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VEHICLE HANDLING STUDY: SECOND INTERIM REPORT

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16. Abstract

Three hundred eighty-seven randomly selected accidents occurring in Washtenaw and part of Oakland Counties, Michigan were investigated. Data relevant to determination of the potential role of vehicle handling in accident causation, particularly tire data, were collected on 518 vehicles in these accidents.

Limited tire data were also obtained during random Michigan State Police checklane inspections in the summer of 1976. The checklane and accident samples were compared on tire pressure, tread depth, and carcass construction. Additional comparisons were made between subsets of the accident sample.

The data reveal generally poor tire maintenance practices in both samples, but there is no evidence to implicate poorly maintained tires as causative factors in accidents except on wet or slippery roads. This conclusion is tentative because of the limited number of vehicles in the accident sample, and because the control group may not adequately represent the population which generated the accident sample.

Larger sample sizes, more definitive control-group data and development of a definition of vehicle-handling accidents are recommended.

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SUMMARY

This second interim report of a project entitled "Vehicle Handling Study" describes work conducted during the period September 1, 1975 to September 1, 1977. It presents findings of analyses of tire data collected on 518 vehicles involved in accidents in Oakland and Washtenaw Counties.

The analyses were conducted to assess the role of tires in accident causation. Given that under-inflated, mismatched, or worn tires negatively affect vehicle-handling properties, the tire data were examined to determine the frequency of such factors and whether they may relate to accident causation.

The data were obtained from cars and light trucks involved in 245 single-vehicle and 142 two-vehicle accidents. Comparative data were also obtained from the Michigan State Police checklane inspections conducted in the summer of 1976. Those inspected vehicles were randomly selected. Thus their tire data represent a quasi-control sample drawn from an exposed population.

The analytical approach consisted of comparing the checklane tire pressure and tread-depth data with similar data from the accident population and with the following subsets of the accident population: single-vehicle accidents; two-vehicle, intersection-type accidents; and two-vehicle, non-intersection-type accidents. More detailed data about the carcass type and about tread depth were available for the accident population, and further comparisons were made on these variables for the accident subsets.

Findings

1. No significant difference was found between the inflation pressures of the accident and control samples. The difference of 3 p.s.i., found in an earlier accident sample and discussed in the first interim report, diminished to less than 0.6 p.s.i. difference between the mean pressures. (See page 23.)

2. Accident vehicles that had the greatest imbalance of tire pressures were those involved in crashes on slippery roads. Of those vehicles, ones that had one or more tires with a tread depth of no more than 2/32 inches

had the highest pressure imbalances. The vehicles involved in slippery-road accidents also had tire pressures that deviated the most from the manufacturers' recommended pressures at maximum load. (Pages 17-20.)

3. The tire pressure imbalances in the accident sample were significantly greater than those in the control sample. The significant difference resulted from higher differences among the vehicles in the single-vehicle and non-intersection, two-vehicle subsets of the accident sample. Exceptions to this were the 1976-model vehicles in the accident sample. Those vehicles had lower mean pressure differences than the checklane vehicles. (Pages 26-27.)

4. In both the accident and checklane samples, pressure imbalances were greater in subcompacts and trucks than they were in compact, intermediate, and full-size body types. The greatest imbalances were found in vehicles in the smallest body type. For each body type, differences between the accident and checklane samples were insignificant. (Page 27.)

5. The difference between the average front pressure and the average rear pressure was computed for each passenger vehicle in the accident and checklane samples. The two resulting distributions differ significantly, with the checklane distribution being displaced in the direction of higher front minus rear differences, compared to the accident distribution. The two positive and the two negative tails of the distributions--i.e., the regions with the largest absolute values of pressure difference--were compared for the two samples, and it was found in both cases that the differences were only marginally significant. It was concluded, therefore, that most of the observed overall difference must have arisen from the central portions of the distributions, wherein the pressure differences are so small as to be of little handling consequence. (Pages 28-32.)

6. The accident and checklane samples had the same percentage of vehicles (1%) with mixed radial and non-radial tires. In the accident sample, 9.6% of the vehicles had mixed bias-ply tires--belted with non-belted. For the checklane sample this percentage was 1.6. This difference would appear to relate more to the drivers than to the physical characteristics of the accidents. (Pages 33-36.)

7. The two samples were not large enough to show any significant

difference in the amount of tire tread for the two groups of vehicles. (Pages 37-49.)

8. No significant difference was found in the mean tread depth of the most-worn tire on vehicles involved in single-vehicle and two-vehicle crashes. However, vehicles having a tire with 2/32 inches or less tread were overinvolved in accidents on wet roads by a factor of more than 2. (Pages 49-52.)

9. The wear patterns of tires were found to vary by wheel position. More rear tires wear convexly (with more tread in the center) than do front tires. Twice as many radial tires had linear wear as did regular bias or belted bias-ply tires. Concave or convex wear was not associated with inflation pressure. (Pages 53-64.)

Conclusions and Recommendations

The central conclusion from the study to date is that there is no compelling evidence that tire factors are causative of accidents on dry roads. However, improper tire matching and maintenance practices appear to be accident-causation factors in crashes involving wet or slippery roads. Inferences concerning the role of tire factors on non-slippery roads are limited partly by the small size of the accident sample. A larger accident sample is needed. The tails of some of the distributions used to conclude that tire performance is not a problem on non-slippery roads contain so few cases that those may result from chance.

The current lack of broad agreement on a practical definition of "a vehicle-handling accident" continues to inhibit development of methods for identifying such accidents and their causes. Certainly collection and analysis of more and better pre-crash data are essential to further progress in the study of vehicle handling.

More definitive control group data should be obtained. The statistical inference approach depends fundamentally on the ability to compare the characteristics of an accident sample with the characteristics of the exposed, at-risk population from which it comes. The pseudo-control group used in this study is not detailed enough to carry out the desired comparisons. It may also be insufficiently representative in time and space to serve as a definitive comparison group.

Manufacturers' recommended tire pressures at average load, and deviations from them, should be obtained for both accident and control groups on a vehicle-by-vehicle basis.

Companion studies to define handling characteristics of the at-risk population of vehicles should be expanded (cf. MVMA Project 4.29, "Develop Accident Causation Investigation Techniques"). Those study results can be used in conjunction with results of studies such as this to clarify the role of vehicle handling as an accident-causation factor.

1.0 INTRODUCTION

The purposes of this second interim vehicle handling report are to describe the data collection and analytical activities conducted since the first report was issued, and to present the more important findings that have emerged from these activities.

The first report reviewed accident investigation procedures relative to vehicle handling, discussed some of the various methodological approaches then under consideration, and identified various strengths and weaknesses of the several approaches. The full discussion contained in the first report will not be repeated here, but it is important to note some of the characteristics that underlie the approach that has been adopted.

Our basic approach to determining the potential role of vehicle handling as a possible contributing factor to accident causation has been the statistical inference approach. In general terms, data elements believed to be relevant to accident causation are identified, and these data elements are then collected on a representative sample of accidents. Ideally, the same data elements are also collected on a representative sample of the exposed, at-risk population of vehicles using the highways at the times and places that the accidents occur. The analysis in this approach consists essentially of comparing the two samples and looking for the overrepresentation or underrepresentation of selected variables in the accident population compared to the control population. Variables that are found to be overrepresented in the accident population with respect to their proportions in the control population are presumed, at the first level of analysis, to be causally related to the occurrence of accidents.

The extent to which the overall statistical inference approach can be implemented in any single project is governed primarily by practical issues. The amount of time that can be spent on any single accident by the field investigators, the number of such cases that can be investigated, and the resources available for a detailed description of the control population are all highly relevant. In the present project it has been necessary to limit the scope of the overall investigation by focusing the data collection activities on a particular topic of interest. Tires were selected initially because it is well known that tires have a highly significant effect on vehicle handling characteristics, and presumably, on vehicle-handling accidents if such exist. Further, it was believed that improperly maintained or used tires could be detected relatively easily (compared to other vehicular components that influence vehicle handling) in the accident population.

Project resources were allocated to accident and accident-involved vehicle investigations, and no resources were devoted to obtaining a comparably detailed description of the control population. A pseudo-control population was available, however, in the form of the checklane data collected by HSRI in its evaluation of the Michigan vehicle inspection program. The data from this program, sponsored by the Michigan Department of State Police, are described subsequently and compared to the accident data.

2.0 DATA SET

The data collection procedures and detailed information about the specific data elements, including data collection forms, were presented in the first interim report. These are reviewed briefly below, and the contents of the data set as it currently exists are given in terms of several descriptive variables.

2.1 Selection Criteria

At the beginning of the current project--September 1, 1975--the case-selection criteria were set to investigate all accidents in which one or two vehicles were involved and in which all involved vehicles were towed from the scene because of damage sustained during the accident sequence. Passenger cars and light trucks with four wheels were required to be among the five most recent model years, whereas all other trucks and buses could be up to ten model years old. Thus 1972 and subsequent model year cars and light trucks were eligible initially, and 1977 vehicles were added as they were introduced into the driving population in late 1976.

Simple random sampling from vehicles meeting both the accident and case-vehicle selection criteria given above was employed. This reduced the accidents and vehicles to be investigated to a number consistent with the size of the field investigation staff. The sampling fraction has been maintained at 0.2 in Washtenaw County. For the Oakland County jurisdictions--Bloomfield Township, Pontiac, Royal Oak, Southfield, Troy, and Waterford Township--the sampling fraction was set initially to 0.2 and subsequently increased to 0.3 on April 1, 1976. (It was reduced to 0.2 on April 11, 1977, but all of the vehicles contained in the present data set experienced their accident prior to that date.)

2.2 Data Elements

All data elements have been collected on the Annotated Collision Performance and Injury Report, Revision 3, Edition 1/76, VH/IC Study, 4/76.

The entire form was reproduced in the earlier report and is not contained here. However, it should be noted that extensive data were collected for each wheel and tire. These data elements include whether the wheel was original equipment and if it was damaged, the tread type, intended use (passenger car, light truck, etc.), size, brand, DOT code, and load range of the tire. Tire construction information including carcass type, number of plies, ply material, and the presence of a tube or retread is also collected. The in-use condition of the tire is characterized by tread depth, cupping, and pressure, and the suspected loss of pressure, damage to the tire and involvement of the damage in accident causation are also noted.

2.3 Accident Population

The accident data set utilized in the subsequent analyses contains data from 387 accidents meeting the selection criteria and occurring between September 1, 1975 and February 23, 1977 in Washtenaw County and the six Oakland County jurisdictions given earlier. Of these 387 accidents, 245 (63%) were single-vehicle accidents and 142 (37%) were two-vehicle accidents.[1] Of the 142 two-vehicle accidents, data were obtained on both vehicles in 126 cases, and data were obtained on only one vehicle in 16 cases. The result is that the data set contains 513 vehicles, 245 (48%) of which were involved in single-vehicle accidents, and 268 (52%) from two-vehicle accidents. Data are missing, of course, on variables even though the vehicle is contained in the file, with the result that the number of vehicles is reduced further in the analytical runs, particularly in those where several variables are used.

The majority--55%--of the 387 accidents occurred at night, with 41% occurring during the day and the remaining 4% at dusk or dawn. Of the single-vehicle accidents, 65% occurred at night, whereas only 39% of the two-vehicle accidents occurred at night.

2.4 Drivers

Of the 513 vehicles involved, three were parked cars and one was a

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[1] The requirement that both vehicles of two-vehicle accidents meet the model-year and tow-away criteria results in the disproportionately high number of single-vehicle accidents.

driverless moving vehicle, leaving 509 involved drivers. For all accidents, 69% of the involved drivers were male. This increases to 76% for male involvements in night-time accidents. Similarly, 74% of the drivers involved in single-vehicle accidents were male.

The mean age of all drivers is 31.2 years, and 51.6% of the drivers are 26 years old and younger. The youngest driver is 15 years old and the oldest is 79 years old. The percentage distribution of the drivers by bracketed age is given in Table 1.

Table 1

Percentage Distribution of Drivers by Age Group

N	Age						
	15-17	18-20	21-24	25-29	30-39	40-59	60-79
508	8.9	16.9	20.9	13.6	15.9	17.9	5.9

Alcohol was noted as an impairing factor by the accident investigators for 28.3% of the 481 drivers for whom an "impairment" judgement was made, and "asleep" was noted for an additional 3.3% as shown in Table 2. A further breakdown by number of vehicles involved and a simple day/night dichotomy shows that alcohol impairment was noted in 45.3% of the single-vehicle accidents, and "alcohol" and "asleep" together increase this to 51.2%. As expected, further subsetting of the single-vehicle accidents into "day" and "night" categories shows that 61.3% of the single-vehicle, nighttime accidents involve drinking to some degree.

The extent of impairment in those drivers for whom alcohol was noted cannot be inferred from the data on hand. This is principally because blood alcohol content (BAC)--in quantitative terms--is rarely determined for accident-involved drivers in Michigan. Only 11 drivers were tested, and results were available for only 5 of these. Further, it is known that not all drivers are equally impaired at the same BAC. Young drivers frequently experience greater impairment than do older drivers at the same BAC. Table

Table 2

Percentage Distribution of Drivers by Accident Subsets and Impairment

Drivers	N	Impairment			
		None	Alcohol	Asleep	Other
All	481	63.8	28.3	3.3	4.6
Sngl. Veh, Day .	86	64.0	14.4	5.8	12.8
Sngl. Veh, Night	150	31.3	61.3	6.0	1.3
Sngl. Veh. . . .	236	43.2	45.3	5.9	5.5
Two Veh, Day . .	150	93.3	2.7	0.7	3.3
Two Veh, Night .	95	68.4	26.3	1.1	4.2

3 shows the percentage distribution of drivers, by age, for whom impairment due to drinking was noted. The table shows that drinking-impairment occurs among all age groups and it is highest among the 21-24 age group.

Table 3

Percentage Distribution of Alcohol-Impaired Drivers by Age Groups

N	Age						
	15-17	18-20	21-24	25-29	30-39	40-59	60-79
136	3.7	15.4	26.5	14.0	18.4	20.6	1.5

Table 4 shows the frequency of alcohol-impaired drivers by age and the proportion noted to be impaired by alcohol (the number of alcohol-impaired drivers in an age group divided by the total number of accident-involved drivers in that age group). It can be seen that, except for the youngest and oldest age groups, the alcohol-impaired proportion ranges from about one-quarter to one-third and is only insignificantly higher for the 21-24 age group than for the 40-59 age group.

Table 4

Frequency of Drivers and Proportion of Alcohol-Impaired Drivers by Age Group

	Age							
	All Ages	15-17	18-20	21-24	25-29	30-39	40-59	60-79
N . .	481	38	82	104	64	79	84	30
Prop.	.283	.132	.256	.346	.297	.316	.333	.067

The purpose of the foregoing discussion is to provide a vantage point for considering the detailed analyses that are presented subsequently. The central point is not that alcohol-impaired drivers or young drivers are common among accident-involved drivers; those facts have been thoroughly demonstrated and driver analyses are not the focus of this report. Nonetheless, driver and vehicle performance are so closely coupled in the vehicle-handling context that it is meaningful to consider vehicle/driver-handling performance as a single entity. The driver, in such a conceptualization, would be considered a component in the same sense as tires, brakes, steering linkages, and the like. In this context, differences between accident subsets--such as single-vehicle versus two-vehicle accidents--are shown more sharply by differences in the age and alcohol factors than they are by differences in the tires discussed in the subsequent sections.

