INFLUENCE OF VEHICLE AND PAVEMENT FACTORS ON WET-PAVEMENT ACCIDENTS

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Five variables believed to be closely associated with the friction available at the tire-pavement interface were analyzed by studying 501 wet-weather vehicular accidents. Tire pressures and tread depths were obtained from the accident vehicles, vehicular speed from the investigating officer's report, and friction and macrotexture from the pavement surface at the accident site. It was concluded that the lack of pavement texture, low pavement friction, high vehicle speed, worn tires, and large vehicle tire pressures all contribute to accidents occurring on wet pavement. The accidents were also categorized into several types, and it was found that the variables are even more significant for certain accident types. Studies should be directed toward cornering friction because some 40 percent of the accidents involved a turning maneuver.

•THE research reported in this paper attempted to determine the effect of certain vehicle and pavement factors on traffic accidents occurring during wet weather. The detailed roadway and wet-weather accident data investigated and analyzed were collected by the Texas Department of Public Safety and the Texas Highway Department in a joint effort that represents the desire of both agencies to reduce the number and severity of accidents that occur on Texas highways.

This report concerns only a portion of the data collected. Five variables were arbitrarily selected for reporting because they were thought to be closely associated with the tire-pavement interaction related to vehicular skidding on wet pavement. The variables analyzed were as follows:

Number	Description	Code
1	Vehicular speeds at the time of or immediately prior to the accident	SP
2	Tread depths of the tires of the accident vehicles	TD
3	Tire pressures of the accident vehicles	PR
4	Pavement friction (skid number) at the accident site	FR
5	Pavement macrotexture at the accident site	TX

The object of the analysis was to determine the degree of influence of each variable on wet-weather accidents.

DATA COLLECTION

The data were collected from 501 wet-weather accidents that occurred from May 1968 through September 1969 in an area that consisted of 10 central Texas counties and covered portions of two highway districts (Fig. 1). The area contained approximately 2,460 miles of the state's highway system, on which the average daily vehicle travel was 3,086,099 miles (1).

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The study area was primarily rural in character. Urban areas with populations of more than 5,000 were not included to simplify data collection; accident investigation and reporting for these areas are the responsibility of the municipalities involved rather than of the Texas Department of Public Safety.

Accident Data

The data were collected by the Department of Public Safety (DPS) and the Texas Highway Department (THD). The DPS, in addition to making the usual accident investigations and gathering documentation for the standard report, collected information for a second special report that contained the tire pressures and tread depths of the accident vehicles.

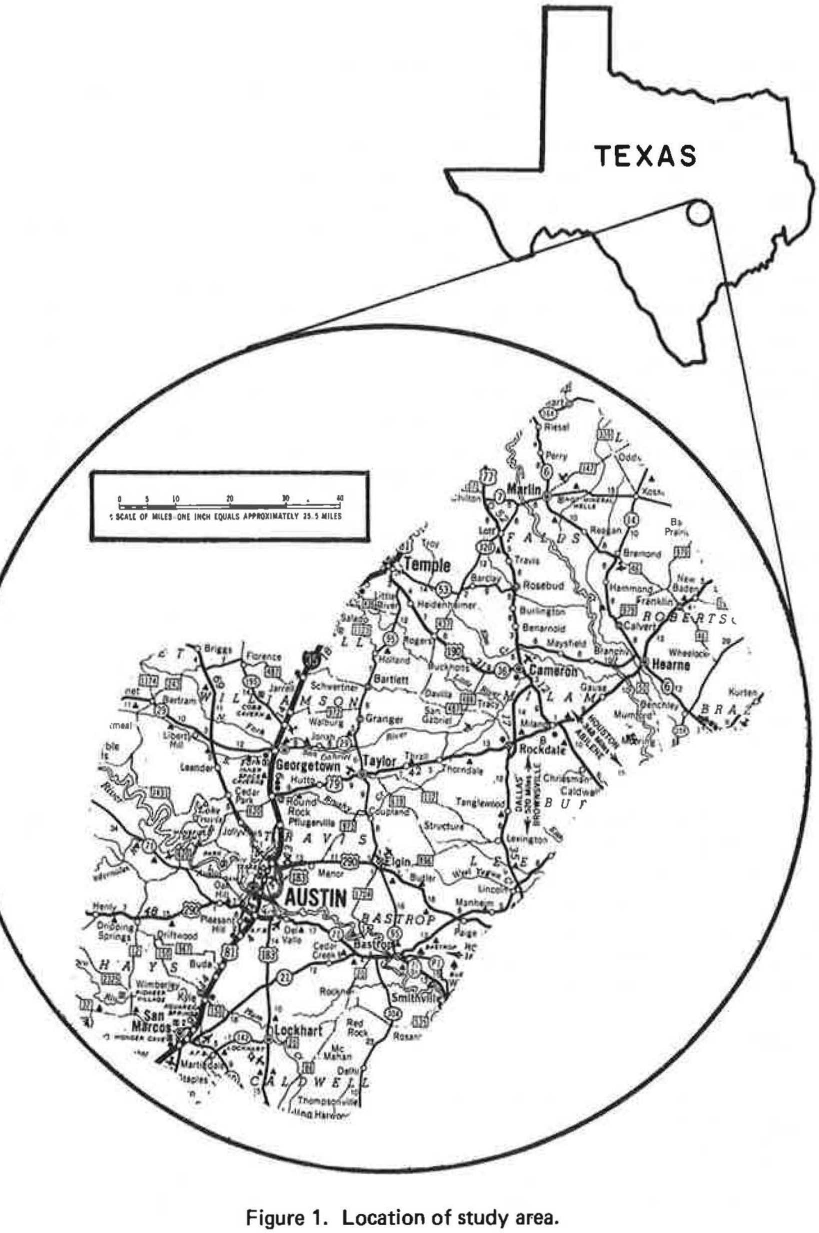

Figure 1. Location of study area.

The pressure for each tire was measured with a commercially produced tire-pressure gage with 2-psi divisions. (It was calibrated before use.) In several instances a tire was so damaged that it was completely deflated, and often a tire appeared to be partially deflated as a result of the accident, especially when a broadside skid had occurred.

The tread depth of each tire on a vehicle involved in a wet-weather accident was measured to the nearest $\frac{1}{32}$ in. with commercially produced tread-depth gages. The minimum and maximum tread depths were reported for each tire. One measurement was made near the edge of the tire and the other near the center of the tire.

The speed of the vehicle immediately prior to the accident was obtained from the standard investigating officer's report. DPS officials indicated that reported speeds could vary from actual speeds and could be biased by the individual officer. They are believed to vary ±10 mph and generally to be lower than the actual values for speeds above 50 mph.

As soon as possible after an accident, THD personnel investigated pavement and roadway conditions at the accident site, which had been conspicuously marked by the DPS investigating officer. Skid resistance was measured with a skid test trailer and texture with a modified Southwest Research Institute (SWRI) texturemeter.

In this project, attempts were made to treat surface macrotexture and the skid number as separate entities. This was accomplished by measuring both variables with the separate instrumentation previously mentioned.

Usually, a skid test was made at the marked location, and three more tests were made over approximately ½ mile in both directions from the accident site (a total of 7 skid tests). On nondivided highways, tests were normally made on lanes in both directions of travel. On divided highways, tests were usually made on all lanes in one direction of travel, but lanes in both directions were tested if vehicles involved in the accident were traveling in opposite directions.

Friction measurements were obtained at the accident site and ½ mile in either direction from the site because the initial postulation had been that a vehicle and driver could be affected by a sudden change in pavement friction; that is, if a vehicle traveling on a pavement with good friction characteristics suddenly maneuvered onto a section of pavement with poor friction, there could be problems in controlling the vehicle.

Skid-resistance measurements were made at 50 mph. Occasionally the accident location, such as a T-intersection, made skid testing unfeasible.

Texture measurements were made at two locations in an area in which a vehicle lost control, and the average of the two measurements was reported. The readings were obtained with a modified version of a profilograph instrument developed at SWRI (2). The texture equipment used was described in a previous report and is actually a mechanical instrument that records the cumulative of the asperities of the texture and scribes a magnified profile of the texture.

Comparison Sample Data

In order to have information with which to compare the accident data and to determine how accident conditions differed from normal driving conditions, special sample data were gathered for each of the five items under study.

Prior to the research reported here, very little information had been gathered on wet-weather driving speeds in Texas. The information contained in this report was obtained by the THD Design Division, Geometric Design Section, which monitored speeds on rural highways in the study area zoned at 70 mph, during periods of rainfall, with radar speed indicators. There was some doubt that the radar would read correctly in rainfall, but a test car was driven through the radar site during the rain and correct readings were obtained.

