to be

$$Ln [p/(1 - p)] = w + w_2 + w_3 + w_5 + w_{25}$$

The chi-square goodness-of-fit statistic for this
model was 17.28 for 12 degrees of freedom (p-value =
0.1394), which indicates a good fit.

The estimated model indicates that the ratios of
wet-pavement to dry-pavement accident involvements,
p/1 - p, were significantly influenced by load sta-
tus (empty/loaded), truck type, accident type
(single-truck/multivehicle), and the interaction
between load status and accident type. However, the
ratios of wet-pavement to dry-pavement accident
involvements were not significantly influenced by
day/night. Tables 3 and 4 give the summary of the
modeling results. Table 5 gives the estimated ratios
of wet-pavement to dry-pavement accident involve-
ments by truck type and empty/loaded separately for
single-truck accidents and multivehicle collisions.

TABLE 4 Parameter Estimates and Standard Errors

Term	Estimate	Standard Error
W	−0.4815	0.0755
W_2	0.4445	0.0617
W_3	−0.1785	0.1819
	0.3883	0.0851
	−0.3072	0.1066
	−0.0545	0.1267
W_5	0.7905	0.0599
W_{25}	0.2169	0.0598

TABLE 3 Summary of Modeling Results

Variable	Chi-Square	Degree of Freedom	P-Values
Load status	55.16	1	0
Truck type	38.03	4	0.0001
Accident type	178.65	1	0
Load status x accident type	14.22	1	0.0002

TABLE 5 Estimated Ratios of Wet-to-Dry Accident Involvements

Truck Type	Load Status	Wet/Dry Ratio Single-Truck	Collisions
Single-unit	Empty	2.21	0.29
	Loaded	0.59	0.19
Van	Empty	3.89	0.52
	Loaded	1.04	0.33
Flatbed	Empty	1.94	0.26
	Loaded	0.52	0.16
Tanker	Empty	2.50	0.33
	Loaded	0.67	0.21
Other	Empty	3.07	0.41
	Loaded	0.82	0.26

Interpretation of Modeling Results

Figures 1 (a) and (b) show the plots of the esti-
mated ratios of wet-to-dry accident involvements for
single-truck accidents and for multivehicle colli-
sions. It can be seen that the ratios of wet-to-dry
accident involvements were consistently higher for
empty than for loaded trucks regardless of the acci-
dent type or the truck type. However, this differ-
ence between empty and loaded trucks was far more
pronounced for single-truck accidents than for mul-
tivehicle collisions. This differential finding was
the result of the interaction between load status
and accident type.

To illustrate this interaction graphically, Fig-
ure 2 shows a plot of the means of the ratios of
wet-to-dry accident involvements for single-truck
accidents and for multivehicle collisions, weighted
by appropriate accident involvement frequencies. If
the effect of wet pavements was not particularly
pronounced for empty trucks in single-truck acci-
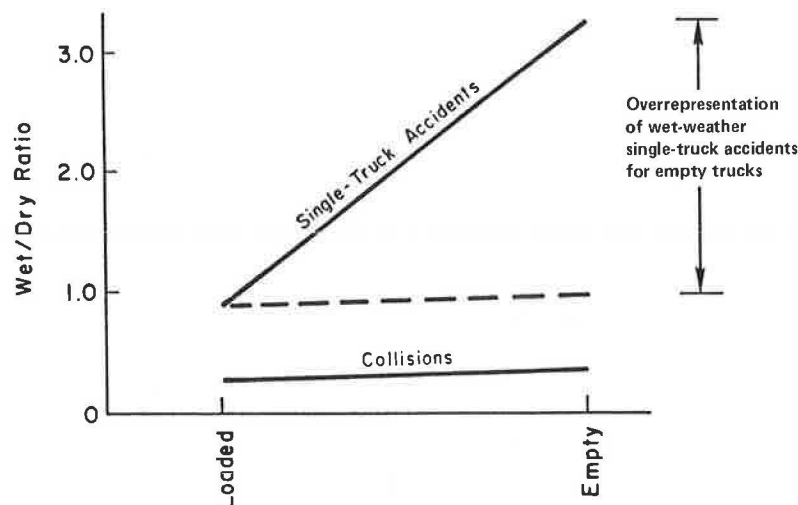dents, the two lines representing single-truck acci-