2.5 Control Population

One of the basic analytic techniques in the following sections is the comparison of the accident sample with a control population on selected variables available for both populations. The purpose of this comparison is to determine overrepresentation (or underrepresentation) of these variables in the accident sample, compared to an at-risk population of non-accident-involved vehicles.

Since May, 1975, HSRI has participated in the evaluation of the Michigan checklane vehicle inspection program. During the summer of 1975, tire pressures were measured on a random sample of all vehicles stopped at State Police random checklane sites in Monroe and Jackson Counties. These data, used as a sample of a control population, were compared with accident-involved vehicles, and the results were given in the first interim report.

During the summer of 1976 the State Police checklane sites, mainly 'feeder' routes with adequate traffic flow, were re-sampled in Jackson County. It became possible, with the cooperation of the Michigan State Police, to gather a small amount of additional data on checklane vehicles. A form designed to obtain more data pertinent to the current study was filled out on randomly selected vehicles. A copy of this form with selected univariate percentages may be found in Appendix A. The data represent primarily passenger cars, although some light trucks and utility vehicles are also included. These data on 1430 vehicles have been used for comparison with the accident population in the following sections.

Ideally the control sample used for comparison with the accident sample would be obtained from the same county, locale, and time as the accident population of vehicles. However, the Jackson County comparison population provided a convenient sample at no cost to the project and is certainly better than any alternatives available.

3.0 RESULTS

This section presents results from analyses of the cases now in the digital file. The digital file contains 518 vehicles as of June 1, 1977. Of these, 513 fully met the study criteria. (The other 5 vehicles were included because data collection had been completed and the data serve the injury-causation portions of the overall study). Univariate distributions of tire variables and other selected variables of interest are also contained in this section as well as analyses of selected variables pertaining to tires. Tire characteristics examined are (1) inflation pressures, (2) mixes of carcass type, and (3) remaining tread depth.

The basic analytic technique involves comparison of various subsets of the accident population and comparison of the accident population to a control population. The object of the analysis is to compare accident-involved vehicles with "at risk" vehicles on selected variables to determine overrepresentation or underrepresentation of tire parameters in the accident population. The first method, using subsets of the accident population, uses the "induced exposure" technique while the second method, comparison with a control population, uses a group external to the accident population.

Measurement of overrepresentation by comparing two populations is a common and appropriate analytical technique. There are cautions that should be observed in its use, however. Determination of real differences between the populations--rather than observed differences resulting from chance--is based on methods of statistical inference. If statistical significance is achieved, two questions must be addressed. One is whether the differences, even if real, are operationally significant, i.e., are important or relevant. The second is whether there is truly a deterministic relationship--a causal effect--as opposed to correlation with an unidentified causal factor.

3.1 Univariate Distributions of Selected Variables.

The distributions of the principal variables--other than inflation pressure and tread depth--which have been added to the data collection form specifically for the vehicle-handling study are presented in Table 5. The total number of cases is 518 and thus entries of 0.2 and 0.4 indicate frequencies of 1 and 2, respectively.

Table 5

Distributions of Selected Variables in Percent of Cases

I. Variables on Wheels and Tires

Variable	Tire Position			
	LF	RF	LR	RR
Wheel O.E.?				
(1) Yes	98.5	98.3	98.1	97.7
(2) No	0.4	0.4	0.6	0.6
(9) Unknown	1.2	1.4	1.4	1.7
Wheel Damaged?				
(1) Yes	14.9	14.1	7.7	5.4
(2) No	84.6	85.3	91.7	93.8
(9) Unknown	0.6	0.6	0.6	0.8
Tire Tread Type				
(1) Regular	97.1	96.7	81.5	81.7
(2) Non-studded Snow	2.7	2.9	18.0	17.6
(9) Unknown	0.2	0.4	0.6	0.8
Tire Intended Use				
(1) Passenger Car	94.6	94.4	94.6	94.2
(2) Light Truck	5.0	4.8	4.8	4.8
(9) Unknown	0.4	0.8	0.6	1.0
Tire Load Range				
(2) B	90.2	89.8	89.0	88.6
(3) C	2.5	2.7	2.3	2.3
(4) D	1.9	1.9	2.9	2.5
(5) E	1.2	1.0	0.8	0.8
(9) Unknown	4.2	4.6	5.0	5.8

Table 5 (Continued)

Variable	Tire Position			
	LF	RF	LR	RR
Tire Retread?				
(1) Yes	0.6	0.4	0.4	0.4
(2) No	98.1	97.7	97.9	97.1
(9) Unknown	1.4	1.9	1.7	2.5
Tire Tube?				
(1) Yes	0.8	0.8	1.0	1.2
(2) No	96.9	96.7	96.7	95.6
(9) Unknown	2.3	2.5	2.3	3.3
Tire Carcass Type				
(1) Bias Ply	19.1	20.1	19.9	19.1
(2) Belted-Bias Ply	29.3	28.2	28.0	28.2
(3) Radial Ply	50.0	50.2	50.2	50.2
(9) Unknown	1.6	1.5	1.9	2.5
Cupping?				
(1) Yes	2.7	2.5	1.9	1.4
(2) No	94.2	93.4	95.8	95.6
(9) Unknown	3.1	4.1	2.3	3.1
Pressure Loss Suspected?				
(1) None	79.0	80.9	90.0	90.5
(2) Pre-Crash	0.2	0.0	0.2	0.2
(3) At Crash	18.1	16.2	7.7	5.6
(4) Post Crash	0.4	0.2	0.0	0.2
(5) Loss Unknown Time	2.3	2.5	1.9	3.1
(9) Unknown If Loss	0.0	0.2	0.2	0.4
Tire Damaged?				
(1) Yes	8.1	7.3	3.9	2.1
(2) No	89.8	90.2	95.4	96.5
(9) Unknown	2.1	2.5	0.8	1.4
Damage Contributory to Accident?				
(1) Yes	0.2	0.0	0.0	0.0
(2) No	8.3	8.3	3.7	1.7
(3) Not Applicable (No Damage)	89.6	90.3	95.2	96.5
(9) Unknown	1.9	1.4	1.2	1.7

Table 5 (Continued)

II. Vehicle Variables

Variable	Percent of Vehicles
Steering Wheel Original Equipment?	
(1) Original Equipment	98.5
(2) Non-original Equipment	0.4
(9) Unknown	1.2
Glazing Obstructions?	
(1) Glazing Obstructions	0.6
(2) No Glazing Obstructions	86.9
(9) Unknown	12.5
Suspension Alterations?	
(1) Suspension Alterations	0.6
(2) No Suspension Alterations	98.1
(9) Unknown	12.5
Fuel Level?	
(1) Full	11.8
(2) 3/4	17.0
(3) 1/2	24.3
(4) 1/4	25.1
(5) Empty	1.9
(9) Unknown	19.1
Air Conditioning?	
(1) Air Conditioning	52.9
(2) No Air Conditioning	44.0
(9) Unknown	3.1
Cargo?	
(1) Cargo	13.3
(2) No Cargo	80.5
(9) Unknown	6.2

3.2 Tire Inflation Pressure

Tire inflation pressure is one of the most important factors that determines tire performance, and it is by far the most important such variable completely under control of the motorist. In this section tire pressures of the accident and checklane samples are discussed, and pressure comparisons between accident subsets and between the accident and checklane samples are presented.

3.2.1 Accident Comparisons on Environmental Variables. Environmental data, collected from the scene of each accident, include several roadway, weather, and location variables which potentially could be related to vehicle control. Subsets of the accident population, formed by the levels of these environmental variables, were tested by the analysis of variance technique (ANOVA) to see if the mean tire pressures and mean tire pressure differentials in the above mentioned subsets were significantly different. Three pressure difference variables were also computed for vehicles which have neither missing data nor a flat tire in any tire position. Front-to-rear difference is the maximum difference between the two front tires and the two rear tires, i.e., the largest of the absolute values of the differences. Side-to-side difference is the maximum difference in the two right tires and two left tires. The third variable, maximum difference, represents the maximum pressure differential between any two tires on the car (and is, in effect, the maximum of the two previous variables for each vehicle).

Most environmental variables did not produce significantly different subsets (at the 0.05 level) of the accident population when tested on the difference variables. Among these non-significant variables were type of road surface (asphalt, concrete, etc.), horizontal and vertical roadway alignment, collision configuration, and the descriptive variables ran-off-the road (before first impact), and case vehicle speed. The mean tire pressure differentials of the subsets defined by the levels of these variables were not significantly different.

The "surface slippery" variable, with levels yes, no, and unknown, is shown in Table 6 for the three difference variables previously described. The significance is based on the comparison of the means and standard deviations of the subsets defined by the yes and no responses. The mean tire pressure differential of vehicles on slippery roads is significantly higher than those on non-slippery roads, and the variance of the differentials is also greater. This seems to indicate that an improper balance of tire pressures is associated with accidents in which driver control is a problem, although it is obviously not conclusive evidence that the imbalance was causative in these accidents.

Table 6
Mean Tire Pressure Differences for Variables in the
Accident Population Subset on Surface Slippery

Variable	Surface Slippery	N	Mean	S.D.	Sig. (F Statistic)
Side-to-side Difference	Yes	77	6.64	6.98	.0095
	No	198	4.75	4.62	
Front-to-rear Difference	Yes	77	6.78	6.91	.0067
	No	198	4.77	4.79	
Overall Maximum Difference	Yes	77	7.09	7.36	.0061
	No	198	4.97	4.92	

(Vehicles with missing data on one or more tire pressures or with non-load range B tires are excluded)

In Table 7 the mean maximum pressure imbalance is compared for vehicles in single and two-vehicle accidents on slippery and non-slippery roads. For single-vehicle accidents (possibly containing a larger proportion of vehicle-handling accidents than multi-vehicle accidents) the mean imbalance on slippery roads (6.88 p.s.i.) is higher than the non-slippery roads (5.83 p.s.i.), but not significantly so. However, the mean pressure imbalance for single vehicles on non-slippery roads (5.83 p.s.i.) is considerably higher than that for multi-vehicle accidents on non-slippery roads (4.55 p.s.i.) or for all vehicles (Table 6) on non-slippery roads (4.97 p.s.i.). Vehicles in multi-vehicle accidents on slippery roads have the highest mean pressure imbalance of any subset (7.33 p.s.i.), and this is significantly different from the non-slippery, multi-vehicle accident mean (4.55 p.s.i.).

Table 7
Mean of Maximum Pressure Differences for Vehicles in Single and Multi-Vehicle Accidents on Slippery and Not-slippery Roads

Surface Slippery	Single				Multi			
	N	Mean	S.D.	Sig.	N	Mean	S.D.	Sig.
Yes	41	6.88	8.00		36	7.33	6.68	
No	65	5.83	5.77	.436	133	4.55	4.42	.0033

Many tests, using the analysis of variance technique, were also done on combinations of pressure differentials, tread depth, and environmental variables. Very few of these produced significant differences, and some of these were not significant in a physical sense, such as 1 or 2 p.s.i. pressure differentials. Most of these tables are not included in the present report because of this, and those tables which are included may or may not have operational meaning.

To investigate the interaction of tread depth with slippery roads and tire pressure imbalances, the minimum tread depth (in groove #3) of the four tires on each vehicle was determined. Table 8 is highly significant (0.003) and indicates that vehicles on slippery roads with at least one tire with 0-2/32 inch or less tread have the highest mean tire pressure imbalances (10.13 p.s.i.), and vehicles not on slippery roads, with the same minimum tread depth, have the next highest mean pressure imbalance (8.43 p.s.i.). If vehicles in multi-vehicle accidents are removed from Table 8 the table is no longer significant (sig. = 0.5863), but if single-vehicle accidents are removed (leaving only vehicles in multi-vehicle accidents) the table remains significant (sig. = 0.007). Just as in Table 7, the mean pressure imbalance of single-vehicle, accident-involved vehicles not on slippery roadways is higher than multi-vehicle, accident-involved vehicles and partially accounts for the lack of significance for single-vehicle accidents only.

Table 8

Means of Maximum Pressure Differences of Accident Vehicles by Tread Depth and Surface Condition

Surface		Maximum Tread Depth (groove #3) of 4 tires			
		0-2/32	3-5/32	6-8/32	9+/32
	N	8	19	26	12
Slippery	Mean	10.13	7.58	6.96	3.00
	SD	10.34	8.39	6.60	2.92
	N	14	41	73	47
Not-Slippery	Mean	8.43	5.20	5.12	3.47
	SD	8.51	5.98	4.17	3.45
sig.=.0030					

The maximum placard difference variable, derived by taking the minimum pressures in the front and rear, subtracting them from the respective manufacturers' recommended pressures (at maximum load), and then taking the larger of the two differences for each vehicle, is shown in Table 9. Again, vehicles having accidents on slippery roads had significantly higher (sig.= 0.0089) mean tire pressure deviations from recommended pressure.

Table 9

Mean of Maximum Placard Differences by Surface Condition

		N	Mean	SD	Sig.
Surface Slippery	Yes	60	6.15	6.14	.0089
	No	162	3.78	5.86	

Another tire pressure difference, the mean difference between the front and rear tires, was also derived. This difference is, of course, highly correlated with other tire pressure differentials, but it was found not to be significantly different on levels of the environmental variables previously discussed.

3.2.2 Accident Population Subsets. In Table 10 subsets of the accident population, as defined by collision configuration, are compared on the three pressure imbalance variables. None of the comparisons is statistically significant. However, single vehicles have a higher mean pressure imbalance than all multi-vehicle, accident-involved vehicles and vehicles in intersection-type, two-vehicle accidents. Non-intersection, two-vehicle accident vehicles (head-on, sideswipe, front-to-rear, etc.), on the other hand, have higher mean imbalances than do single-vehicle accidents.

Table 10

Comparison of Accident Subsets on Mean Pressure Differences

Var.	Sngl	Multi	Sig.	Sngl	Int.	Sig.	Sngl	Non-Int	Sig.	Int.	Non-Int.	Sig.
Max. S-S Diff.												
N	113	179	.448	113	131	.286	114	48	.880	131	48	.324
Mean	5.70	5.18		5.70	4.94		5.70	5.85		4.94	5.85	
S.D.	5.90	5.48		5.90	5.23		5.90	6.15		5.22	6.15	
Max. F-R Diff.												
N	113	179	.395	113	131	.268	113	48	.983	131	48	.375
Mean	5.77	5.18		5.77	4.95		5.77	5.79		4.95	5.79	
S.D.	6.07	5.58		6.07	5.40		6.07	6.07		5.40	6.07	
Max. Diff.												
N	113	179	.430	113	131	.291	113	48	.938	131	48	.365
Mean	6.00	5.44		6.00	5.20		6.00	6.08		5.20	6.08	
S.D.	6.20	5.78		6.21	5.62		6.21	6.19		5.62	6.19	

The manufacturers' recommended tire pressures (at maximum load) minus the actual tire pressures are shown by tire position for the accident population subsets in Table 11. Negative mean values are the result of average tire pressures higher than those recommended. However, there is no significant difference between the subsets; mean front pressure differences are all near zero (except the intersection-type, right-front tire cell), whereas mean rear pressure differences are all 2-3 p.s.i. below recommended pressure. This is probably a result of the fact that, for maximum loading, rear recommended pressures are generally higher than front recommended pressures.