Sample tread depths and tire pressures from 250 parked vehicles were obtained in two large cities in the study area, Austin and Bryan, and in two smaller cities, Rockdale and Smithville.

A sample of the friction on the highways in the area was collected from routine friction tests performed during the period of this study. These routine tests were performed at 40 mph rather than at the 50-mph test speed maintained at the accident sites. Experience in performing skid tests over the same test section at different speeds indicates friction differentials on the order of 0.02, or two skid numbers generally occur between 40 and 50 mph. Because of this small friction differential, no attempt was made to correct the comparison sample or the accident sample to a constant velocity.

The texture sample for the area highways was determined from the type of pavement and the type of coarse aggregate used on the surface. The pavement and aggregate types were determined for every highway in the study area. The length of each highway segment containing a specific pavement material type was recorded with the average daily traffic count for each segment, and a daily vehicle-miles of travel was calculated for each type. A texture value for each pavement material type was obtained from another publication (3). Substituting texture values for pavement material types gave the daily vehicle-miles of travel for each texture group.

ANALYSIS

The relationship of the accident data and the area sample, representing the normal driving conditions, is shown in Figures 2 through 12.

Figure 2 shows a comparison of the speeds of the accident vehicles and the area sample vehicles. The accident vehicle generally traveled at a slower speed. For example, only 2 percent of the vehicles in the area traveled at speeds of 30 mph or less, whereas approximately 8 percent of the accidents occurred at speeds of 30 mph or less. It must be admitted that this condition was not expected; however, it was noted that many of the accidents reported at low speeds were rear-end collisions in which one vehicle had slowed for a turning maneuver.

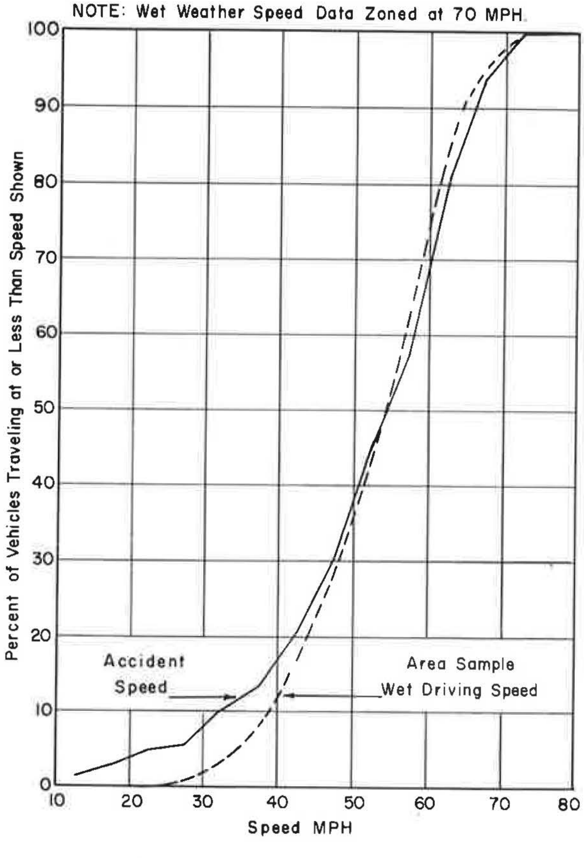

Figure 2. Comparison of vehicular speeds.

Figures 3 through 6 show that accident vehicles generally had less tire tread depth compared to the average vehicle in the study area. This is particularly true for the rear tires; about 10 percent of the rear tires of all accident vehicles were completely smooth.

The same general trends are shown in Figures 7 through 10 with the exception that there is a considerable increase in the number of accidents involving vehicles containing tire pressures of 28 to 29 psi.

As stated previously, the skid number was measured with a trailer at the accident site and in the ½-mile area in both directions from the site. Dean (4), in a previous report for this project, has shown that, statistically, there is no significant difference between the skid number of the average site (35) and that of the average of a statewide sample consisting of more than 2,000 sections (39). It has since been found that the average friction for a sample of pavements in the study area is also 39, with the variance in the study area similar to the statewide variance. The average for the 1-mile vicinity

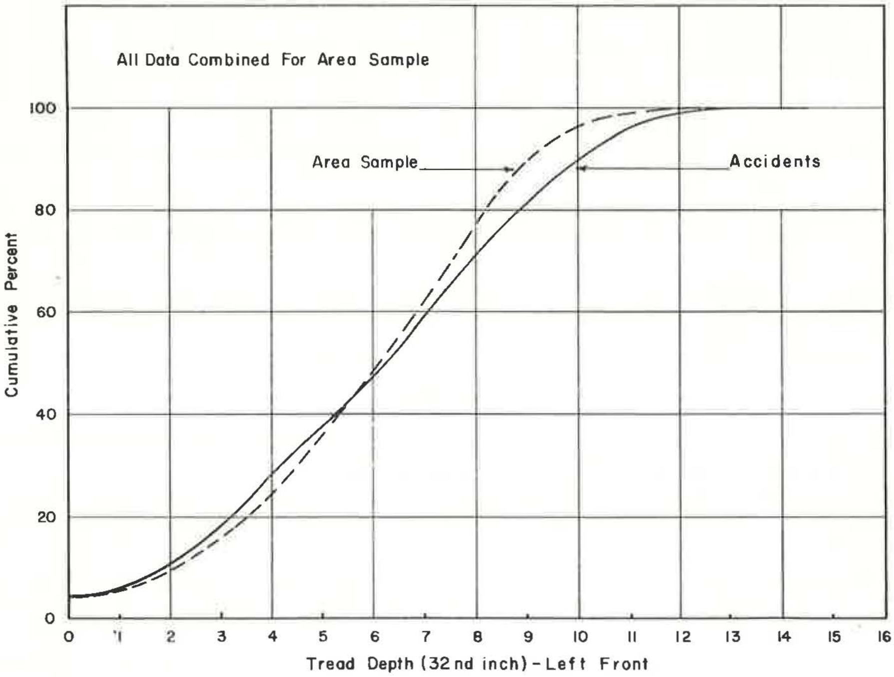

Figure 3. Comparison of left front tire tread depths.

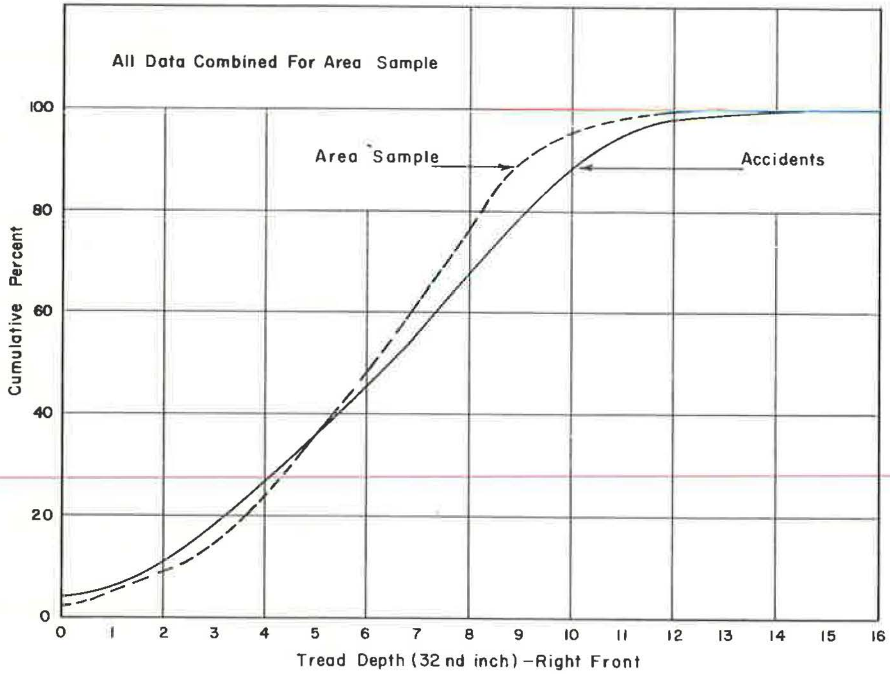

Figure 4. Comparison of right front tire tread depths.