FIGURE 1 Estimated ratios of wet-to-dry accident involvements.
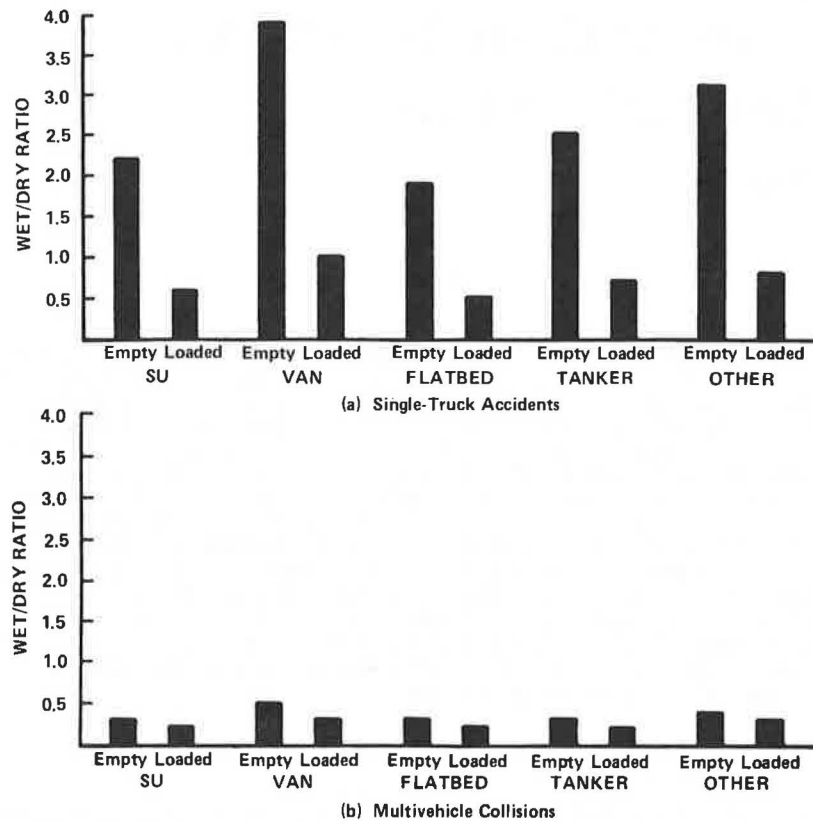
FIGURE 2 Weighted means of wet-to-dry truck accident involvement ratios.

dents and multivehicle collisions would be parallel as indicated by the dotted line. The data in Figure 2 indicate that the ratios of wet-to-dry accident involvements for empty trucks on four-or-more-lane highways in Texas were, on the average, about three times higher than expected when heavy-truck involvements in multivehicle collisions were used as a comparison group. This immediately suggests a very strong influence of wet pavements on single-truck accident involvements for empty trucks that was not observed for loaded trucks.

CONCLUSIONS

The foregoing analysis results clearly indicate that in wet conditions, empty trucks had a considerably higher estimated propensity for single-truck accident involvements than did loaded trucks. This higher propensity was indicated for all five truck types considered: single-unit trucks, combination trucks with van trailers, with flatbed trailers, with tankers, and with other trailer styles. Day/night had no significant influence on such propensity.

Whether the higher single-truck accident propensity of empty trucks in wet conditions was attributable to dynamic hydroplaning problems or whether some other factors were the primary causes warrants further research and investigation. Nevertheless, the accident analysis thus far appears to strongly support the prediction by Horne (2) and the recent laboratory findings by Ivey concerning the dynamic hydroplaning of truck tires at highway speeds.

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