Table 11

Manufacturers' Recommended PSI
(at Maximum Loading) Minus Actual PSI by
Tire Position for Accident Population Subsets

Tire	Sing	Multi	Sig.	Sing	Int	Sig.	Sing	Non-Int	Sig.	Int	Non-Int	Sig.
LF												
N	120	171	.66	120	123	.59	120	48	.98	123	48	.61
Mean	-.12	.20		-.12	.32		-.12	-.08		.32	-.08	
S.D.	7.94	4.61		7.94	4.23		7.94	5.50		4.23	5.50	
RF												
N	133	176	.20	133	132	.17	133	44	.73	132	44	.49
Mean	-.04	.85		-.04	1.02		-.04	.34		1.02	.34	
S.D.	6.67	5.53		6.67	5.83		6.67	4.53		5.83	4.53	
LR												
N	157	187	.52	157	133	.35	157	54	.85	133	54	.34
Mean	2.95	2.49		2.95	2.22		2.95	3.15		2.22	3.15	
S.D.	7.14	6.02		7.14	6.06		7.14	5.93		6.06	5.93	
RR												
N	151	188	.57	151	137	.49	151	51	.97	137	51	.63
Mean	2.73	2.33		2.73	2.20		2.73	2.69		2.20	2.69	
S.D.	6.54	6.23		6.54	6.48		6.54	5.54		6.48	5.54	

The comparisons involving inflation pressure differences have stressed differences of actual inflation pressures measured in the field. While the various observed pressure differences have been contrasted by partitioning the accident data, little has been done to compare observed pressures with manufacturers' recommended pressure.

Such comparisons are appropriate and indeed could be highly valuable, but have been severely limited by lack of data. Recommended pressures are given on a placard on all cars in accordance with S4.3 of FMVSS 110. Most manufacturers have elected to list the recommended inflation pressures for an "average" or "normal" load in addition to that required for the maximum load, and the data collection protocol includes recording the placard data.

The placard is usually affixed to the inside of the glove-box door, the rear edge of a front door, or to a B-pillar. Unfortunately, these locations are frequently inaccessible to the investigator because the glove-box or car is locked, or because doors are jammed closed. Consequently, the desired data are missing on about 70 percent of the cases.

Using published data, we have been able to obtain the recommended pressure for maximum load conditions for most vehicles and reduce the missing data to about 25 percent. We have not found a reference source for recommended inflation pressures for "average" or "normal" loads. This is unfortunate, as most cars involved in accidents (and probably in normal use) are lightly loaded. Since the recommended pressures, and in particular the front-to-rear differential that results from recommended practice, can vary substantially between average and maximum load conditions, use of the maximum-load recommendations can lead to inappropriate inferences.

Another method of partitioning the accident population, using the weight of the vehicle, also produced significant results. Table 12 shows the mean maximum pressure differences for 1000-pound weight groupings of the accident vehicles. The mean pressure differences decrease as the weight of the car increases. The weight of the car is correlated with the size, of course, and comparisons of the accident and control populations by size is made in the next section.

3.2.3. <u>Accident vs. Checklane.</u> Figure 1 shows the distributions of all tires with valid pressures for the accident and control populations. The distributions are not significantly different, but the accident distribution is somewhat "flatter" than the control distribution.

Comparison of the accident population and the control population on actual tire pressure, by tire position, is shown in Table 13. Only the right-rear tire pressure mean is significantly different between the two

Table 12

Mean Maximum Pressure Differences for Accident Vehicles by Weight

Weight	N	Mean	S.D.	Sig.
1501-2000 lbs.	45	7.07	6.13	0.0317
2501-3500	90	5.99	6.92	
3501-4500	99	4.56	3.93	
4501-5500	24	4.04	3.25	

Table 13

Accident and Checklane Tire Pressures by Tire Position

Tire Position	Accident			Control			(F-stat.)
	N	Mean	S.D.	N	Mean	S.D.	Sig.
LF	393	26.04	6.52	1340	25.83	4.25	.4511
RF	404	25.84	6.52	1362	25.89	4.19	.8568
LR	446	25.55	6.01	1312	25.38	4.72	.5382
RR	446	25.67	6.52	1305	25.08	4.95	.0466
All Tires	1688	25.74	6.27	5324	25.54	4.65	.1694

populations, and the actual mean difference is less than 0.6 p.s.i. This finding differs drastically from the finding in the first interim report where the earlier control population had pressure means about 3 p.s.i. higher in each tire position. We had postulated that the pressures in the first control population were higher due to the conditions under which the pressures were measured, hot vs. cold. The new control population, however, was measured in the same manner as the old and the difference between the accident and control populations was still expected to exist. It is possible that the two control populations were different,

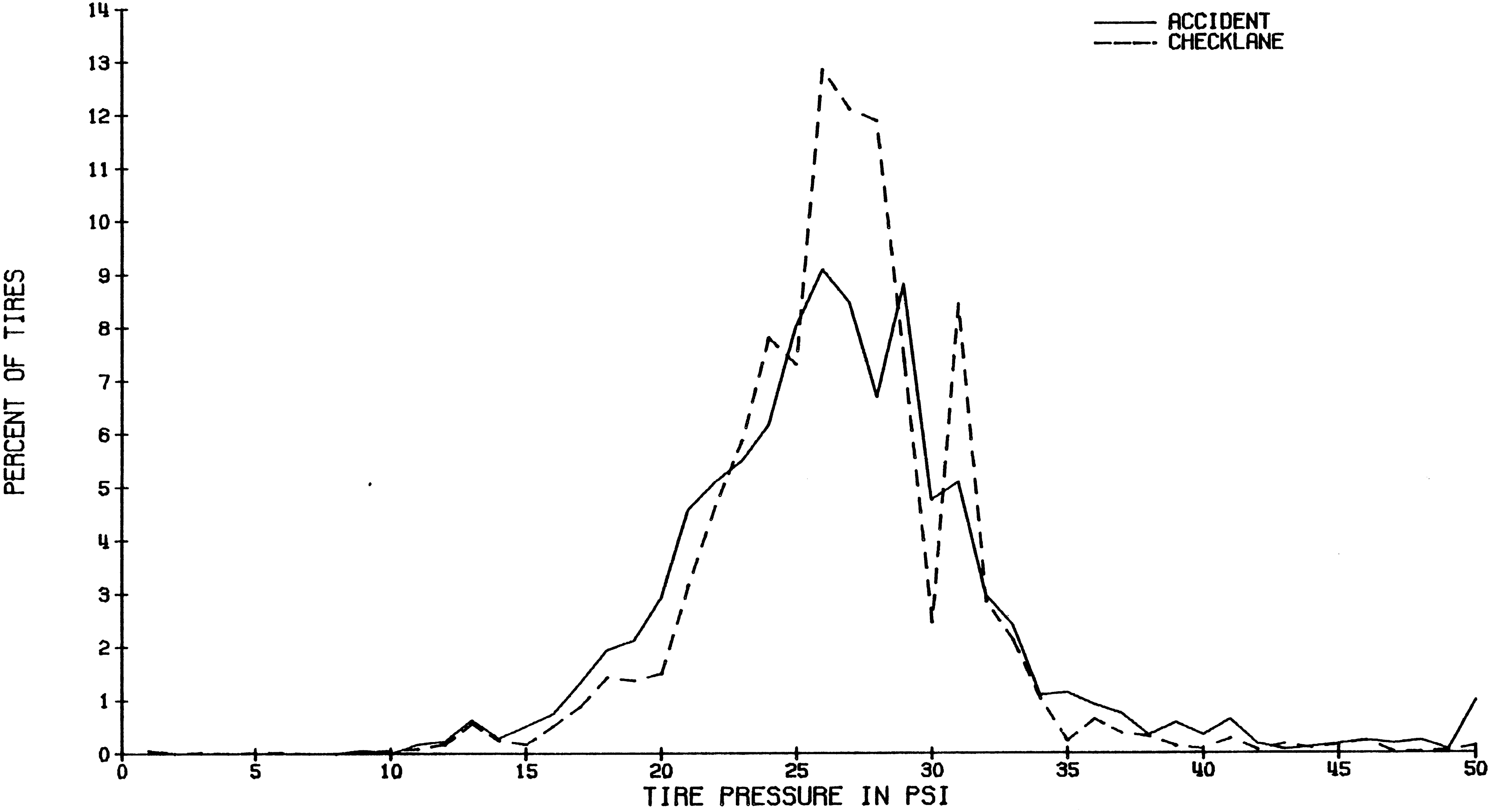

FIGURE 1
DISTRIBUTIONS OF TIRE PRESSURES
IN ACCIDENT AND CHECKLANE SAMPLES

but this is not the most likely explanation. The difference in tire pressure gauges is the more likely explanation since the gauges used in the first checklane were not calibrated, while the gauges used by the HSRI investigators in the second checklane were calibrated and known to be accurate.

Despite the similarity of actual pressures in the two populations, the difference of tire pressures on wheels of the same vehicles is believed to be the best measure of tire pressure deviation, and we have continued to use the difference variables here. Table 14 shows the comparison of the accident and control populations on the pressure imbalance variables for 1972-1977 vehicles. All three variables are significantly different between the two populations, and the accident-involved vehicles have higher pressure differences than the control population for each variable.

Table 14

Mean Pressure Differences for 1972-1977
Accident and Checklane Vehicles

	Accident	Checklane	Sig.
Side-to-side Difference			
N	292	708	.0175
Mean	5.38	4.62	
S.D.	5.64	4.08	
Front-to-Rear Difference			
N	292	708	.0257
Mean	5.41	4.68	
S.D.	5.77	4.20	
Maximum Overall Difference			
N	292	708	.0212
Mean	5.65	4.88	
S.D.	5.94	4.29	

Subsets of the accident population are compared to the control population for 1972-1977 vehicles in Table 15. Only the single-vehicle subset is significantly different from the control population at the 0.02 level. However, the non-intersection subset is significantly different from the control population at the 0.05 level for maximum side-to-side pressure imbalances. A comparison of the two populations by model year (for the model years for which both have data) is shown in Table 16 on the same three variables. Except for the 1976 model year, the accident population means are higher for each of the model years. Comparisons of the populations with the 5 model years pooled are all significant at the 0.02 level.

Table 15

Comparison of Accident Subsets with the Control Population (Model Years 1972-1977) on Mean Tire Pressure Differences

Var.	Single	Check	Sig.	Inter	Check	Sig.	Non-Int	Check	Sig.	Multi	Check	Sig.
S-S												
N	113	708	.015	131	708	.439	48	708	.052	179	708	.128
Mean	5.70	4.62		4.94	4.62		5.85	4.62		5.18	4.62	
S.D.	5.90	4.08		5.22	4.08		6.15	4.08		5.48	4.08	
F-R												
N	113	708	.017	131	708	.506	48	708	.085	179	708	.183
Mean	5.77	4.68		4.95	4.68		5.79	4.68		5.18	4.68	
S.D.	6.07	4.20		5.40	4.20		6.07	4.20		5.58	4.20	
Max.												
N	113	708	.016	131	708	.457	48	708	.069	179	708	.151
Mean	6.00	4.88		5.20	4.88		6.08	4.88		5.44	4.88	
S.D.	6.21	4.29		5.62	4.29		6.19	4.29		5.78	4.29	

Comparisons of the tire pressure imbalances for the checklane population are presented in Table 17 and the same comparisons are presented in Table 18 for the accident population. Pressure imbalances are significantly different by body type for both data sets, and subcompacts and truck (pickups, vans, utility vehicles) imbalances are higher in both sets. A cell-to-cell comparison of the two tables showed no significant difference between the two populations.

Table 16

Accident and Control Populations by
Mean Tire Pressure Differences by Model Year

		Side Diff.		F to R Diff.		Max.Diff.	
		Acc.	Check	Acc.	Check	Acc.	Check
1972	N	53	154	53	154	53	154
	Mean	6.08	4.90	5.91	4.96	6.45	5.23
	S.D.	5.24	3.94	5.66	4.04	6.09	4.18
1973	N	58	177	58	177	58	177
	Mean	5.83	4.68	5.78	4.69	6.02	4.85
	S.D.	6.16	3.96	5.97	4.05	6.18	4.07
1974	N	72	164	72	164	72	164
	Mean	5.97	4.82	6.21	4.88	6.38	5.11
	S.D.	5.73	4.33	6.20	4.54	6.22	4.62
1975	N	60	121	60	121	60	121
	Mean	5.67	4.65	5.70	4.71	5.83	4.92
	S.D.	6.67	4.53	6.55	4.63	6.71	4.73
1976	N	46	92	46	92	46	92
	Mean	3.00	3.66	3.00	3.76	3.17	3.88
	S.D.	2.72	3.31	2.75	3.44	2.76	3.57

Another series of tests was performed on the distributions of the difference D formed by subtracting the average of the rear tire pressures from the average of the front tire pressures for each passenger car in the checklane and accident samples.[1] The difference D ranged from -14.5 p.s.i. to +15.5 p.s.i. for 622 checklane vehicles, with a mean of +0.55 p.s.i. and a standard deviation of 3.1 p.s.i. Comparative figures for the 255 accident-vehicles are: range, -12.5 p.s.i. to +18.5 p.s.i.; mean, +0.14 p.s.i.; and standard deviation, 4.0 p.s.i. Little operational meaning would be attached to a statistically significant difference between the mean of the D measures for the two samples even if such existed. The fact is, however, that the two means do not differ in a statistical sense, and the

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[1] Vehicles in the accident sample were excluded if any of the four tires was suspected of having lost pressure during the accident sequence.

Table 17

Mean Tire Pressure Differences by Model for 72-77 Vehicles in the Control Population

	Side-to-Side Difference	Front-to-Rear Difference	Maximum Difference
Full			
N	248	248	248
Mean	4.08	4.07	4.26
S.D.	3.39	3.33	3.47
Intermediate			
N	195	195	195
Mean	4.92	4.96	5.20
S.D.	4.48	4.48	4.52
Compact			
N	105	105	105
Mean	4.21	4.21	4.39
S.D.	3.37	3.27	3.39
Sub-Compact			
N	74	74	74
Mean	5.97	6.28	6.42
S.D.	5.50	5.90	5.93
Trucks			
N	59	59	59
Mean	5.42	5.51	5.75
S.D.	4.75	4.94	5.05
Sig.	0.0020	0.0004	0.0006

difference in means of 0.41 p.s.i. is of no operational consequence. We note, however, that the positive means of the D measures require that, on the average, the front tires have higher pressures than the rear tires for both populations.

The two D distributions were also compared using Flora's RIDITS[1] on grouped data as shown in Table 19, and also using the Mann-Whitney U-

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[1] J.D. Flora, Jr. "RIDITS: A New Look at an Old Technique for the Analysis of Accident Injury Data," HIT LAB REPORTS, Vol. 5, NO. 3, Highway Safety Research Institute, The University of Michigan, November, 1974.

Table 18

Mean Tire Pressure Differences by Model for 1972-1977 Accident Vehicles

	Side-to-Side Difference	Front-to-Rear Difference	Maximum Difference
Full			
N	58	58	58
Mean	4.72	4.50	4.84
S.D.	4.72	4.45	4.75
Intermediate			
N	60	60	60
Mean	4.40	4.40	4.52
S.D.	4.00	3.96	4.04
Compact			
N	56	56	56
Mean	4.09	4.63	4.64
S.D.	4.05	5.20	5.21
Sub-Compact			
N	81	81	81
Mean	6.81	6.94	7.19
S.D.	6.81	6.96	7.14
Trucks			
N	37	37	37
Mean	6.84	6.30	6.95
S.D.	7.48	7.30	7.51
Sig.	0.0094	0.0269	0.0163

statistic and the median test statistic on the individual measurements. All three analyses indicate that the two distributions differ from each other in a statistically significant sense. The difference is such that the checklane D distribution is "more positive" than the accident D distribution. In other words, the checklane D distribution is somewhat to the right of the accident D in a manner analogous to the mean of the checklane D (+0.55 p.s.i.) being more positive and to the right of the mean of the accident D (+0.14 p.s.i.). In terms of tire pressures, it can be inferred that the trend to having higher front pressures than rear pressures is stronger in the checklane sample than in the accident sample.