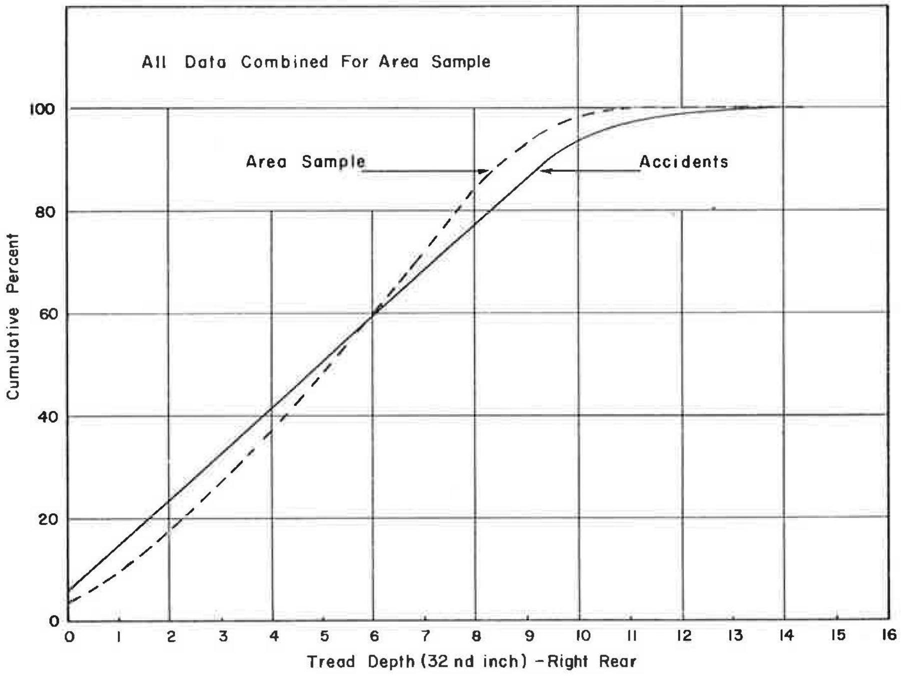

Figure 5. Comparison of right rear tire tread depths.

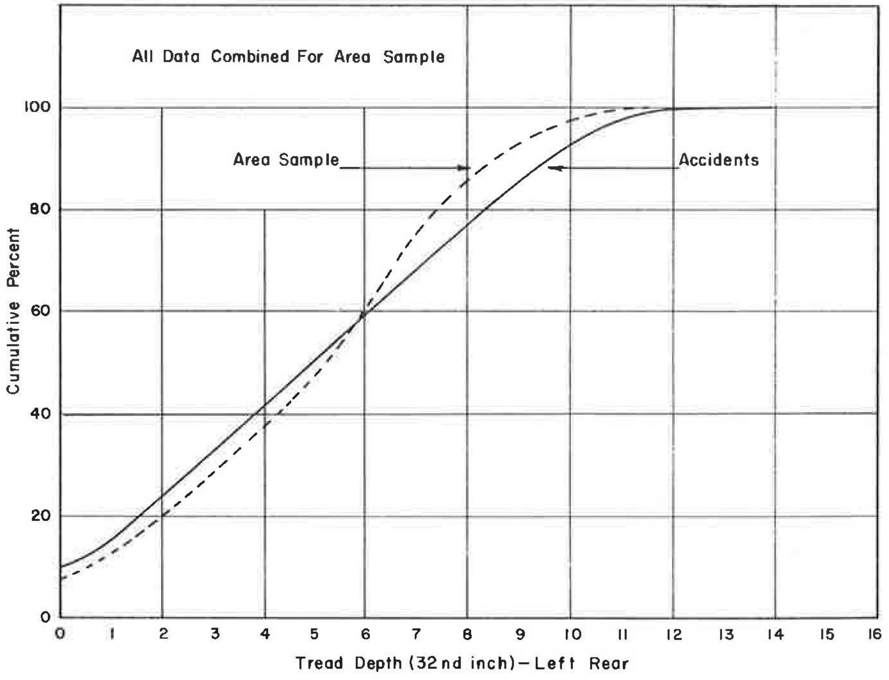

Figure 6. Comparison of left rear tire tread depths.

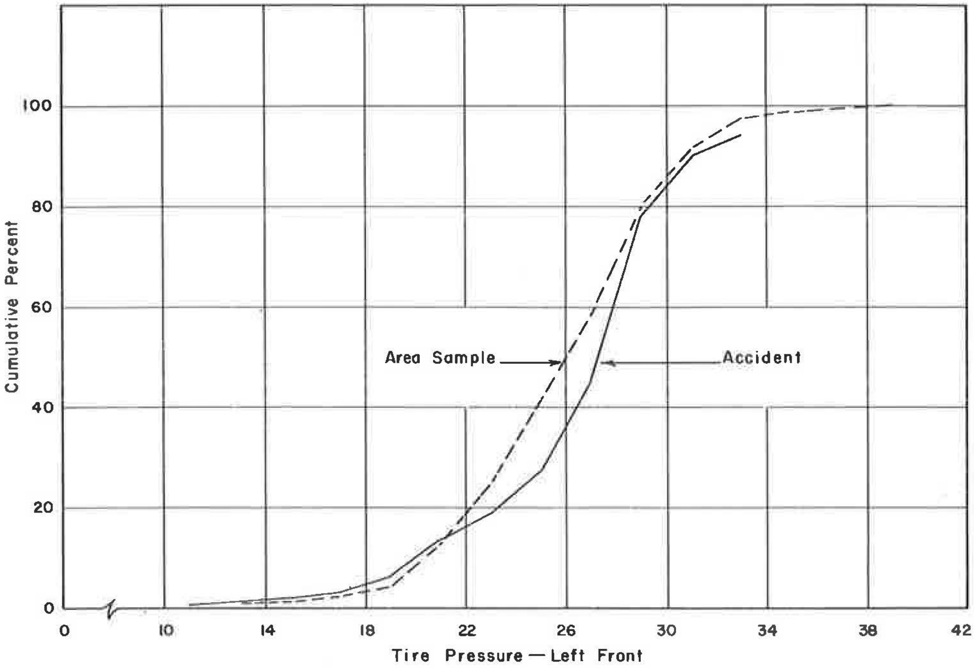

Figure 7. Comparison of left front tire pressures.

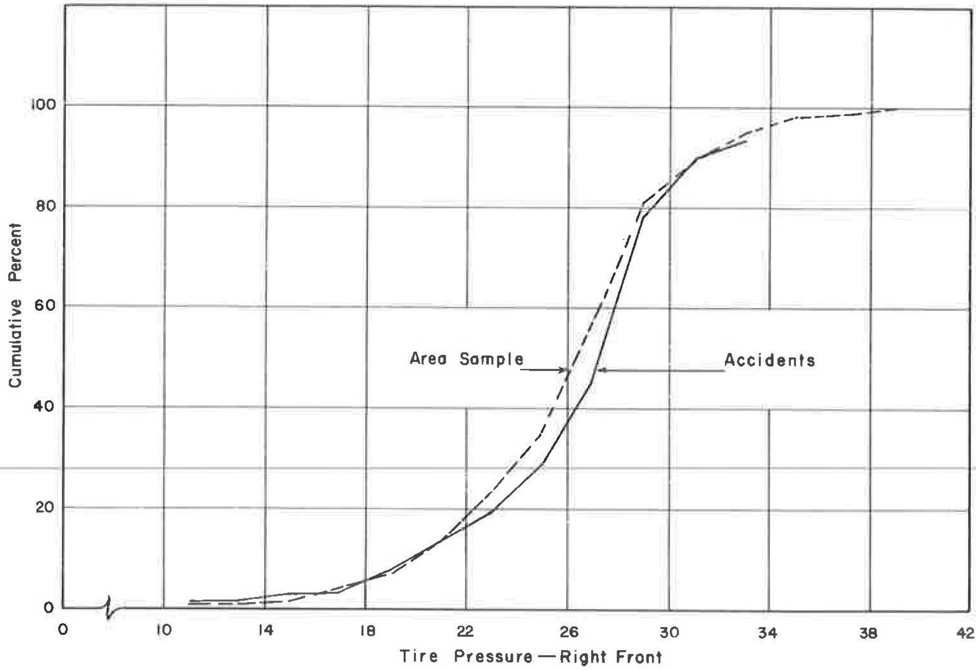

Figure 8. Comparison of right front tire pressures.