Table 19

Distributions of Front Average PSI Minus Rear Average PSI (D) for Accident and Checklane Samples of Passenger Cars

	Pressure Difference Interval (Inclusive)		Checklane		Accident	
			N	%	N	%
R>F	-15	-12	2	0.3	1	0.4
	-11.5	- 8.5	5	0.8	4	1.6
	- 8	- 5	12	1.9	10	3.9
	- 4.5	- 3.5	28	4.5	22	8.6
	- 3	- 2	56	9.0	29	11.4
	- 1.5	- 1	77	12.4	35	13.7
	- 0.5	+ 0.5	189	30.4	65	25.5
F>R	1	1.5	78	12.5	31	12.2
	2	3	81	13.0	20	7.8
	3.5	4.5	41	6.6	13	5.1
	5	8	44	7.1	16	6.3
	8.5	11.5	6	1.0	4	1.6
	12	15	2	0.3	3	1.2
	15.5	18.5	1	0.2	2	0.8
Total			622	100.0	255	100.0

RIDITS Test: Odds Ratio=1.25, Sig. Level=0.008

However, the statistically significant difference that has been observed may have arisen from the numerous observations in the central part of the D distributions wherein the small pressure differences--2 or 3 p.s.i.--have little meaning in a vehicle dynamics context. Therefore the tails of the two D distributions were compared in a series of 2 x 2 Chi-square tests as shown in Table 20. It can be seen that only the test of the negative tail of the accident D versus that of the checklane D--with the negative tail defined by D<-3.5[1]--showed statistically significant differences between the accident and checklane samples at the 5 percent

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[1] Rear tire pressure greater than front tire pressure by at least 3.5 p.s.i.

level. Both the positive and negative tails of more than 5 p.s.i. absolute difference are significant at the 10 percent level. All of these observations support the inference that the two D distributions, although different, differ mainly in their central regions.

Table 20

Comparisons of the Tails of the Distributions of D

D=F-R	Tests of Positive Tails				Tests of Negative Tails			
	Tail		Tail		Tail		Tail	
	<5	≥5	<3.5	≤3.5	>-3.5	≤-3.5	>-5	≤-5
Checklane	613	9 (1.4%)	569	53 (8.5%)	575	47 (7.6%)	603	19 (3.1%)
Accident	246	9 (3.5%)	230	25 (9.8%)	218	37 (14.5%)	240	15 (5.9%)
Chi-Square	2.9		0.23		14.5		3.16	
Sig. Level	0.087		0.63		0.002		0.076	

Other variables, in particular environmental variables available in the accident file only, were tested using the ANOVA test with the rear minus the front mean PSI as the dependent variable. None of the comparisons produced significant results, and the means of the subsets formed by these environmental variables were quite similar. Variables tested included surface slippery, vehicle-to-vehicle configuration, road alignment, ran-off-the-roadway before first impact, and the derived variable wet/dry.

3.3 Mixing of Types of Carcass Construction

Mixing tires of different types of carcass construction (regular bias, belted bias, and radial ply) can substantially affect the handling characteristics of vehicles.[1] In general, the different types of construction provide different cornering stiffnesses, and altering the relative front/rear cornering stiffness changes the understeer characteristics. This can be most pronounced if radials are mixed with non-radials.

The checklane data collected in 1976 contain 22 vehicles with mixed carcass types among 1381 vehicles with no missing data on construction, or 1.6 percent. The 513 vehicles in the accident sample include 49 with mixed carcass types or 9.6 percent. The difference is statistically significant at less than the 0.0001 percent level, with X^2=63 and d.f.=1.

The accident data collection period includes winter months so a number of cars equipped with snow tires were investigated. Since the checklane data were collected in late summer, the greater mix of carcass constructions found in the accident sample could have resulted partly from the use of snow tires. If the vehicles in the accident sample with carcass mixes and snow tires (with snow tires and regular tread of different carcass types) are removed from the mixed category and treated as not-mixed, the frequency of mixes in the accident sample becomes 5.3 percent. While 45 percent of the mixes in the accident sample are eliminated by this procedure (for purposes of a comparison with the summer checklane data), the frequency is still significantly greater than in the checklane sample at less than the 0.0001 level with X^2=18.6 and d.f.=2.

The above cases of mixing types of carcass construction include all combinations of regular bias, belted-bias, and radial. Mixing radials with non-radials is frequently noted as a particularly dangerous practice. There are 14 such samples in the checklane data, or 1.01 percent of the vehicles. The accident sample contains 5 vehicles with radials mixed with non-radials, or 0.97 percent--nearly identical to the proportion in the checklane sample.

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[1] Bernard, James E. et al., "Vehicle-In-Use Limit Performance and Tire Factors," Technical Report UM-HSRI-PF-75-1-2, Contract DOT-HS-031-3-693, Highway Safety Research Institute, The University of Michigan, Jan. 31, 1975.

While the mixing of radials with non-radials is the same in both samples, there is substantially more mixing of bias and belted-bias tires in the accident sample as noted above. This apparent overinvolvement of mixed bias and belted-bias tires is of interest. When the vehicles in the accident sample are partitioned into those in single-vehicle crashes and those in multi-vehicle crashes, 49.0 percent of those in single-vehicles are found to have mixed carcass types, compared with 47.5 percent for those in multi-vehicle crashes. The difference is not significant.

A comparison of carcass mixing with a trichotomous variable for road surface condition is shown in Table 21. While a greater proportion of the vehicles with mixes were involved on roads which were either wet or covered with ice or snow, the differences are not statistically significant (X^2=3.1, d.f.=2). When mixes which may have resulted from the use of snow tires are discounted, the results shown in Table 22 are obtained.

Table 21

Mixing of Carcass Types
by Road Surface Condition

Surface	Carcass Types			
	Mixed		Non-Mixed	
	N	%	N	%
Dry	24	49.0	286	61.8
Wet/Water Covered	14	28.6	103	22.2
Ice/Snow	11	22.4	74	16.0

While the proportions are slightly different with mixes from the use of snow tires discounted, the differences are still not significant (X^2=2.2, d.f.=2).

In no case did an accident-involved car equipped with snow tires have a mix of radials with non-radials. Either the public or dealers (or both) are apparently following the precaution of not mixing radials and non-radials

Table 22

Mixing of Carcass Types
by Road Surface Conditions
Discounting Mixes Possibly Resulting
from the use of Snow Tires

Surface	Carcass Type			
	Mixed		Non-Mixed	
	N	%	N	%
Dry	15	53.6	295	64.3
Wet/Water Covered	9	32.1	94	20.5
Ice/Snow	4	14.3	70	15.3

when installing snow tires.

A variable labeled "driver impairment" denotes involvement of alcohol if it has been detected by officers at the scene or by the accident investigators. While other conditions such as fatigue or sleep are also noted when known, alcohol is the most frequent impairment. The driver impairment variable is a double response variable, so the total number of responses is double the number of drivers. These responses also include "no impairment." Among the drivers of vehicles with mixed carcass types, 21.6 percent of the responses indicated alcohol involved and only 14.2 percent for drivers without carcass mixes.

The Rubber Manufacturers Association publishes a wall chart for the use of tire dealers that describes acceptable and non-acceptable combinations of tire construction and aspect ratios.[1] Three categories of combinations are listed. These are "preferred" (for identical aspect ratio and carcass construction), "acceptable", and "no." The guide is rather liberal. For example, it lists as acceptable the use of radials on the rear and non-

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[1] "Tire Application Guide for Passenger Cars," published by the Rubber Manufacturers Association, 1901 Pennsylvania Avenue, N.W., Washington, D.C. 20006.

radials on the front unless the front tires are of the 50 or 60 series.

Using the RMA guide as criteria, 13 of the carcass mixes in the checklane sample are unacceptable mixes or a proportion of 0.9 percent, while 25 or 3.9 percent of the vehicles in the accident sample have unacceptable mixes. While the incidence of unacceptable mixes is about half that for all mixes of carcass constructions, the difference between the two samples is still highly significant with $X^2=29$, d.f.=1.

The higher frequency of carcass mixes in the accident-involved vehicles compared to the checklane vehicles is just the sort of overrepresentation that would implicate carcass mixes as a factor associated with accidents, either causally or through correlation with a causal factor. However, a causal inference from the data presented here must be tempered for two reasons. One is that the association between carcass mixes and the indication of impairment of the driver by alcohol suggests that mixing may be a result of driver characteristics which are associated with accidents, rather than a direct causal factor. The second reason is that there may be basic differences between the populations from which the checklane and accident samples were taken that account for the difference in the observed carcass mixes. Evidence of this will be discussed relative to tread depth in Section 3.4.1, where the analyses include control for the effects of confounding variables whose distributions differ in the two populations. The number of cases of mixes of types of carcass construction is too small to permit such statistical control.

The five vehicles having radial tires mixed with non-radial tires are insufficient for any but the cursory analysis given above. Because the number is small, a brief summary of each case is included in Appendix B.

3.4 Tread Depth

This section presents an examination of tread depth measured on the accident sample. The section is divided into three subsections. Subsection 3.4.1 presents comparisons of the accident sample with the control (checklane) sample. Since only one measurement was made per tire in the checklane data collection, the comparisons are limited to the use of one groove measurement on each tire in the accident sample.

In 3.4.2, subsets of the accident sample are compared. The objective of 3.4.2 is to examine the overall tread depth in the accident sample. Since all grooves were measured on the accident vehicles, the mean depth of all grooves on each tire is used as the measure of overall tread depth. Much of the material in this section is based on the minimum mean depth on the vehicle--that is, the mean depth of the tire which had the lowest mean depth of all four tires.

Lastly, two characteristics of the pattern of wear that can be deduced from measurements of all grooves are examined in 3.4.3 for subsets of the accident sample. The two pattern characteristics are the concavity/convexity of the pattern, and lateral asymmetry of wear on each tire.

3.4.1 Tread Depth Comparisons of Accident and Checklane Samples. Tread depths were measured in both the accident and control samples. The measurement for the control group was made while the cars were waiting in line for the Michigan State Police checklane, and thus the time available was limited. Because of this only one tread depth measurement was made on each of the four tires. The single measurement was made in the center groove of tires with an odd number of grooves, or in the groove nearest the center on the side toward the observer (outside) in the case of an even number of grooves. The observer was instructed to take the time necessary to be sure the measurement was not over a tread wear indicator. All comparisons of tread depths in the accident and control groups are based on a consistent depth measurement. This is accomplished by using the depth of the groove in the accident data that corresponds to the groove measured in the checklane data.

The checklane sample collected in the summer of 1976 included vehicles over 20 years old. Tread depth is correlated with age, and since the vehicles in the accident sample are no more that 5 years old (model years 1972-1977), the use of the checklane data has been limited to those vehicles that were no more than 5 years old at the time of the data collection.

The distributions of tread depths on the tires in the two samples are shown in Figure 2. Since the checklane data were collected in the summer, presumably with few snow tires, snow tires which have deep treads have been

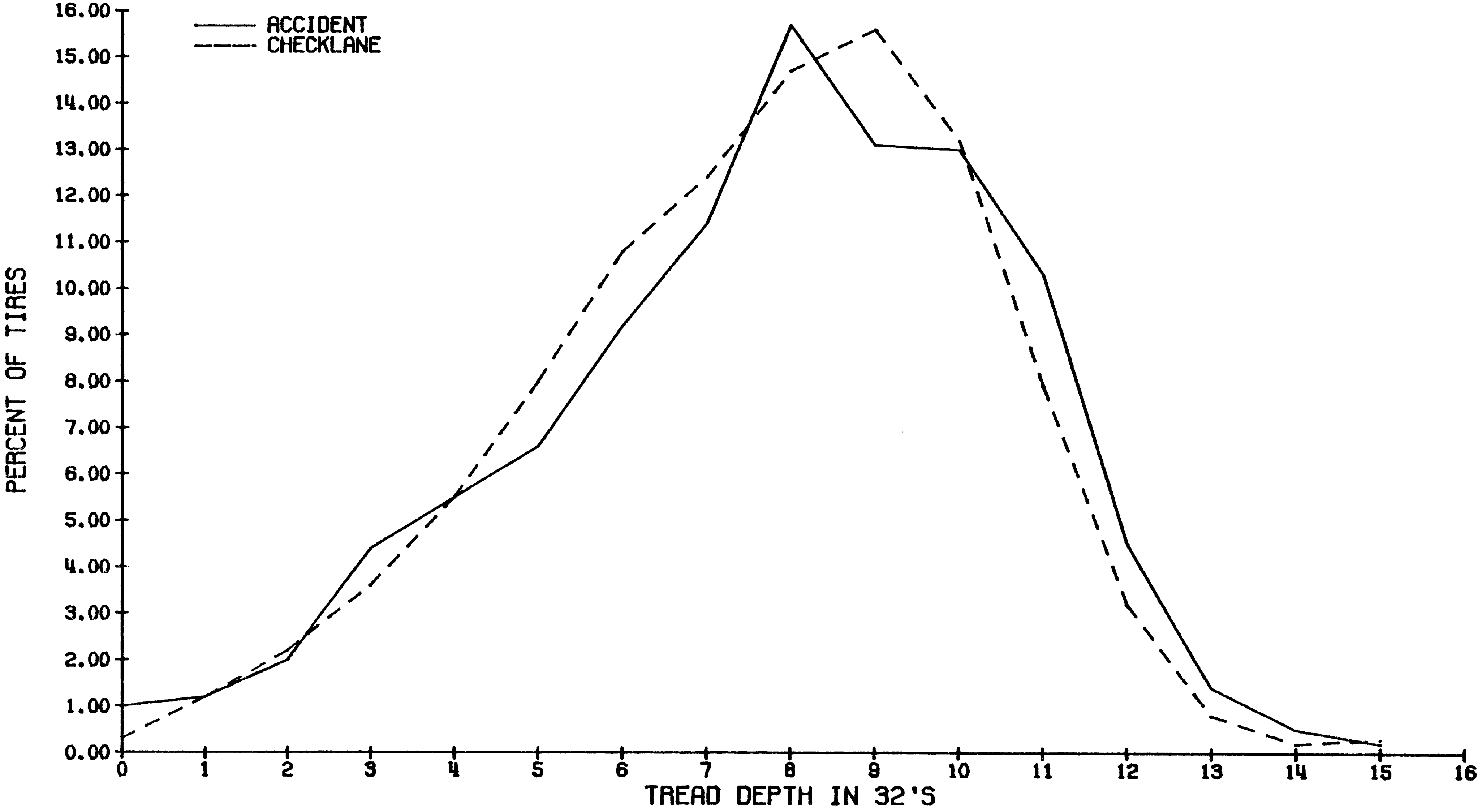

FIGURE 2
DISTRIBUTION OF TREAD DEPTH OF EACH TIRE
0-5 YEAR OLD VEHICLES

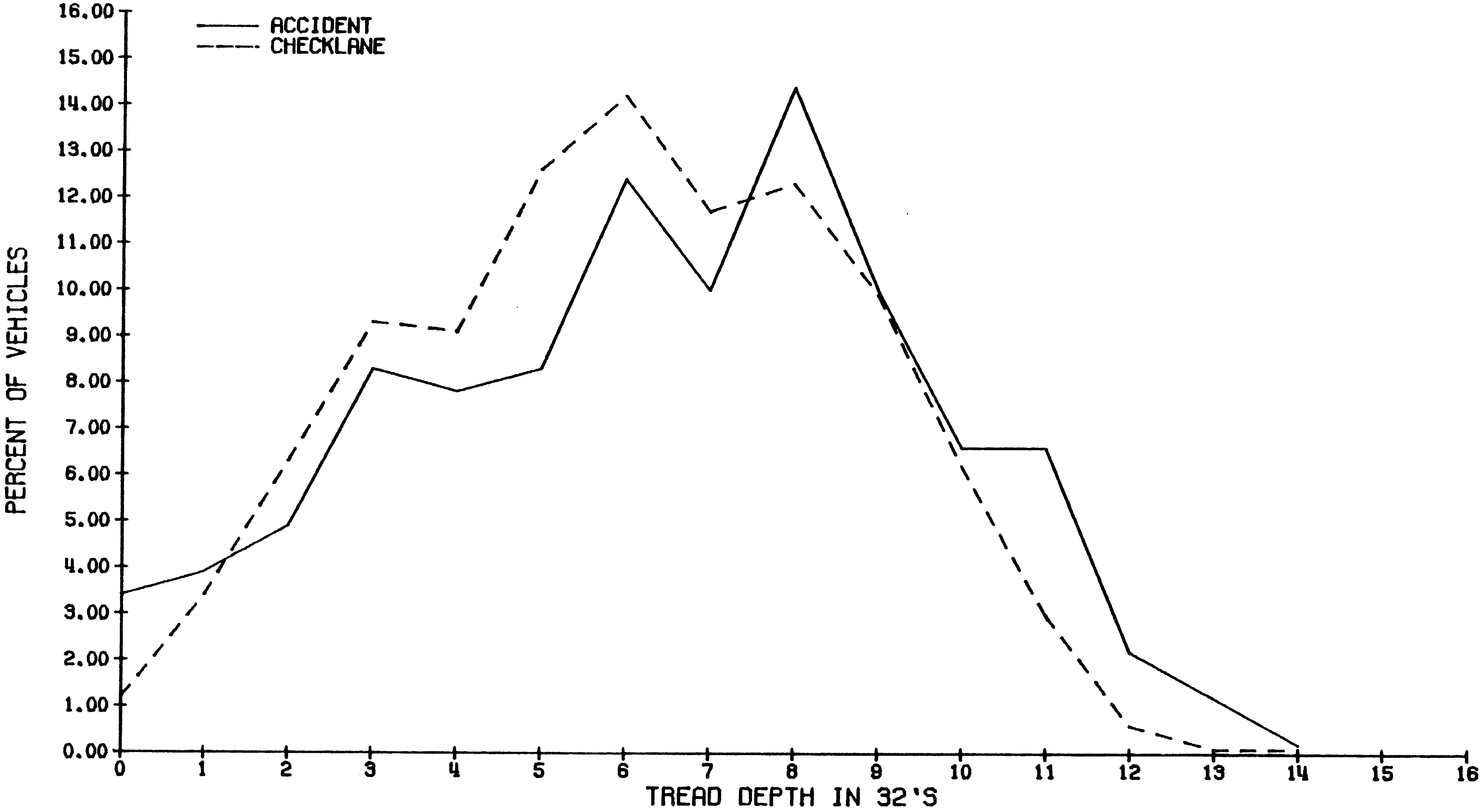

FIGURE 3
DISTRIBUTION OF MINIMUM TREAD DEPTH
ON EACH VEHICLE. 0-5 YEAR OLD VEHICLES

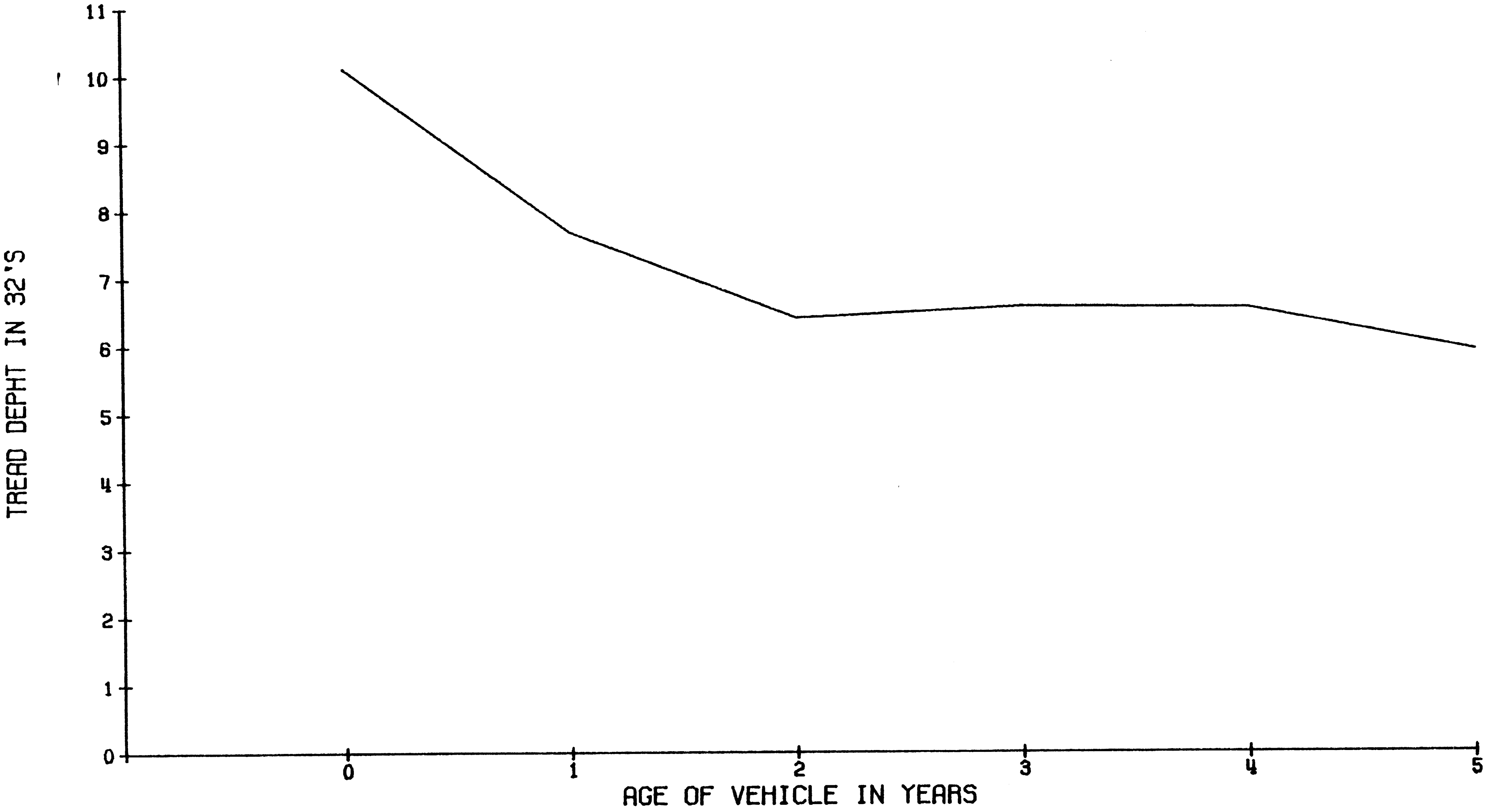

FIGURE 4
MEAN MINIMUM TREAD DEPTH BY VEHICLE AGE
COMBINED CHECKLANE AND ACCIDENT DATA

deleted from the accident data in Figure 2. Tires with missing data on tread depth are also excluded. Consequently, Figure 2 is based on 3787 tires from the checklane sample and 1629 tires from the accident sample.

The distributions are very similar in both samples, with both having a mode at 8/32 to 9/32. However, the curve for the accident sample is displaced slightly to the right above 4/32, indicating the tires in the accident population had slightly more tread. The difference between the two distributions is statistically significant at the 0.0214 level.[1] The proportion of tires with tread depths of 0-2/32 is 4.24% in the accident sample, and 3.75% in the checklane sample. This difference is not significant (X^2=0.7, d.f.=1). Figure 3 gives the distribution of the minimum tread depth on each vehicle, i.e., the minimum of the four tires. Those vehicles are included for which all four tires met the requirements given relative to the previous figure, 949 vehicles in the checklane and 411 in the accident samples. Almost all observations made with regard to Figure 2 also apply to Figure 3. The difference in the two distributions is significant at the 0.014 level using Flora's technique. The mean minimum depth in the accident sample is 7.4 (32's) and 7.0 for the checklane sample. While the difference is significant (at the 0.017 level using the Students test), it is small.

The proportion of accident-involved vehicles with minimum tread of 0-2/32 is 12.2%, but only 10.9% for the checklane sample, although the difference in the two proportions is not significant (X^2=0.49, d.f.=1).

The greater tread depths on tires of the accident-involved vehicles shown in Figure 2 are surprising, but can be explained in part by differences in the two samples. It was noted earlier that tread depth is correlated with vehicle age. Figure 4 indicates the mean depth (of four tires) decreases, particularly in the first two years. The proportion of vehicles with at least one tire with a tread depth of 0-2/32 also increases with age, even more markedly than the mean. This is shown in Table 23.

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[1] The RIDITS Technique of Flora was used for the tests. This technique was used because it is a distribution-free method of determining if the numbers (scores) of one population are greater than those of a second. The significance levels given by Flora's technique are the same as those given by the Mann-Whitney (U) test to which it is closely related.

Table 23

Proportion of Vehicles in the Combined Accident and Checklane Samples with a Minimum Mean Tread Depth 2/32 or less by Age.*

Age in Years	Proportion in Percent
0	1.0
1	5.7
2	12.9
3	14.4
4	15.2
5	18.3
Mean	11.3
Total N	1360

*Vehicles with snowtires have been excluded from the accident sample

The age of vehicles in the two samples is different. Table 24 shows that a greater proportion of the vehicles in the accident sample are less than two years old. The associations between sample (accident, checklane) and age, and between tread depth and age, suggest that comparisons of tread depth in the two samples could be confounded by vehicle age and that the comparisons should be controlled for the effects of age. Multivariate linear regressions were used to provide such control.

In the regressions to be discussed below for comparing tread depths in the accident sample with those in the checklane sample, tires on trucks in both samples, and snowtires on cars in the accident sample were excluded. Only vehicles in a common range of ages--0-5 years old--were included. The tread depths in the regressions are of the tire with the minimum tread on the vehicle. Consequently, the basic observational unit is a vehicle. The regressions provide predicted values of a dependent variable Y (in this case tread depth) as a linear function of several dependent variables X_i,

$$\hat{Y} = b_0 + b_1X_1 + b_2X_2 \ldots .$$

The least squares method selects the coefficients such that the sum of squares of the differences between the predicted and observed values of Y is

Table 24

Vehicle Age By Population

Age in Years	Proportion of vehicles of each age in percent for:	
	Checklane	Accident*
0	10.5	21.6
1	14.3	22.5
2	20.7	22.5
3	22.4	20.6
4	19.7	12.0
5	12.3	0.7
Total %	100.0	100.0
N	950	417

*Vehicles with snowtires have been excluded.

minimized.

A regression of tread depth (in 32's) against sample (1=checklane, 2=accident) gives the results in Table 25.

Table 25

Least Squares Regression
by Tread Depth by Sample and Vehicle Age

$R^2=0.12$

Variable	Coefficient	Significance Level
Constant	9.507	0.00
Sample	-0.106	0.53
Age	-0.660	0.00

These results indicate that after controlling for age, the difference in the two samples was not significant (sig. level=0.53), while the effect of age was, with each additional year of age, to reduce the mean tread depth by 0.66/32 inch. However, the conclusion must be tempered by the fact that the model only explained 12 percent of the variability in the data as indicated by the value of R^2. Nevertheless, the result is consistent with the observation that while the accident sample has more tread than the checklane sample, it also has more new cars which in general have more tread.

The regression using tread depth in 32's effectively examines differences in the means of the samples. Since the mean minimum tread depths are substantial, about 7/32, small differences in the means may have little influence on accident experiences. Therefore the remaining comparisons of tread depth will examine the proportions of the vehicles in each sample which have minimum tread depths of 0-2/32. For examining proportions, it is possible to use weighted least squares models. Basically, the proportions used as the dependent variables are computed for the group of observations (vehicles) that fall in each of the population cells defined by the combinations of values of the independent variables. Each cell, i, has n_i observations with a cell proportion of p_i. In the weighted least squares, the variables are weighted for each cell by the square root of W_i, where

$$W_i = n_i/p_i(1-p_i).$$

This weighting avoids problems associated with non-uniform variances in the cells.

The weighted least squares regression of the proportion of vehicles with a minimum tread depth of 0-2/32 against sample and vehicle age gives the information in Table 26. The coefficient for sample is statistically significant at the 0.012 level, indicating the two samples are different. The coefficient for sample indicates that the difference in the proportions with low tread depth is 3.38%--above and beyond any effect of age on the two samples--with the accident sample having more such vehicles.

Model (body type) is also a candidate control variable. Table 27 gives the distribution of model in the two samples. Full sized cars occur about half as frequently in the accident sample. The four-level model variable for passenger cars results in 48 cells when crossed with sample (2 levels) and vehicle age (6 levels). This results in many empty or nearly empty

Table 26

Weighted Least Squares Regression of Tread Depth less than 3/32 by Sample and Vehicle Age
$R^2=0.836$
Total Degrees of Freedom = 12

Variable	Coefficient	Significance Level
Constant	-0.0736	0.001
Sample*	0.0338	0.012
Age**	0.0408	0.000

*1=checklane sample, 2=accident sample
**The age variable used is the age of the vehicle plus one.

cells with the quantity of data available. Hence a two-level model variable was used. Full sized and intermediate cars were pooled into level 1, while compacts and sub-compacts were pooled into level 2. The distribution given in Table 27 suggests this pairing.

Table 27

Distribution of Model in Each Sample

Model	Distribution in Percent	
	Checklane	Accident
Full Size	38.1	20.9
Intermediate	28.0	19.5
Compact	14.7	21.4
Sub-Compact	10.2	26.3
Small Truck	8.9	11.9
Total	100.0	100.0

Table 28 substantiates the choice of the dichotomous model variable as a control since small cars have a greater incidence of little tread in both samples.

Table 28

Proportion of Cars with Minimum
Tread Depth of 0-2/32 in Percent by Sample and Model

Sample	Model	
	Large	Small
Checklane	9.33	15.02
Accident	7.87	14.21

The weighted least squares regression using both vehicle age and the two-level model variable--generating 24 cells in all--is given in Table 29.

Table 29

Weighted Least Squares Regression of Tread
Depth of 2/32 or Less by Sample, Age, and Model
$R^2=0.51$
Total Degrees of Freedom = 24

Variable	Coefficient	Significance Level
Constant	-0.0637	0.000
Sample	-0.0052	0.263
Age	0.0362	0.000
Model	0.0283	0.027

This regression indicates that controlling on model as well as vehicle age results in no significant difference in the proportion of cars with low tread in the two samples. However, this regression does not explain as much of the variability as does the regression in Table 26. Nevertheless, it strongly suggests that model is an important confounding variable since it is highly significant, at the 0.027 level.