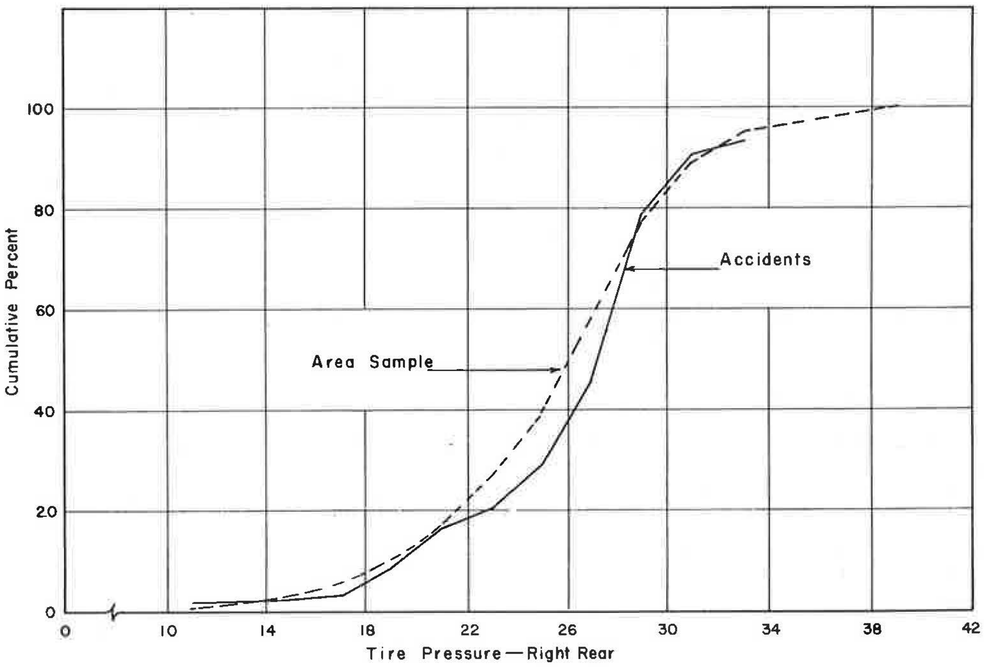

Figure 9. Comparison of right rear tire pressures.

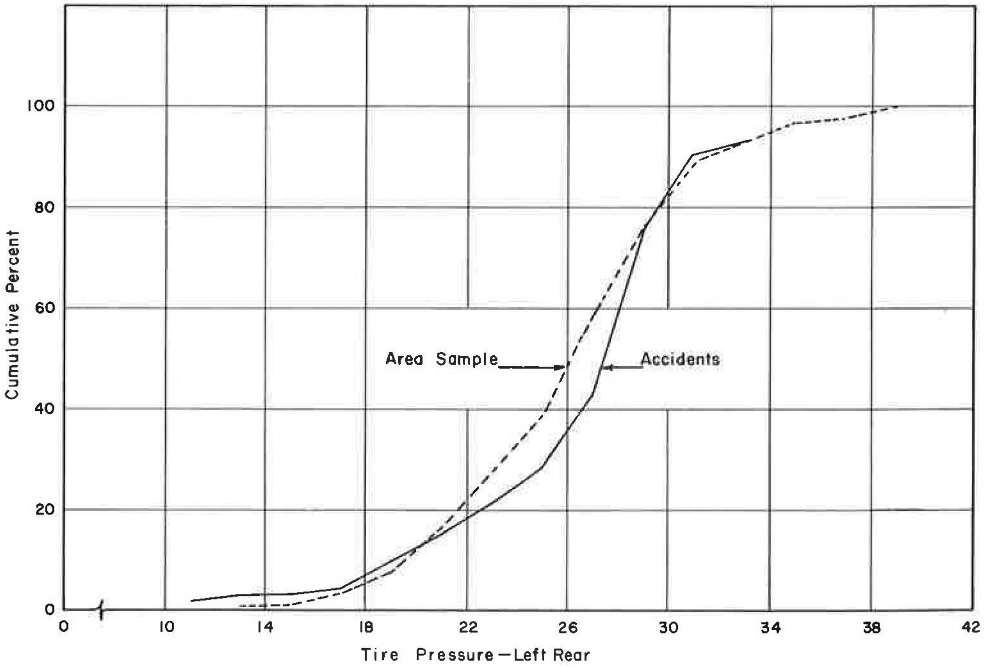

Figure 10. Comparison of left rear tire pressures.

is 36; therefore, it is concluded that there is no significant difference between skid numbers of the accident site and the 1-mile vicinity, or between the accident site and area sample. The skid numbers in Figure 11 were obtained at the accident site; the accidents generally occurred on pavements with lower skid numbers compared with the area sample.

Perhaps the most striking data collected were those of surface texture. Texas had never before obtained the quantity of texture readings collected in this project, and the distribution of data caused immediate concern. The data indicated that a very large percentage of wet-weather accidents occurred on pavement surfaces with small macrotexture values. The cumulative frequency distribution of daily vehicle-miles of travel for each texture grouping is shown in Figure 12 together with the cumulative frequency data for the accident sites. There is a large difference in percentages in the lower texture values. Near the 0.1 texture group, it appears that 40 percent of the accidents occurred on 10 to 15 percent of the pavements.

Classification of Accidents

Research personnel are sometimes accused of dividing data into increasingly smaller groups until a point can be satisfactorily supported. This may seem true at times, but here the data were believed to require certain groupings and the exclusion of some accidents in order to avoid bias. Accidents involving intoxicated drivers were removed from consideration, and vehicles with more than four tires were not included. If a multivehicle accident occurred that involved a vehicle with more than four tires, this vehicle was omitted from study because of the obviously large tire pressure and tread depth considerations; however, the other four-wheeled vehicles involved were included. There remained a total of 396 accidents, involving 540 vehicles.

The categories of accidents were arbitrarily selected, but it was believed that categories such as hydroplaning, stopping friction, and cornering friction would be particularly useful because these are amenable to remedial action and seem much more pertinent to the engineer than do the usual categories such as fatal or personal injury

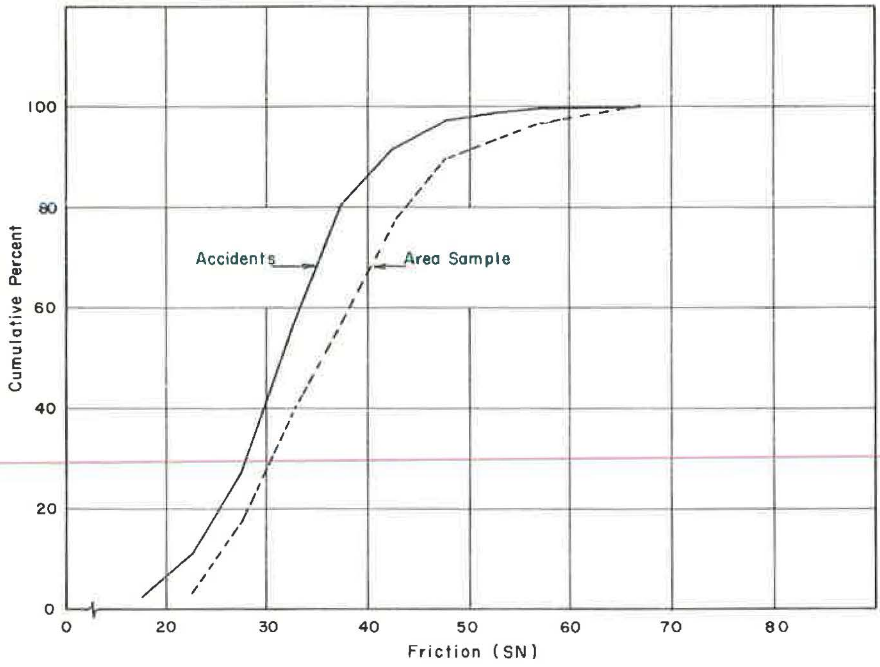

Figure 11. Comparison of friction values.

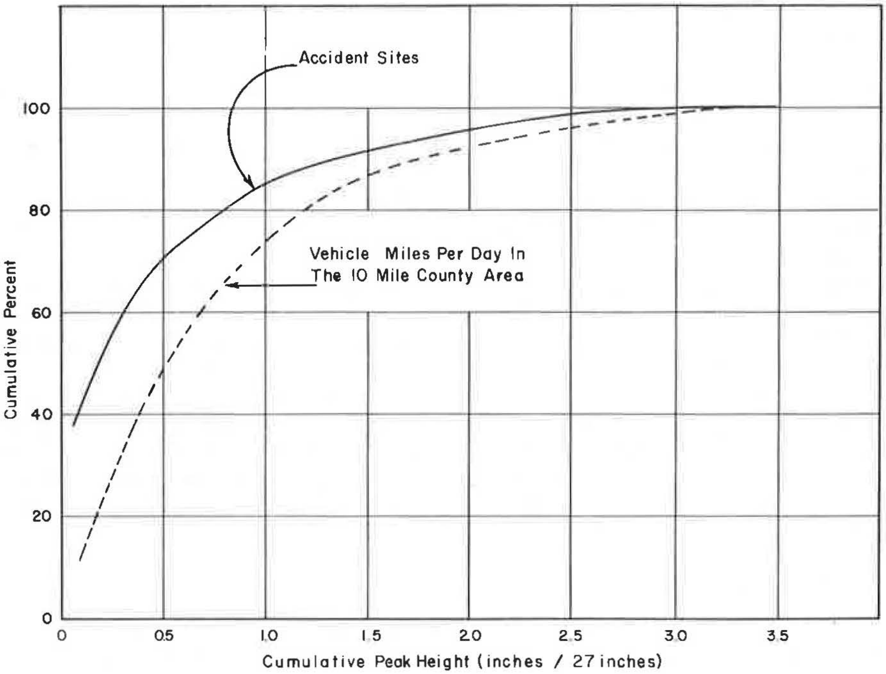

Figure 12. Comparison of macrotexture.

accident. Also, several research projects were planned for the skidding-accident area, and determination of the urgency of needed information for each friction type to establish priority ratings was required. Table 1 gives the categories into which the accidents were classified.

Originally the accidents occurring on curves were divided into those that involved a vehicle skidding to the inside of the curve, toward the radius point, and those skidding to the outside. However, little information related to the accident was provided, and the number of accidents involving skidding inside the curve was approximately equal to those skidding outside. In a large number of cases it appeared that the rear end lost traction, which caused the vehicle to spin around. Therefore, all accidents occurring on curves were included in category 2.

Categories 1, 2, 3, and 5 are thought to be closely associated with a skidding or out-of-control vehicle and tent to be single-vehicle accidents. Categories 2 and 5 generally

TABLE 1

CLASSIFICATION OF ACCIDENTS

Category		Accidents	
Description	Number	Number	Percent
Accidents occurring on a tangent or straight roadway section with no braking involved	1	57	14.4
Accidents occurring on curves	2	125	31.5
Accidents occurring on a tangent with braking involved	3	42	10.6
Accidents involving multiple vehicles	4	56	14.2
Accidents occurring while passing	5	28	7.1
Miscellaneous accidents	6	88	22.2
Accidents in categories 1, 2, 3, and 5	7	252	63.6
Accidents in all categories	8	396	100.0

involve some measure of cornering friction, category 3 involves braking friction, and category 1 involves a drive friction mode, with skidding believed to be initiated near the hydroplaning point.

Category 4 accidents include many rear-end collisions, in which at least one vehicle was moving much slower than the other vehicles involved. Category 6 accidents are those that did not fit any other specific type. (Categories 7 and 8 are discussed later.)

Each accident was classified according to the decision of the researcher. A duplicate set of accidents was classified by another member of the staff. Conflicts in categories were reviewed by both staff members and a final decision was reached. The number of accidents in each category is also given in Table 1.

The data given in Table 1 show that 25 percent of the accidents studied were single-vehicle accidents occurring on tangents. In many instances, the records of accidents in category 1 contained officers' notes that indicated the possible presence of hydroplaning and slick tires. Some 38.6 percent of the accidents involved turning or cornering manuevers (categories 2 and 5), and 14.2 percent were multivehicle. Five multivehicle accidents occurred on curves but were retained in category 4. Finally, 22.2 percent were placed in the miscellaneous category. These were accidents about which no decision could be reached concerning the grouping; for example, an accident was reported in which the vehicle was washed down a stream while the driver was attempting to negotiate a low water crossing.

Analysis of Accidents

The advantage of studying accidents by category became immediately apparent. Large differences were found in each of the five variables for accidents in a given category as compared to the study of all accidents. For example, during the course of this project it was desired to study the data concerning tread depths. Many states require tires to exhibit $^2/_{32}$-in. tread depth at the time of vehicular inspection. It was, therefore, decided to determine the percentages of vehicles with tire tread depths of $^2/_{32}$ in. or less and compare the accident vehicle sample with the area sample, or the average vehicle in the study area.

It was found that only 7 percent of the vehicles in the study area had tire tread depths of $^2/_{32}$ in. or less on the front tires. Some 8 to 9 percent of the accident vehicles had tires with $^2/_{32}$-in. tire tread depths or less. This would indicate that there is not much difference between the average vehicle and the accident vehicle; however, the rear tires caused concern because almost 25 percent of the vehicles that had an accident on wet pavement in the study area also had tires with $^2/_{32}$-in. tread depths or less. In comparison, the rear-tire tread depth of the average vehicle appears much better, with 13 to 16 percent of vehicles meeting the requirement.

The tire tread depths of the accident vehicles were also studied. The percentage of accident vehicles with $^2/_{32}$-in. or less tire-tread depth was as follows:

Category	Left Front	Right Front	Right Rear	Left Rear
1	19	22	54	52
2	12	15	38	35
3	12	19	26	23
4	8	5	5	11
5	7	21	32	46

More than 50 percent of the vehicles that had wet-weather accidents on a tangent with no braking also had rear tires with tread depths of $^2/_{32}$ in. or less. In comparison, the multivehicle accidents (predominately where one vehicle had slowed or stopped on the pavement) had tires with strikingly greater tread depths.

The rolling friction mode found in category 1 accidents requires less friction to maintain a vehicle in a selected path than does an accident related to any other friction mode. Yet this friction was not available or the accident would not have occurred. The fact that the percentages of vehicles are ordered as previously shown is considered significant in that (a) tread depth is a factor to be considered in the friction of the tire-pavement interface; (b) the classification of each individual accident (which was possibly biased by the selection determined by the researcher) was accomplished with some degree of success; and (c) the data reveal the necessity of tire inspection.

The remaining four variables could be treated as previously explained; however, it was decided to use a different statistical treatment to analyze the five variables in combination.

Degree of Influence of Factors by Accident Category

The five variables were studied by use of a statistical analysis of variance procedure. Each of the accident categories was studied separately and in total. The analysis was conducted in the following manner:

1. The 50 percentile value for each variable was found for the samples collected in the study area;
2. For each accident category, each accident was reviewed and each variables was placed in one of two groups, either greater than the 50 percentile value (+) or less (-);
3. The groups for each variable were combined into tables similar to the summary given in Table 2; and
4. An analysis of variance study of the collected data was conducted.

Two addtional accident categories were defined for this part of the study. Category 7 consists of cumulative information for categories 1, 2, 3, and 5, all of which were believed to be closely associated with a skidding (out-of-control) vehicle. Category 8 represents all accidents classified, that is, those involving four-wheeled vehicles and sober drivers.

The 50 percentile values of the samples were used because the samples represent "that which was available to the driver." Any percentile point could have been selected for study, but the 50 percentile value represented the midway point. After finding the number of accidents that occurred when the variable studied was greater or less than the established 50 percentile point, it was possible to estimate the influence of the variable. Also, combining the variables made it possible to estimate the influence of a combination of variables. It should be noted that the tire pressures and tread depths for the four wheel positions of a given vehicle were averaged for this study.

The results of the 50 percentile grouping are given in Table 2. The results are indicated for each accident category where both the number of accidents and the percentage represented by the number may be found. The numbers in the last column were obtained by adding the numbers in the preceding columns. For example, in the first row, it may be found that 13 of the category 1 accidents occurred where speed and tire pressures were greater than the 50 percentile value and where tread depths, friction (SN at 50 mph), and pavement texture are less than the 50 percentile values. These 13 accidents represent 22.7 percent of the 57 category 1 accidents. In this method of analysis, the accident sites and accident vehicles are compared to the sample pavements and vehicles that represent the normal driving condition.

By using the information given in Table 2, we can analyze individual variables; that is, the number of accidents involving a positive variable (one with a greater than 50 percentile value) may be summed and compared to the sum of the negative variable (less than 50 percentile value). Table 3 gives the results of this analysis. The percentages indicate the variables that were present in most accidents in each category. The order in which they were present is as follows:

Category	Variable Order
1	-TX, +SP, -TD, -FR, +PR
2	-TD, -FR, +PR, +SP, -TX
3	-FR, +PR, -TX, +SP, -TD
4	-SP, +TD, -FR, +PR, -TX
5	-TX, +SP, -PR, -TD, -FR
6	+PR, +TD, -TX, -SP, FR
8	-TD, -FR, +PR, -TD, +SP