The less adequate "fit" could have several reasons. The introduction of model increases the number of cells from 12 to 24, thereby increasing the variability. The high value of R^2 in Table 26 could in fact result from too much pooling of the data. An interaction between independent variables could also result in the low R^2, e.g., interactions between model, sample, and tread depth.

The possibility of the above interaction was examined by a regression of tread against sample, age, and two variables representing model. The two model variables were structured as shown in Table 30. The same data structure of 24 cells was used.

Table 30

Dummy Model Variables for Interaction

Sample	Model	Model Variable 1	Model Variable 2
Checklane	Large	1	0
	Small	-1	0
Accident	Large	0	1
	Small	0	-1

By using this variable structure the effect of model can be examined separately for each sample.

The regression results are shown in Table 31. There is a moderate interaction between model and sample. The effect of model is not significant in the checklane sample, but is in the accident sample. Furthermore the estimated effect of model (as given by the coefficients) is 2.7 times as great in the accident sample as in the checklane sample. Again, the effect of the sample itself on the proportion with low tread depths is not significant. However, the addition of the interaction terms has only resulted in a 3% reduction in the unexplained variability--R^2 has increased from 0.51 (Table 29) to 0.54.

Table 31

Weighted Least Squares Regression of Tread Depth
Less than 3/32 by Sample, Age, and Model with Interaction

$R^2=0.54$
Total Degrees of Freedom = 24

Variable	Coefficient	Significance Level
Constant	-0.0172	0.075
Sample	-0.0114	0.102
Age	0.0356	0.000
Model 1 (checklane)	-0.0099	0.158
Model 2 (accident)	-0.0267	0.032

The last two regressions, those presented in Tables 29 and 31, were based on a population (cells) of 24 rather than 12 as in Table 26. Table 32 gives the results of a regression on the same 24-cell data, but using only sample and age as independent variables. This result may be compared to

Table 32

Weighted Least Squares Regression of Tread Depth
less than 3/32 by Sample and Age with 24 Degrees of Freedom

$R^2=0.47$

Variable	Coefficient	Significance Level
Constant	-0.0327	0.0005
Sample	-0.0050	0.331
Age	0.0370	0.0000

Table 26 to show the effects of the greater pooling of data in the regression of Table 26.

As in all previous examples, age is very significant. However, in this regression the sample is not significant while it is in Table 26. The lack of pooling here has reduced R^2 to about half that of Table 26.

The regressions that have been presented for comparing the proportion of vehicles with minimum tread depths of 0-2/32 in the checklane and accident samples are admittedly confusing and may appear inconsistent. The conclusion that can be drawn from them is this: both vehicle age and model are variables that differ in the two samples, and confound comparisons of tread depth in the two samples. Any difference that may exist in the proportion of vehicles with little tread in the two samples is small, and cannot be detected with validity unless these confounding factors are accounted for. However, the total quantity of data available is insufficient to adequately examine the three variables simultaneously.

3.4.2 Mean Tread Depths in the Accident Sample. Data are collected on the depth of each groove of each tire. One measurement is made in each groove at a point not over a tread wear indicator. Two of the 2052 tires currently in the accident data set have nine grooves; the others have from two to eight grooves. Of the 2050 with two to eight grooves, tread depth measurements were completed for 2013.

The parameter selected as a measure of the amount of tread on each tire is the mean of the groove measurements. Since the number of grooves varies from 2 (on some snow tires) to 8, the means are based on 2 to 8 measurements. The comparisons to be presented for subsets of the accident-involved cars are based on cars rather than individual tires. In these cases, that tire which had the lowest mean tread depth was selected to represent the vehicle in the comparisons. This was done under the assumption that little tread would more likely be a causal accident factor than ample tread.

Admittedly this is a simplistic--although not unreasonable--view of the role of tread. The combination of tires with different tread depths can have subtle effects on the handling performance of a car, e.g., the understeer coefficient (even on dry pavement), but this is difficult to study with the existing data structure. The effects of tire-to-tire differentials in tread depth on accident involvement can best be studied when related parameters such as the understeer coefficient become available for statistical analysis.[1]

The distribution of the mean depth for each of the four wheel positions is given in Table 33. Since the data set includes a small number of light trucks and vehicles with snow tires, the means exceed the depths that would be found on new passenger car tires with regular highway tread. The break is quite evident at depths of 14/32 and greater. The modes are at 8/32-9/32 for front tires and about 11/32 for rear tires. The depth for new passenger car tires is about 11/32-13/32.

The two right-hand columns give the distribution of the minimum mean depth on the car. The mode is at 7/32, while the median is between 6/32 and 7/32. The mean minimum depth is 9.4(32's).

The number and percentage of tires with tread depths of 2/32 or less is given for each wheel position in the bottom row. Of the 2013 tires in the table, 61 or 3% have 2/32 or less. In general, the tires with low tread appear singly; they are distributed over 50 (9.9%) of the vehicles.

The distributions of the minimum mean tread depths (given in the right-hand column of Table 33 for the entire accident sample) have been compared for specific subsets of the accident population. Subsets were selected either to (1) compare those groups that might be expected to have the greatest difference in incidence of "handling" accidents or, (2) compare those in which tread depth could be expected to play a role with those in which it is least likely to be a factor. Since the data thin out at the higher tread depths, cases with depths of 15/32 or greater were pooled, thus giving 16 levels of depth. Two tests were used. The Students-T test of means, and the Mann-Whitney (U) test of ranks. Both methods are appropriate and have their strengths and weaknesses. The means test is straightforward to interpret and simply tests for equality of means. However, it depends on the assumption of normality of the distributions. The Mann-Whitney test is distribution free, and tests for equality of ranks of scores (ordered variables). However, it is invalid if ties are frequent. With large data sets the difference in results of the two tests is small.

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[1] MVMA Project Number 4.29, "Develop Accident Causation Investigation Techniques."

Table 33

Distribution of Mean Tread Depth

Depth in 32's	Left Front		Right Front		Left Rear		Right Rear		Minimum Mean On Vehicle	
	N	%	N	%	N	%	N	%	N	%
0	0	0	3	0.6	2	0.4	2	0.4	6	1.2
1	4	0.8	6	1.2	5	1.0	8	1.6	20	4.0
2	10	2.0	12	2.4	11	2.2	8	1.6	24	4.7
3	17	3.4	27	5.4	15	3.0	11	2.2	37	7.3
4	35	7.0	24	4.8	25	5.0	20	4.0	42	8.3
5	26	5.2	23	4.6	24	4.8	29	5.8	42	8.3
6	48	9.5	48	9.5	45	8.9	45	9.0	61	12.1
7	60	11.9	60	11.9	47	9.3	53	10.6	62	12.3
8	72	14.3	54	10.7	62	12.3	56	11.2	54	10.7
9	65	12.9	74	14.7	73	14.5	69	13.7	51	10.1
10	56	11.1	58	11.5	45	8.9	50	10.0	27	5.3
11	52	10.3	61	12.1	73	14.5	73	14.5	50	9.9
12	34	6.8	28	5.6	33	6.5	31	6.2	16	3.2
13	11	2.2	11	2.2	13	2.6	19	3.8	5	1.0
14	5	1.0	8	1.6	14	2.8	12	2.4	4	0.8
15	2	0.4	2	0.4	7	1.4	6	1.2	0	0
16	0	0	0	0	2	0.4	2	0.4	0	0
17	2	0.4	1	0.2	3	0.6	2	0.4	2	0.4
18	1	0.2	1	0.2	0	0	2	0.4	0	0
19	1	0.2	0	0	2	0.4	1	0.2	1	0.2
20	0	0	2	0.4	1	0.2	0	0	1	0.2
21	1	0.2	0	0	1	0.2	2	0.4	0	0
22	1	0.2	1	0.2	1	0.2	1	0.2	1	0.2
Total	503	100.0	504	100.0	504	100.0	502	100.0	506	100.0
0-2	14	2.8	21	4.2	8	1.6	18	3.6	50	9.9

Table 34 gives the results of three comparisons. Mean minimum tread depths are given for each subset along with significance levels for both tests.

Single-vehicle versus two-vehicle crashes are not significantly different. Comparisons of single-vehicle crashes with subsets of two-vehicle crashes (head-on, rear-end, etc.) show equally insignificant differences.

Table 34

Minimum Tread Depth

Comparison	Mean	Sig. Level
Single vs. Multi		
Single	7.717	0.45 mean test
Multi	7.935	0.34 Mann-Whitney
Dry vs. Others		
Dry	7.80	0.16 mean test
Others	7.59	0.17 Mann-Whitney
Dry vs. Wet		
Dry	7.80	0.21 mean test
Wet	7.55	0.17 Mann-Whitney

Vehicles in crashes on dry roads do not have significantly different minimum tread depths than those on other surfaces (wet, icy, or snow covered). The comparison of dry surfaces with wet surfaces was made to "sharpen" the contrast. If tread, regardless of depth, is unable to cope with ice or packed snow, the former comparison would be "diluted." Almost identical results were obtained when ice/snow were removed.

Carrying this reasoning one step further, the wet-dry comparison could also be "diluted" if moderate tread is sufficient to provide braking and cornering forces with the most frequently encountered degrees of wetness. Since only a small proportion of the vehicles had little tread, under the above conditions small differences in mean tread depths could not be expected to result in different accident experience.

Consequently a wet-dry comparison was made using a dichotomous minimum tread depth variable. Vehicles with at least one tire with a mean depth of 0-2/32 were pooled, and compared with those with more tread. The result is shown in Table 35. The chi-square test of homogeneity gives $X^2=7.9$ with d.f.=1 and a significance level of 0.005. Thus we may conclude that vehicles with a tire with less than 3/32 mean tread depth are overrepresented in accidents on wet roads by over 2 to 1.

Table 35

Comparison of Wet and Dry
Surfaces with a Dichotomy
of Minimum Mean Tread Depths

Tread Depth	Dry	Wet
Up to 2/32	7.4%	17.3%
Over 2/32	92.6%	82.7%
Total %	100.0	100.0
N	309	110

3.4.3 Tread Wear Patterns in the Accident Sample. Since one depth measurement is made in each groove of a tire, the data are available to examine the pattern of tread wear, i.e., the pattern generated by differential wear across the surface of the tire in the lateral direction. The pattern itself may not be directly related to vehicle handling or accident causation. If it is, it would be through a complex relation between cornering or braking forces and tire pressure, load, lateral acceleration, carcass construction, etc. However, the wear pattern is directly related to tire pressure maintenance practices and suspension system geometry, particularly toe and camber. These factors, in turn, directly affect handling characteristics. Thus one might expect to find some association between wear patterns and accident experience, albeit indirect.

Unfortunately, the large amount of data generated by the individual groove measurements is difficult to categorize and analyze. One of the more convenient measures of the pattern to obtain is the range of groove depths on each tire. The distribution of ranges for front and rear tires is given in Table 36. Although front tires have a greater range (the odds of a front tire having a greater range than a rear tire: 1.02/1), the difference is small and not statistically significant (significance level = 0.58).[1]

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[1] The odds ratio and significance level were obtained by Flora's RIDITS technique. J.D. Flora, *op cit.*

Table 36

Tread Depth Range on Each Tire
(Maximum-Minimum Groove Depth)

Range in 32's	Front Tires N	Front Tires %	Rear Tires N	Rear Tires %
0	192	19.5	229	23.2
1	229	30.3	281	28.4
2	241	24.4	193	19.6
3	119	12.1	130	13.2
4	64	6.5	67	6.8
5	24	2.4	41	4.2
6	30	3.0	19	1.9
7	12	1.2	13	1.3
8	2	0.2	8	0.8
9	3	0.3	4	0.4
10	1	0.1	0	0
11	0	0	2	0.2
Total	987	100.0	987	100.0
≤2/32	732	74.2	703	71.2

Although front tires have a greater range (the odds of a front tire having a greater range than a rear tire is 1.02), the difference is not significant. The significance level=0.58 using Flora's RIDITS.

The range of groove depths is a rather crude measure of the wear pattern. A more descriptive procedure is provided by least squares fitting a second order equation to the groove depths given for each tire. This technique provides a predicted (or estimated) pattern defined completely by the three coefficients of the second order equation. Appendix C describes the procedure and results, and the derivation of the pattern characteristics that will be discussed here.

Two pattern characteristics will be discussed. One is the concavity or convexity of the pattern. Convex patterns are those that have more tread in the middle grooves than on either side, and are characteristic of continual underinflation. Concave patterns are those that have less tread in the middle than on either side, characteristic of continual overinflation. The amount of concavity or convexity is measured by the depth of the pattern, i.e., the maximum distance from a straight line joining the outside groove depth and the inner groove depth as shown in Figure C of Appendix C.

The second pattern characteristic to be discussed is lack of symmetry about the lateral center--more wear on one side than the other. This pattern is usually characteristic of improper toe, but can be caused by incorrect camber.

Pattern Concavity/Convexity

The distribution (density function) of the depth of concavity/convexity is shown in Figure 5. Concave patterns are more common than convex patterns. This is surprising since it is characteristic of continued overinflation, while one might expect underinflation to be more common. The mode is at zero, which represents a linear pattern. Note that new passenger car tires have outside grooves about 2/32 deeper than middle grooves. Thus, a new tire would be concave with a pattern depth of 2/32. This may account for the skewness of Figure 5.

In the discussions of concavity/convexity to follow, the patterns have been trichotomized into groups that are concave, convex, and linear. The linear group has been expanded to include those with pattern depths of -1/32 to +1/32 inch inclusive. This represents the resolution of depth measurements and is probably not an operationally significant departure from linear.

Pattern direction by wheel position is given in Table 37. The rear tires have a higher incidence of convex patterns, with fewer linear and concave patterns. The differences are statistically significant at the 0.000 level. The side to side differences are small.

Table 38 gives the pattern direction by carcass type and this table is also significant at the 0.000 level. Radials have a high (66.8%) incidence of linear patterns, while Bias ply tire have a high incidence of convex patterns.