TABLE 2
RESULTS OF VARIABLE ANALYSIS

Variables					Category 1		Category 2		Category 3		Category 4		Category 5		Category 6		Category 7		Category 8	
					Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent
+SP	+PR	+TD	+FR	+TX	2	3.5	2	1.6	0	0	1	1.8	0	0	5	5.8	4	1.6	10	2.5
				-TX	2	3.5	3	2.4	0	0	0	0	0	0	4	4.5	5	2.0	9	2.3
			-FR	+TX	0	0	6	4.8	2	4.8	2	3.6	1	3.6	2	2.3	9	3.6	13	3.3
				-TX	6	10.4	5	4.0	6	14.2	4	7.1	1	3.6	4	4.5	18	7.0	26	6.6
		-TD	+FR	+TX	1	1.8	4	3.2	0	0	0	0	0	0	1	1.1	5	2.0	6	1.5
				-TX	4	7.0	2	1.6	2	4.8	0	0	3	10.7	4	4.5	11	4.4	15	3.8
			-FR	+TX	2	3.5	4	3.2	2	9.4	1	1.8	0	0	2	2.3	8	3.2	11	2.8
				-TX	13	22.7	19	15.2	4	9.4	0	0	0	0	4	4.5	36	14.1	40	10.0
	-PR	+TD	+FR	+TX	0	0	1	0.8	2	4.8	0	0	0	0	4	4.5	3	1.2	7	1.8
				-TX	0	0	2	1.6	0	0	0	0	1	3.6	1	1.1	3	1.2	4	1.0
			-FR	+TX	0	0	4	3.2	0	0	0	0	1	3.6	1	1.1	5	2.0	6	1.5
				-TX	2	3.5	1	0.8	2	4.8	3	5.4	1	3.6	2	2.3	6	2.4	11	2.8
		-TD	+FR	+TX	1	1.8	5	4.0	0	0	1	1.8	2	7.1	3	3.4	8	3.2	12	3.0
				-TX	3	5.3	7	5.6	1	2.4	0	0	2	7.1	0	0	13	5.2	13	3.3
			-FR	+TX	1	1.8	5	4.0	0	0	0	0	2	7.1	2	2.3	8	3.2	10	2.5
				-TX	7	12.2	5	4.0	1	2.4	0	0	5	17.9	1	1.1	18	7.0	19	4.8
-SP	+PR	+TD	+FR	+TX	0	0	1	0.8	1	2.4	3	5.4	0	0	6	6.9	2	0.8	11	2.8
				-TX	0	0	3	2.4	3	7.1	4	7.1	0	0	6	6.9	6	2.4	16	4.0
			-FR	+TX	0	0	5	4.0	2	4.8	4	7.1	0	0	5	5.8	7	2.8	16	4.0
				-TX	0	0	2	1.6	1	2.4	11	19.5	2	7.1	4	4.5	5	2.0	20	5.1
		-TD	+FR	+TX	0	0	6	4.8	0	0	1	1.8	0	0	1	1.1	6	2.4	8	2.0
				-TX	1	1.8	5	4.0	1	2.4	0	0	2	7.1	3	3.4	9	3.6	12	3.0
			+FR	+TX	1	1.8	4	3.2	2	4.8	2	3.6	0	0	4	4.5	7	2.8	13	3.3
				-TX	3	5.3	5	4.0	4	9.4	4	7.1	0	0	6	6.9	12	4.8	22	5.6
	-PR	+TD	+FR	+TX	1	1.8	0	0	0	0	0	0	0	0	0	0	1	0.4	1	0.3
				-TX	2	3.5	2	1.6	0	0	2	3.6	0	0	3	3.4	4	1.6	9	2.3
			-FR	+TX	0	0	0	0	1	2.4	2	3.6	0	0	1	1.1	1	0.4	4	1.0
				-TX	1	1.8	2	1.6	0	0	5	8.9	1	3.6	3	3.4	4	1.6	12	3.0
		-TD	+FR	+TX	0	0	2	1.6	0	0	1	1.8	0	0	0	0	2	0.8	3	0.8
				-TX	2	3.5	3	2.4	1	2.4	2	3.6	1	3.6	3	3.4	7	2.8	12	3.0
			-FR	+TX	0	0	4	3.2	1	2.4	2	3.6	0	0	1	1.1	5	2.0	8	2.0
				-TX	2	3.5	6	4.8	3	7.1	1	1.8	3	10.7	2	2.3	14	5.5	17	4.3
Total					57	100.0	125	100.0	42	100.0	56	100.0	28	100.0	88	100.0	252	100.0	396	100.0

TABLE 3

RESULTS OF SINGLE VARIABLE ANALYSIS

Variable	Category 1		Category 2		Category 3		Category 4		Category 5		Category 6		Category 8	
	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent
+SP	44	77	75	60	22	52	12	21	19	68	40	46	212	54
-SP	13	23	50	40	20	48	44	79	9	32	48	54	184	46
+PR	35	61	76	61	30	71	37	66	9	32	61	69	248	63
-PR	22	39	49	39	12	29	19	34	19	68	27	31	148	37
+TD	16	28	39	28	20	48	41	73	10	36	51	58	175	44
-TD	41	72	90	72	22	52	15	27	18	64	37	42	221	56
+FR	19	33	48	38	11	26	15	27	11	39	44	50	148	37
-FR	38	67	77	62	31	74	41	73	17	61	44	50	248	63
+TX	9	16	53	48	13	31	20	36	6	21	38	43	139	35
-TX	48	84	72	58	29	69	36	64	22	79	50	57	257	65

Variables for categories 1, 2, and 3 are similar to those for category 8; that is, the large percentages of accidents occurred at high speeds, high tire pressures, small tread depths, low friction, and low textures. Variables for category 5 were similar to those for categories 8, 1, 2, and 3 except for tire pressure, which was below the 50 percentile range in category 5.

High number of accidents seem to appear randomly in the cells of Table 2, but closer study shows that there is a pattern. As an example, the largest number for category 1 accidents was 13 (22.7), which reflected high speed, high pressure, small tread depths, low friction, and small textures. The largest number for category 2 occurred with the same combination of variables. This kind of pattern is believed to result from the interaction of variables. Generally, every fourth cell, observed horizontally across the table, has a high number of accidents. This pattern shows the importance and danger of the combination of three variables: small tread depths, low friction, and small textures. However, based on these data, there would not be much danger from a category 1 accident if low speed, high pressure, and good tread depths were maintained because none of the 57 accidents studied occurred under these conditions.

Probably the best way to analyze the interaction of variables is through the use of the statistical analysis of variance procedure. The data given in Table 2 actually conform to a 2^5 factorial, which can be easily used in a computer program developed for this purpose. The computer program selected was the step-wise regression program developed at the University of California (5). The program calculates the sum of squares for each variable or combination of variables studied. For a factorially designed experiment, the sum of squares value can be used to reveal the amount each variable or combination of variables explains, or contributes to, the number of accidents found in the study. By accumulating the sum of squares values for each variable, a total sum of squares can be determined. Because we wanted to determine the significance of each variable or combination of variables, the sum of squares for each individual variable was divided by the total sum of squares to determine the percentage of contribution. These percentages are given in Tables 4 through 11.

An inadequacy of the method of analysis, i.e., the small number of observations or accidents available for study, should be noted. There were five original variables and 26 other possible combinations of the original variables. Including the number of accidents as the variable for study (the dependent variable), there is a total of 32 variables.

This inadequacy was severe for category 5 (Table 8), for which there were only 28 accidents or observations. Here the attempt to solve for the contribution of 32 variables was made by using the distribution of only 28 accidents. As an indication of what to accept and what not to accept, the authors arbitrarily selected as significant any analysis of variance study containing at least 32 observations.

It is obvious from the data given in the tables that each of the five variables is an important contributor to the accidents studied and that some are more important to certain

TABLE 4

CONTRIBUTION OF VARIABLES TO CATEGORY 1 ACCIDENTS

Variable	Sum of Squares	Percent	Cumulative Percent
TX	47.5	21.5	21.5
SP	30.1	13.6	35.1
TD	19.5	8.8	43.9
SP, TX	13.8	6.1	50.0
FR, TX	13.8	6.1	56.1
FR	11.2	5.1	61.2
SP, PR	11.3	5.1	66.3
TD, TX	11.3	5.1	71.4
SP, FR, TX	11.3	5.1	76.5
SP, FR	9.0	4.1	80.6
SP, TD	7.0	3.2	83.8
TD, FR	7.1	3.2	87.0
PR	5.3	2.4	89.4
SP, PR, TX	5.2	2.4	91.8
PR, FR	3.8	1.7	93.5
SP, TD, TX	2.5	1.1	94.6
PR, FR, TX	2.6	1.1	95.7
PR, TX	1.5	0.7	96.4
PR, TD, FR	1.5	0.7	97.1
SP, PR, FR, TX	1.6	0.7	97.8
PR, TD	0.8	0.4	98.2
SP, PR, TD	0.7	0.4	98.6
SP, TD, FR	0.8	0.4	99.0
TD, FR, TX	0.8	0.4	99.4
SP, PR, TD, FR	0.8	0.4	99.8
PR, TD, TX	0.3	0.1	99.9
SP, TD, FR, TX	0.2	0.1	100.0
SP, PR, FR	0.1		
SP, PR, TD, TX			
PR, TD, FR, TX			
SP, PR, TD, FR, TX			
Total	221.5	100.0	

TABLE 5

CONTRIBUTION OF VARIABLES TO CATEGORY 2 ACCIDENTS

Variable	Sum of Squares	Percent	Cumulative Percent
TD	69.0	20.2	20.2
FR	26.3	7.8	28.0
TD, FR, TX	26.3	7.8	35.8
PR	22.8	6.8	42.6
SP, PR, FR	22.8	6.8	49.4
SP	19.5	5.8	55.2
SP, PR, TD, FR	19.5	5.8	61.0
SP, PR, FR, TX	19.5	5.8	66.8
PR, TD, FR, TX	16.6	4.8	71.6
SP, PR, TX	13.8	4.0	75.6
TX	11.2	3.3	78.9
PR, FR	11.3	3.3	82.2
SP, FR	9.0	2.6	84.8
TD, TX	9.1	2.6	87.4
SP, TD, TX	9.0	2.6	90.0
PR, FR, TX	9.0	2.6	92.6
SP, TD, FR, TX	5.3	1.6	94.2
PR, TD, TX	3.8	1.1	95.3
SP, PR, TD, FR, TX	3.8	1.1	96.4
SP, TD	1.5	0.5	96.9
SP, TX	1.5	0.5	97.4
TD, FR	1.6	0.5	97.9
FR, TX	1.5	0.5	98.4
SP, TD, FR	1.5	0.5	98.9
SP, PR, TD, TX	1.6	0.5	99.4
PR, TX	0.8	0.2	99.6
PR, TD, FR	0.7	0.2	99.8
SP, PR	0.3	0.1	99.9
PR, TD	0.3	0.1	100.0
SP, PR, TD			
SP, FR, TX			
Total	342.7	100.0	

TABLE 6

CONTRIBUTION OF VARIABLES TO CATEGORY 3 ACCIDENTS

Variable	Sum of Squares	Percent	Cumulative Percent
FR	12.5	18.7	18.7
PR	10.1	15.2	33.9
TX	8.0	12.1	46.0
SP, TD, FR, TX	6.2	9.4	55.4
PR, FR	4.5	6.8	62.2
SP, PR, FR	4.5	6.8	69.0
SP, TD, FR	4.5	6.8	75.8
SP, FR, TX	3.1	4.6	80.4
PR, TX	2.0	3.0	83.4
TD, TX	2.0	3.0	86.4
SP, PR, TD, FR	2.0	3.0	89.4
SP, TD	1.1	1.6	91.0
FR, TX	1.1	1.6	92.6
SP, PR, TD	1.1	1.6	94.2
SP, FR	0.6	0.9	95.1
SP, TX	0.5	0.7	95.8
TD, FR	0.5	0.7	96.5
SP, PR, TX	0.4	0.6	97.1
SP, TD, TX	0.5	0.7	97.8
PR, TD, TX	0.6	0.9	98.7
SP	0.1	0.1	98.8
TD	0.1	0.1	98.9
SP, PR	0.1	0.1	99.0
PR, TD	0.2	0.3	99.3
PR, FR, TX	0.1	0.1	99.4
TD, FR, TX	0.1	0.1	99.5
SP, PR, FR, TX	0.1	0.1	99.6
PR, TD, FR, TX	0.2	0.3	99.9
SP, PR, TD, FR, TX	0.1	0.1	100.0
PR, TD, FR			
SP, PR, TD, TX			
Total	66.9	100.0	

TABLE 7

CONTRIBUTION OF VARIABLES TO CATEGORY 4 ACCIDENTS

Variable	Sum of Squares	Percent	Cumulative Percent
SP	32.0	20.0	20.0
TD	21.1	13.1	33.1
FR	21.2	13.1	46.2
TD, TX	10.1	6.3	52.5
PR	10.1	6.3	58.8
TX	8.0	5.0	63.8
PR, TD	8.0	5.0	68.8
TD, FR	8.0	5.0	73.8
FR, TX	6.1	3.8	77.6
SP, TX	4.5	2.8	80.4
PR, FR	4.5	2.8	83.2
TD, FR, TX	4.5	2.8	86.0
SP, PR, FR, TX	4.5	2.8	88.8
SP, PR	3.2	2.0	90.8
SP, TD	3.1	2.0	92.8
SP, FR	3.1	2.0	94.8
SP, PR, TD	2.0	1.3	96.1
PR, FR, TX	2.0	1.3	97.4
SP, PR, TX	1.1	0.7	98.1
SP, TD, TX	1.2	0.7	98.8
SP, PR, FR	0.5	0.3	99.1
SP, PR, TD, TX	0.5	0.3	99.4
PR, TX	0.1	0.1	99.5
SP, FR, TX	0.1	0.1	99.6
PR, TD, FR	0.1	0.1	99.7
SP, PR, TD, FR	0.2	0.1	99.8
PR, TD, FR, TX	0.1	0.1	99.9
SP, PR, TD, FR, TX	0.1	0.1	100.0
SP, TD, FR	0.0		
PR, TD, TX	0.0		
SP, TD, FR, TX			
Total	160.0	100.0	

TABLE 8

CONTRIBUTION OF VARIABLES TO CATEGORY 5 ACCIDENTS

Variable	Sum of Squares	Percent	Cumulative Percent
TX	8.0	17.7	17.7
TD	4.5	9.9	27.6
PR, TD, FR	4.5	9.9	37.5
PR, TD, FR, TX	4.5	9.9	47.4
SP	3.1	6.9	54.3
PR	3.2	6.9	61.2
PR, TD	3.1	6.9	68.1
SP, PR	2.0	4.5	72.6
PR, FR	2.0	4.5	77.1
TD, TX	2.0	4.5	81.6
PR, FR, TX	2.0	4.5	86.1
FR	1.1	2.5	88.6
SP, TD	1.1	2.5	91.1
TD, FR	1.1	2.5	93.6
SP, PR, TD	0.6	1.1	94.7
SP, FR, TX	0.5	1.1	95.8
SP, PR, TD, TX	0.5	1.1	96.9
SP, TD, FR, TX	0.5	1.1	98.0
SP, TX	0.1	0.2	98.2
PR, TX	0.1	0.2	98.4
FR, TX	0.1	0.2	98.6
SP, PR, FR	0.2	0.2	98.8
SP, TD, TX	0.1	0.2	99.0
PR, TD, TX	0.1	0.2	99.2
TD, FR, TX	0.1	0.2	99.4
SP, PR, TD, FR	0.2	0.2	99.6
SP, PR, FR, TX	0.1	0.2	99.8
SP, PR, TD, FR, TX	0.1	0.2	100.0
SP, FR			
SP, PR, TX			
SP, TD, FR			
Total	45.5	100.0	

TABLE 9

CONTRIBUTION OF VARIABLES TO CATEGORY 6 ACCIDENTS

Variable	Sum of Squares	Percent	Cumulative Percent
PR	36.1	36.1	36.1
SP, PR, TX	10.1	10.1	46.2
TD	6.2	6.2	52.4
TD, FR	6.1	6.1	58.5
TX	4.5	4.5	63.0
SP, TX	4.5	4.5	67.5
SP, FR, TX	4.5	4.5	72.0
PR, TD, FR	4.5	4.5	76.5
PR, TD, TX	5.0	5.0	81.5
PS, PR	2.6	2.6	84.1
SP	2.0	2.0	86.1
SP, FR	2.0	2.0	88.1
PR, TD	2.0	2.0	90.1
SP, PR, TD, FR	2.0	2.0	92.1
PR, TX	1.2	1.2	93.3
TD, TX	1.1	1.1	94.4
TD, FR, TX	1.1	1.1	95.5
SP, PR, FR, TX	1.1	1.1	96.6
SP, TD, FR, TX	1.2	1.2	97.8
FR, TX	0.5	0.5	98.3
SP, PR, TD	0.5	0.5	98.8
SP, PR, TD, FR, TX	0.5	0.5	99.3
SP, TD	0.1	0.1	99.4
PR, FR	0.1	0.1	99.5
SP, PR, FR	0.1	0.1	99.6
SP, TD, FR	0.2	0.2	99.8
SP, TD, TX	0.1	0.1	99.9
PR, FR, TX	0.1	0.1	100.0
FR			
SP, PR, TD, TX			
PR, TD, FR, TX			
Total	100.0	100.0	