Table 39 gives the pattern direction by tire aspect ratio. Only two ratios are common, 0.70 and 0.78. The differences in the distributions of

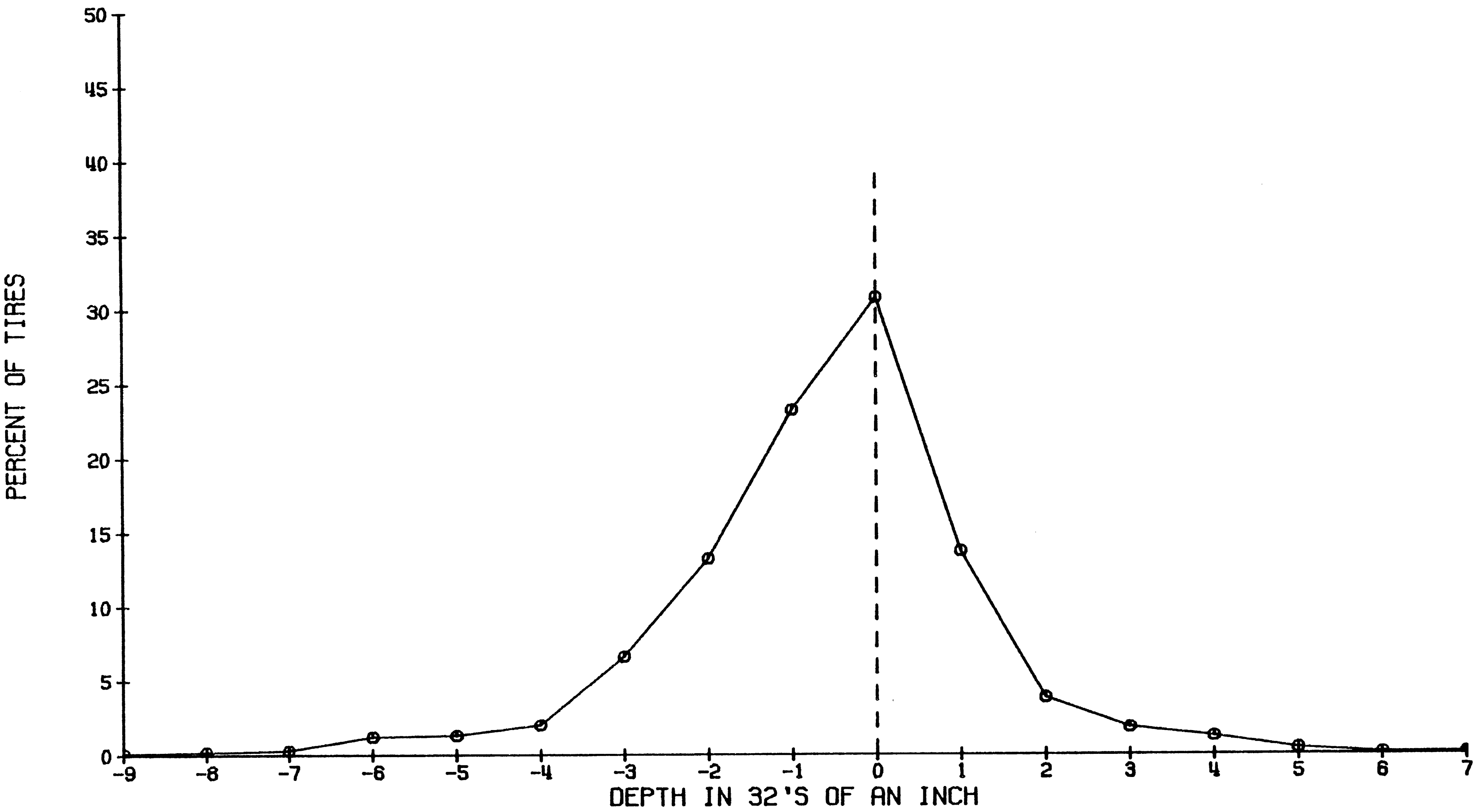

FIGURE 5
DEPTH OF TREAD WEAR PATTERN
OF TIRES IN ACCIDENTS
NEGATIVE VALUES INDICATE TREAD LOW IN CENTER

Table 37

Tread Wear Pattern Direction and Wheel Position

Position	Number of Tires and Row Percent		
	Direction		
	Convex	Linear	Concave
Left Front	142 29.2	260 53.5	84 17.3
Right Front	145 29.7	261 53.4	83 17.0
Left Rear	207 46.7	193 43.6	43 9.7
Right Rear	201 45.6	204 46.3	36 8.2

Table 38

Tread Wear Pattern Direction and Carcass Type

Carcass Type	Number of Tires and Row Percent		
	Direction		
	Convex	Linear	Concave
Bias Ply	204 62.0	96 29.2	29 8.8
Belted-Bias Ply	284 54.3	153 29.3	86 16.4
Radial Ply	198 20.0	661 66.8	130 13.1

0.70 and 0.78 are not significant at the 0.05 level (X^2=4.8, d.f.=2). The distributions for other ratios differ, but are based on small numbers of cases.

Table 39

Tread Wear Pattern Direction
and Tire Aspect Ratio

Aspect Ratio	Number of Tires and Row Percent		
	Direction		
	Convex	Linear	Concave
0.50	1 50.0	1 50.0	0
0.60	17 51.5	12 36.4	4 12.1
0.65	4 33.3	8 66.7	0
0.70	104 31.0	181 54.0	50 14.9
0.74	7 53.8	4 30.8	2 15.4
0.78	512 37.5	673 49.3	181 13.3
0.80	5 27.8	11 61.1	2 11.1
0.88	39 57.4	23 33.8	6 8.8

Pattern directions by model type are given in Table 40. Passenger cars and small trucks are significantly different (X^2=24, d.f.=1) with essentially an interchange of the incidence of convex and linear patterns. This is not surprising since truck's tires are more likely to be inflated for load capacity than for comfort or handling characteristics. Differences among the four passenger car models are also significant at the 0.5% level with $X^2=28$, d.f.=6. However, the differences are not consistent with size. For example, compacts have the highest incidence of convex while intermediates have the fewest. The largest and smallest cars are in between. The highest incidence of linear patterns is on intermediates and the lowest on compacts. While these differences are statistically significant, they may not be operationally significant.

Table 40

Tread Wear Pattern Direction and Model Type

Model Type	Number of Tires and Row Percent		
	Direction		
	Convex	Linear	Concave
Full size	124 31.4	208 52.7	63 15.9
Intermediate	117 30.7	219 57.5	45 11.8
Compact	179 43.1	174 41.9	62 14.9
Sub-compact	180 36.7	260 53.0	51 10.4
Total of above	600 35.7	861 51.2	221 13.1
Small trucks	92 53.2	56 32.4	25 14.5

The pattern directions were also examined by inflation pressure. The tires used here were limited to load range B with no suspected loss of pressure during the accident. Table 41 gives the results of an ANOVA test of the means. The mean pressures do not differ significantly among the three patterns; in fact, they are almost identical. The Mann-Whitney test of ranks also indicates no differences in the pressures in the three groups (the significance level of U is 0.62).

Table 41

Means Test of Inflation Pressure
by Wear Pattern Direction

Load Range B tires with no suspected pressure loss

Pattern Direction	Mean Pressure in PSI	Standard Deviation of the Mean
Convex	26.09	5.7
Linear	26.22	5.4
Concave	26.01	5.5

Between Group: F statistic = 0.14 Degrees of freedom = 2 Significance level = 0.87

Lack of association between pattern direction and inflation pressure is surprising since relative inflation pressure is one of the primary mechanisms of pattern generation. However, the pattern is a function of the history of inflation over the entire period of wear, rather than pressure at a single point in time. It was also noted that convex patterns were much more frequently on front tires than on rear tires. This wearing on the outside of front tires is not simple to explain. However, it is likely caused by the transient lateral (cornering) forces on front tires in turns, particularly in the transient portion when raw rates are changing. During these periods, the influence of the steering and suspension geometry of typical independent front suspensions can contribute to increased wear on the outside of the tread and produce convex patterns.

Pattern Asymmetry

The second characteristic of wear pattern examined is asymmetry of wear. Asymmetric wear is simply the loss of more tread from one side of a tire than from the other. The derivation of this wear characteristic from the mathematical representation of the groove depth profile is discussed in Appendix C. Briefly, the asymmetry was classified into groups depending on whether they were worn more heavily on the outside, inside, flat (uniform depth), or were symmetrical but not flat. This was done by considering the location of the minimum depth of convex patterns, the maximum for concave patterns, or the sign of the slope of linear wear. The incidence of the asymmetry classifications for all tires in the accident data is presented in Table 42.[1] In this and subsequent tables the asymmetry will be classified by the location of maximum wear (minimum tread groove depth). Tires in the outside and inside categories include cases of convex or concave patterns with the axis of symmetry displaced laterally from the mid-point of the tire, and those with linear wear with a non-zero slope. In subsequent tables the tires with flat patterns will be aggregated with the symmetrical cases.

Table 42

Incidence of Tire Tread Wear Asymmetry

Location of Maximum Wear	Number of Tires	Percent
Outside	468	25.2
Symmetrical	295	15.9
Inside	721	38.8
Flat (uniform depth)	375	20.2

The distribution of the location of maximum wear is given for each wheel position in Table 43. Left-front tires are worn on the inside more frequently than right-front tires, and more frequently than they are on the outside. Right-front tires are worn on the inside and outside with equal

---

[1] Table 42 and subsequent tables on asymmetry exclude 193 tires for which the tread depth data are not complete.

frequency. The difference between right-and left-front tires is significant at the 0.0005 level (X^2=15.1, d.f.=2).

Table 43

Wear Pattern Asymmetry by Wheel Position

Number of Tires and Column Percent

Location of Maximum Wear	Position			
	Left Front	Right Front	Left Rear	Right Rear
Outside	112 23.0	159 32.5	100 22.6	97 22.0
Symmetrical	165 34.0	171 35.0	173 39.1	161 36.5
Inside	209 43.0	159 32.5	170 38.4	183 41.5

Front tires, as an aggregate, have a significantly different distribution than rear tires (X^2=7.6, d.f.=2), with significance at the 0.022 level. Rear tires, compared to front tires, are worn more on the inside and less on the outside.

The difference in the distribution of the two rear tires is not statistically significant (X^2=0.95, d.f.=2).

Asymmetry by model type is given in Table 44. Differences in the table (5x3) are significant at the 0.001 level with X^2=25.4 and 8 degrees of freedom. Compacts have the highest incidence of low tread on the outside, while small trucks have the highest incidence on the inside. Nearly equal proportions of all cars have symmetrical wear patterns, although trucks have substantially fewer.

The distribution of asymmetry for dry road surfaces is compared to all other surface conditions (wet, snow, ice) in Table 45 for passenger cars only. The differences are small, but they are significant at the 0.0003

Table 44

Wear Pattern Asymmetry by Model Type

Number of Tires
and Column Percent

Location of Maximum Wear	Model Full Size	 Intermediate	 Compact	 Subcompact	 Small Truck
Outside	95 24.1	94 24.7	78 18.8	139 28.3	62 35.8
Symmetrical	151 38.2	132 34.6	157 37.8	180 36.7	49 28.3
Inside	149 37.7	155 40.7	180 43.4	172 35.0	62 35.8

level with X^2=15.9 and 2 degrees of freedom. The distribution for wet surfaces only is outside, 24.6%; symmetrical, 36.2%; inside, 39.1%. This distribution is not significantly different than for dry surfaces (X^2=1.1, d.f.=2). Thus, the significance in Table 45 is largely because of the winter accidents on snow or ice.

The associations of asymmetry with road surface coverings that are significant are small, and it is not yet possible to identify them as causal accident factors.

The asymmetries of wear on tires of cars in one-and two-vehicle accidents are compared in Table 46. The differences are significant at the 0.0007 level (X^2=10.1, d.f.=2), with more tires with wear on the outside in single-vehicle accidents. Collision configurations among the two-vehicle accidents showed no significant differences in tire wear asymmetry.

Table 45

Wear Pattern Asymmetry by Road Surface Condition Passenger Cars

Location of Maximum Wear	Number of Tires and Column Percent — Surface: Dry	Number of Tires and Column Percent — Surface: Other
Outside	257 24.0	149 24.5
Symmetrical	362 33.8	258 42.4
Inside	452 42.2	202 33.2

Table 46

Wear Pattern Asymmetry by Number of Vehicles in Accident

Passenger Cars

Location of Maximum Wear	Number of Tires and Column Percent — Number of Vehicles in Accident: 1	Number of Tires and Column Percent — Number of Vehicles in Accident: 2
Outside	218 27.5	188 21.2
Symmetrical	289 36.4	331 37.3
Inside	287 36.1	369 41.6

APPENDIX A

Control Population Data Collection Form
with
Selected Univariate Percentages

HIGHWAY SAFETY RESEARCH INSTITUTE 6/76(2)

TIRE CONDITION SURVEY

POLICE FORM
NUMBER ____________________

CAR MODEL __________________________

	RF	RR	LR	LF
TIRE TYPE (check one):				
UNKNOWN	0.3%	0.2%	0.6%	3.2%
BIAS PLY	16.3	16.3	16.4	15.6
BELTED BIAS PLY	50.8	51.6	50.8	48.8
RADIAL PLY	32.5	31.9	32.2	32.3
TIRE PRESSURE (PSI)	___ ___	___ ___	___ ___	___ ___
TREAD DEPTH (Center groove, 32nd's inch)	___ ___	___ ___	___ ___	___ ___
CHECK IF PRESENT:				
CUPPING	6.5	3.5	3.1	4.3
UNEVEN TREAD WEAR	7.6	5.1	4.1	5.8
BULGES OR BREAKS	1.1	0.5	0.3	0.8
TREAD SEPARATION	7.3	4.5	3.9	6.0

SIZE: RF ____________________

RR ____________________

LR ____________________

LF ____________________

APPENDIX B

Individual Case Summaries of Accident-Involved Vehicles with Radial Tires Mixed with Non-Radial Tires

Case HS 2180

1974 Dodge Charger 2-door sedan. Drinking driver fell asleep on a gentle curve in an urban area. Spun to left, sideways into a tree at right front door. Speed before impact 45 mph.

CDC = 03RPAW4, crush 23 in.

One occupant, alcohol noted.

Dry asphalt pavement at 2:19 am.

Tires:	Right	Left
Front-Construction	Belted-Bias	Belted-Bias
Size	F78-14	F70-14
Tread Depth	5/32 in	5/32 in
Inflation Pressure	26 psi	24 psi
Rear -Construction	Radial	Radial
Size	HR78-14	HR78-14
Tread Depth	6/32 in	5/32 in
Inflation Pressure	25 psi	26 psi

Case OK 2415

1974 Chevrolet Van 20. Single vehicle collision on US-10. Ran through a puddle. Slewed right over 5" curb, rolled to right, slid on right side, rolled down embankment onto left side, skidded on left side, rotated back on wheels.

CDC = OOLDAO3 Prim. crush 7 in.
OORDAO1 Sec. crush 3 in.

One occupant, no alcohol noted.

6 lane divided depressed expressway, concrete - no rain, but pavement puddled.

Tires:	Right	Left
Front-Construction	Belted-Bias	Belted-Bias
Size	unknown	unknown
Tread Depth	5/32 in	7/32 in
Inflation Pressure	28 psi	Deflated in crash
Rear -Construction	Belted-Bias	Radial
Size	L78-15	LR78-15
Tread DEpth	10/32 in	2/32 in
Inflation Pressure	33 psi	26 psi

Case OK 2805

1973 Cadillac Calais, Head-on collision with a 1973 Chevy pickup. Cadillac driver said she went over the centerline because of ice, struck other vehicle head-on. Other vehicle was driving without lights (at 1:40 a.m. on a December morning). Neither driver drinking.

2 lane asphalt road, snow covered in moderate snowfall.

Speed - case vehicle 15 mph at impact.
other vehicle could not be located.

CDC = 12FREW1, crush 9 in.

Tires:	Right	Left
Front-Construction	Radial	Belted-Bias
Size	225-15	unknown
Tread Depth	7/32 in	10/32 in
Inflation Pressure	20 psi	20 psi
Rear -Construction	Radial	Radial
Size	225-15	225-15
Tread Depth	7/32 in	2/32 in
Inflation Pressure	20 psi	20 psi

Case HS 2272

1972 Buick Skylark 2-dr, H.T. Driver ran red light at intersection, struck in left side at "C" pillar. Driver & pass (unknown age, etc.) fled from scene. Speed before and at impact 26 mph.

CDC = 10LZEW3, crush 12 in.

Two occupants, asphalt pavement - slippery, snow covered at 4:40 p.m.