TABLE 10

CONTRIBUTION OF VARIABLES TO CATEGORY 7 ACCIDENTS

Variable	Sum of Squares	Percent	Cumulative Percent
TX	253.1	18.2	18.2
TD	231.2	16.6	34.8
FR	171.1	12.2	47.0
SP	144.4	10.3	57.3
TD, TX	84.6	6.0	63.3
PR	72.0	5.1	68.4
SP, FR	45.1	3.2	71.6
SP, PR, FR	45.1	3.2	74.8
SP, PR, TX	45.1	3.2	78.0
FR, TX	40.5	2.9	80.9
SP, FR, TX	40.5	2.9	83.8
PR, FR	36.2	2.6	86.4
SP, PR, FR, TX	32.0	2.3	88.7
SP, TX	28.1	2.0	90.7
TD, FR, TX	28.1	2.0	92.7
SP, TD, TX	18.0	1.3	94.0
SP, TD	15.1	1.1	95.1
TD, FR	12.5	0.9	96.0
SP, PR, TD, FR	12.5	0.9	96.9
PR, TX	10.2	0.7	97.6
SP, PR	8.0	0.6	98.2
PR, FR, TX	8.0	0.6	98.8
PR, TD, FR, TX	6.1	0.4	99.2
SP, PR, TD, TX	4.5	0.3	99.5
PR, TD	2.9	0.2	99.7
PR, TD, TX	2.0	0.1	99.8
SP, TD, FR, TX	1.1	0.1	99.9
SP, PR, TD, FR, TX	1.2	0.1	100.0
SP, PR, TD	0.1		
SP, TD, FR	0.0		
PR, TD, FR			
Total	1,399.5	100.0	

TABLE 11

CONTRIBUTION OF VARIABLES TO CATEGORY 8 ACCIDENTS

Variable	Sum of Squares	Percent	Cumulative Percent
TX	435.1	24.9	24.9
PR	312.5	17.9	42.8
FR	312.5	17.9	60.7
FR, TX	91.2	5.2	65.9
SP, PR, TX	78.1	4.4	70.3
PR, FR	72.0	4.1	74.4
TD	66.1	3.8	78.2
SP, FR, TD	66.1	3.8	82.0
TD, TX	50.0	2.9	84.9
SP, TD	36.1	2.0	86.9
PR, TD	36.2	2.0	88.9
SP, PR, FR	32.0	1.8	90.7
SP	24.5	1.4	92.1
SP, TD, TX	24.5	1.4	93.5
PR, TX	21.1	1.3	94.8
PR, FR, TX	51.1	0.8	95.6
SP, FR	12.5	0.7	96.3
PR, TD, TX	12.5	0.7	97.0
TD, FR	10.1	0.6	97.6
SP, PR, TD, TX	8.0	0.5	98.1
PR, TD, FR	6.2	0.4	98.5
SP, PR, FR, TX	6.1	0.4	98.9
TD, FR, TX	4.5	0.3	99.2
PR, TD, FR, TX	4.5	0.3	99.5
SP, PR, TD	3.1	0.2	99.7
SP, PR, TD, FR	3.1	0.2	99.9
SP, TX	1.2	0.1	100.0
SP, PR	0.5		
SP, TD, FR	0.1		
SP, TD, FR, TX	0.0		
SP, PR, TD, FR, TX			
Total	1,745.5	100.0	

types of accidents than are others. For example, the more complex interactions of four and five variables are not so important as the less complex interactions of two and three variables. In each case, a single variable is most important. Category 2 and category 6 accidents appear to be the most complex because of the more complex interactions. It is possible that this complexity is associated with the miscellaneous nature of category 6 accidents and with the variables selected for measurement in the category 2 accidents. For example, the cornering slip friction may not be directly related to the pavement surface friction (SN at 50 mph).

CONCLUSIONS

Macrotexture, vehicle tread depth, pavement surface friction (SN at 50 mph), vehicle speed, and vehicle tire pressure were found to be important variables in the wet-weather accidents studied.

Compared to the sample data, the accident data indicated that a larger number of accidents occurred under the following conditions:

1. The texture of the pavement at the accident site was small (or fine macrotexture);
2. The tread depths of the vehicle involved were small;
3. The friction value of the pavement at the accident site was low;
4. The speed of the vehicle immediately prior to the accident was high; and
5. The tire pressures of the accident vehicle were high.

The relative importance of these five variables was found to depend on the type of general accident situation.

Single variables were the most significant contributors to wet-weather accidents. Complex interactions of the five variables studied did not influence accidents to a great degree, but several interactions of two or three contributed significantly.

Approximately 40 percent of the vehicles involved in wet-weather accidents were, at the time of the accident, in a turning maneuver, about 33 percent were on horizontal curves, and 7.1 percent were passing. It is apparent that research efforts should be directed toward obtaining more information on cornering friction and that remedial measures should be directed to horizontal curves.

For a skidding accident in wet weather (category 7), the order of importance of the five variables studied was (a) texture, (b) tread depth, (c) friction, (d) speed, and (e) tire pressure. Little difference was found in the percentage of contribution of each variable, with values ranging from 5.1 to 18.2 percent.

One of the purposes of collecting accident information should be to detect trouble areas in order that remedial measures may be developed. It would seem to the design engineer that the sole purpose of maintaining accident records is to determine the number of people killed or injured per year in order to make annual comparisons. The results of this report indicated that close study of the reports of the investigating officers should help to classify accidents into preselected categories. It is believed that the classification of wet-weather accidents into categories that contain the various friction modes would be of benefit because these friction modes are also used in highway design. It is concluded that accident information should also be reported in terms useful to the engineer.

The most striking result of the study was the importance of texture. As stated previously, few texture measurements had been obtained prior to this project, and the first indication of the effect of texture was the distribution of texture values (Fig. 12). When texture at the accident site was compared to the texture available on the roadways in the area, an even greater importance was indicated. The texture sampling procedure for the area was poor because funds sufficient to sample the study area had not been provided, but the evidence accumulated appeared to offer cause for concern.

It should be noted that macrotexture of the surface itself is not the item of interest; the minute water drainage channels that texture provides when a tire passes over it are the significant effects. A porous surface through which the water could drain when the tire passes (or under its own head) would be as beneficial, but a textured surface would probably be the most economical type of construction in Texas.

The distribution of accidents given in Tables 2 and 3 is considered to be significant and to show the benefit of studying accidents by categories. Except for tire pressures, the distribution is as expected. The most dangerous combination of variables is high speeds, low tread depths, low friction, and small textures. Each of these variables helps to bring about a very low available friction between the tire and the pavement under wet-weather conditions.

The absence of low tire pressures in the accidents is puzzling. According to hydroplaning theory, low tire pressures are directly related to the velocity of dynamic hydroplaning; that is, the lower the tire pressure is, the lower the speed is at which hydroplaning occurs (6, 7). When a vehicle is hydroplaning, the available tire-pavement friction must be very low and, prior to this study, it would have seemed that all proven principles associated with hydroplaning would also hold for tire-pavement friction. Yet in only one accident type, passing, were low tire pressures found to be significant. Apparently, the absence of low tire pressures from the group of significant variables can be explained by viscous hydroplaning, which is generally associated with slick pavements, small water depths, and high tire pressures. It is possible that both viscous and dynamic hydroplaning are involved in these accidents, and the two could not be separated with the methods used in this analysis. However, it does appear that the accidents occurring because of hydroplaning cannot be separated from accidents occurring at a low friction level. In other words, the situation is dangerous whenever friction is reduced to a low level. It is obvious that the pavement is not the only contributor to low friction. Low tread depths and high speeds also contribute to an accident. A good measure of water film depth on the pavement at the time of the accident was not obtained in this study, but all the evidence when combined with theory leads to the importance of this variable. Water depths greater than those emitted by the skid trailer must be present at the time of the accident.

Accidents are complex, and in many cases no remedial measure is available as far as design, construction, and maintenance of highways or enforcement of laws are concerned. Highway departments and law enforcement agencies can do much to reduce accidents, but the evidence in this study indicates that the driver must also act independently to prevent the accidents analyzed here.

The following items are suggested for implementation. Ways to obtain sufficient texture should be considered in highway design, construction, and maintenance. A minimum texture of 0.5 in. per 27 in., measured with SWRI texturemeter, equivalent to approximately 0.035 in. by the sand patch method, is suggested for design purposes. At this value, the numbers of accidents appeared to decrease to a relatively constant value (Fig. 12). The suggested value does not provide an exceedingly coarse or harsh texture and, therefore, the high-speed friction should be optimized with road noise.

Continuing effort should be made to maintain sufficient friction on the pavement surface. Efforts being made throughout the nation to specify a nonpolishing aggregate for use in the pavement surface could be used to advantage. A method to reduce driving speeds in wet weather should be developed, and minimum tread depths should be required on vehicles that use public highways.

A skid trailer test value alone is not sufficient to establish the skidding safety of a highway or a safe friction value for a highway. However, skid trailer values must be considered in skidding safety and cannot be taken lightly. Efforts should be made to provide a tire-pavement interface friction value that is more representative of the friction available to the driver at the time of a wet-weather accident. The trailer skid number should be modified by a water depth factor and a factor for the tire-pavement drainage characteristic to give a skid number that is more representative of the actual accident conditions. The friction should be further modified by use of tread depths, tire pressures, and speeds more representative of the actual accident vehicle.

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