Tires:	Right	Left
Front-Construction	Radial	Radial
Size	GR70-14	GR70-14
Tread Depth	4/32 in	3/32 in
Inflation Pressure	unknown	22 psi
Rear -Construction	Belted-Bias	Belted-Bias
Size	H78-14	H78-14
Tread Depth	4/32 in	0/32 in
Inflation Pressure	Deflated in crash	21 psi

Case OK 2680

1973 Olds Toronado. Single vehicle collision. Driver went through a "T" intersection into a house. Told police brakes failed, but police tried them and said they worked OK. Driver also said accelerator stuck. Investigator could not check because of jammed hood.

Speed before impact 25, at impact 20 mph.

CDC = 12FDEW2 pri. house crush 18"
12FLMS1 sec. chain link fence

One occupant, no alcohol noted.

Road: 2 lane asphalt, dry, no precip.

Tires:	Right	Left
Front-Construction	Radial	Radial
Size	LR70-15	LR70-15
Tread Depth	12/32 in	12/32 in
Inflation Pressure	25 psi	25 psi
Rear -Construction	Belted-Bias	Belted-Bias
Size	J78-15	J78-15
Tread Depth	4/32 in	6/32 in
Inflation Pressure	21 psi	27 psi

APPENDIX C

Mathematical Representation of Tread Wear Patterns

The tread on each tire is described by a simple measurement of the depth of each groove in a location not over a wear indicator. This gives substantial data on each tire, sufficient to describe wear patterns. However, the fact that each tire is described by up to ten variables makes analysis cumbersome. The technique that was used to represent the wear pattern of each tire for analytical purposes is described below.

The wear pattern given by a depth measurement in each groove can be conceptualized in the framework of a cartesian coordinate system in which the groove number is the abscissa and the depth (in 32nds of an inch) is the ordinate.

These points can be represented--i.e., the pattern they describe can be characterized--by a curve (envelope) passing through them. The curve used in this study is the second order equation:

$$\hat{Y} = a_0+a_1X+a_2X^2$$

where: $\hat{Y}$ = the estimated depth of groove X in 32's of an inch

X = the groove number ($1 \leq X \leq N$)

a_0,a_1,a_2 = constants unique to each tire

Groove 1 is the outside groove of the mounted tire and N is the number of grooves on the tread (the sidewall "grooves" of radial tires were not included in the data collection).

The constants a_0, a_1, and a_2 were determined by a least squares fit for each tire in the accident sample. The number of grooves on tires in the data set ranges from 2 (136 tires) to 9 (2 tires). The tires with 2 grooves are snow tires and 80% of them were on rear wheels. For the sake of simplicity only tires with 3 to 8 grooves were fit with the quadratic. Thus 1859 of the 2052 tires in the accident data file were "fit," with missing data for each coefficient for 193 tires.

An example is shown in Figure C1. The circled points are the depth of each groove--eight in this example--as measured in the field. Values of the constants for the least squares fit are:

$$a_0 = 7.321$$

$$a_1 = 2.262$$

$$a_2 = -0.333$$

The curve of predicted values given by these constants is the solid line of the figure. Other features of the figure will be explained later. For this tire the fit is excellent.

In general the second order function was successful in representing the profile (or pattern) of worn tires. The root-mean-square error (residuals) for all grooves of all 1859 tires was 0.0183 inches. Figure C2 gives the cumulative distribution of the maximum error for each tire. Thus 50% of the tires have maximum errors in the predicted pattern of 0.17/32 or less,[1] while 90% have maximum errors of 0.69/32 or less. Figures C3 and C4 give histograms of the computed values of a_0 and a_1 respectively, while Figure C5 gives the distribution of a_2.

It may be noted that a_1 can have large absolute values. These should not be interpreted as high slopes. The constant a_1 can be interpreted as a slope only when $a_2=0$, in which case the wear pattern is linear. If $a_2 \neq 0$, the predicted pattern is parabolic, and much of a_1 results from translation of the axis of the parabola away from the origin, usually to a location between the outside groove (X=1) and the inside groove (X=N).

Interpretation of the Mathematical Representation

The parabolic representation of tread wear patterns is convenient because only three parameters are required--rather than a variable number ranging up to eight--and because certain key features of the patterns can be readily determined. Two particular features are addressed in this study. One is the concavity or convexity of the pattern, the other is unsymmetrical wear.

The example shown in Figure C1 has higher tread in the center. As a result, the parabola fitting the pattern opens downward. Such a pattern will be denoted as convex, and exemplifies the classical pattern from under-

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[1] This strange notation is used because the basic unit of measurement was 1/32 of an inch, and all computations are in terms of this basic unit.

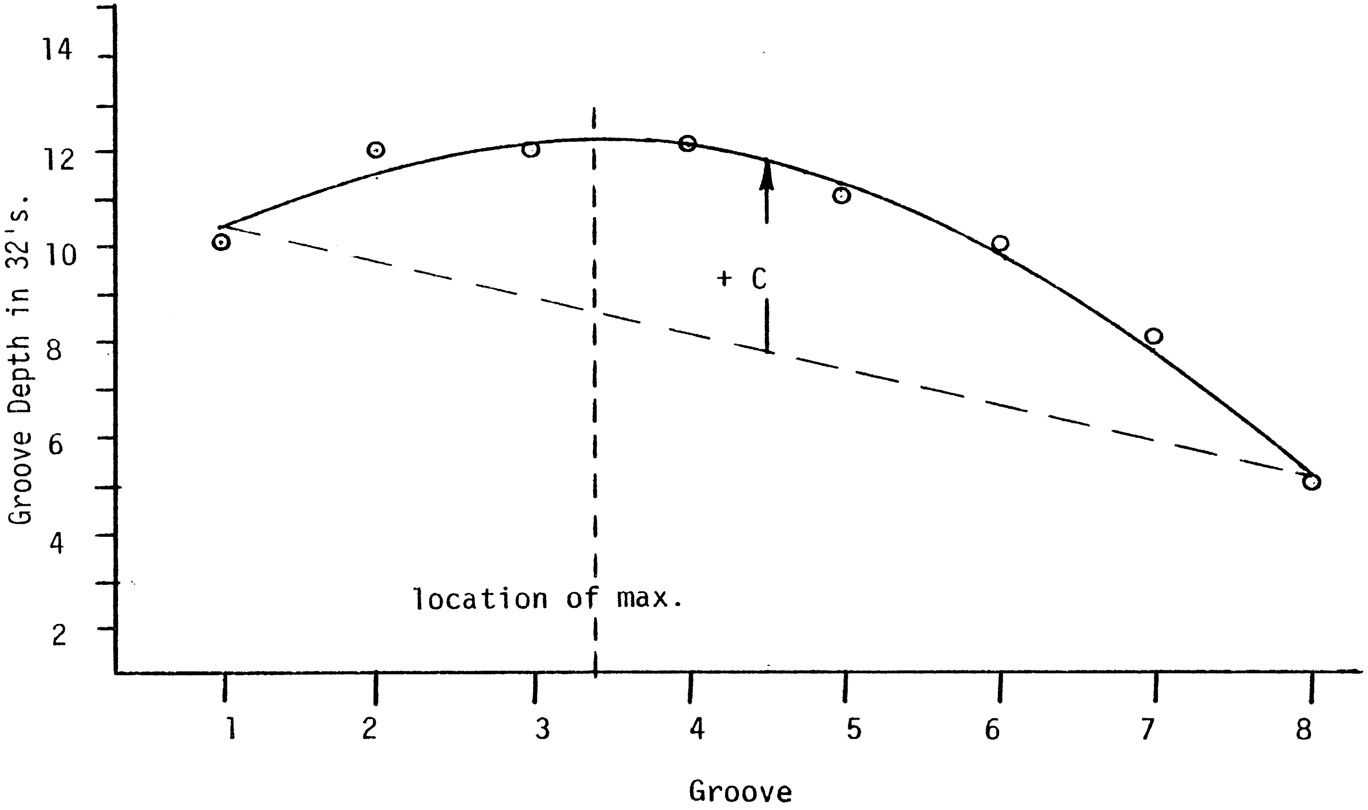

Figure C1

Sample Representation of a Tread Wear Pattern by a Second Order Curve

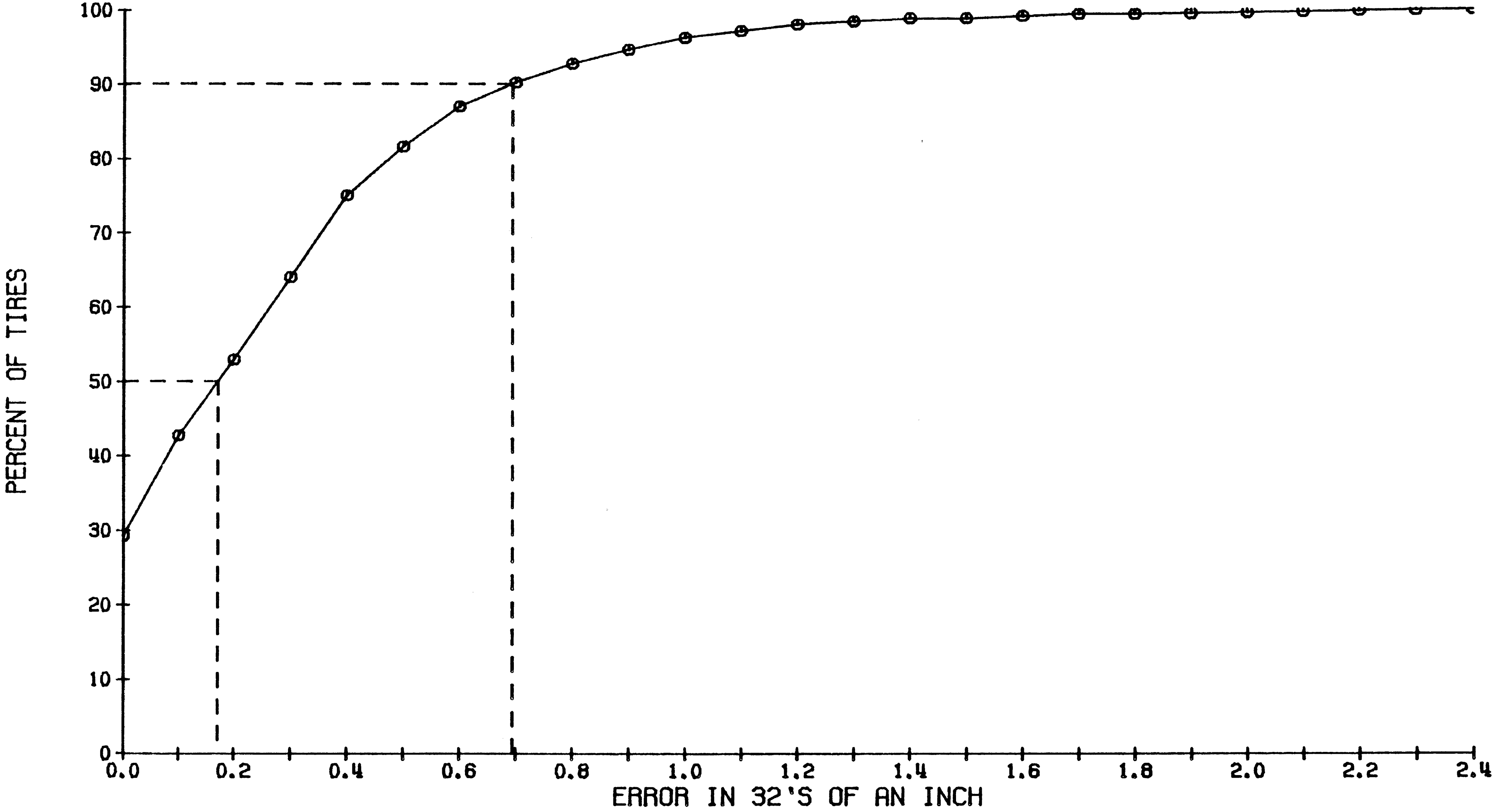

FIGURE C2
CUMULATIVE DISTRIBUTION OF THE MAXIMUM
DIFFERENCE BETWEEN OBSERVED AND PREDICTED
GROOVE DEPTH FOR EACH TIRE

```
Midpoint   Percent  Count for 701.A0  (Each X= 6)

-9.0000       .1     1 +X
 . . .
-5.0000       .1     1 +X
-4.0000       .2     4 +X
-3.0000       .3     5 +X
-2.0000       .6    12 +XX
-1.0000       .7    13 +XXX
 0.           .9    16 +XXX
 1.0000      1.4    26 +XXXXX
 2.0000      1.5    27 +XXXXX
 3.0000      2.0    37 +XXXXXXX
 4.0000      2.1    39 +XXXXXXX
 5.0000      3.3    61 +XXXXXXXXXXX
 6.0000      4.1    76 +XXXXXXXXXXXXX
 7.0000      5.2    97 +XXXXXXXXXXXXXXXXX
 8.0000      6.2   116 +XXXXXXXXXXXXXXXXXXXX
 9.0000      9.1   169 +XXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 10.000      9.4   174 +XXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 11.000     10.3   192 +XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 12.000     11.5   213 +XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 13.000      8.0   148 +XXXXXXXXXXXXXXXXXXXXXXXXX
 14.000      7.2   133 +XXXXXXXXXXXXXXXXXXXXXXX
 15.000      5.9   109 +XXXXXXXXXXXXXXXXXXX
 16.000      3.2    59 +XXXXXXXXXX
 17.000      2.5    47 +XXXXXXXX
 18.000      1.3    24 +XXXX
 19.000       .7    13 +XXX
 20.000       .6    11 +XX
 21.000       .3     6 +X
 22.000       .3     5 +X
 23.000       .1     2 +X
 24.000       .2     3 +X
 . . .
 26.000       .1     2 +X
 27.000       .1     2 +X
 . . .
 29.000       .1     2 +X
 30.000       .1     1 +X
 31.000       .1     2 +X
 32.000       .1     1 +X
 33.000       .1     2 +X
 . . .
 35.000       .2     3 +X
 36.000       .1     2 +X
 37.000       .1     1 +X
 . . .
 39.000       .1     1 +X
 . . .
 44.000       .1     1 +X

 Missing          193
 Total           2052
```

Note: The width of each interval is 0.2.

Figure C3

Histogram of the Constant Term in the Second Order Equation for Tread Pattern

```
Midpoint   Percent  Count for 702.A1  (Each X= 14)

-36.000       .1      1 +X
 . . .
-30.000       .1      1 +X
-29.000       .1      2 +X
-28.000       .1      1 +X
 . . .
-26.000       .1      1 +X
-25.000       .1      2 +X
-24.000       .1      1 +X
 . . .
-21.000       .1      1 +X
-20.000       .1      1 +X
 . . .
-17.000       .1      1 +X      Note:  The width of each
-16.000       .2      4 +X             interval is 1.0.
 . . .
-14.000       .1      1 +X
-13.000       .2      3 +X
-12.000       .3      6 +X
-11.000       .1      1 +X
-10.000       .3      5 +X
-9.0000       .3      6 +X
-8.0000       .5      9 +X
-7.0000      1.3     25 +XX
-6.0000      1.0     18 +XX
-5.0000      3.1     57 +XXXXX
-4.0000      3.8     71 +XXXXXX
-3.0000      6.2    116 +XXXXXXXXX
-2.0000     15.7    292 +XXXXXXXXXXXXXXXXXXXXX
-1.0000     16.1    300 +XXXXXXXXXXXXXXXXXXXXXX
 0.         29.6    550 +XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 1.0000     10.5    196 +XXXXXXXXXXXXXX
 2.0000      5.0     93 +XXXXXXX
 3.0000      3.1     57 +XXXXX
 4.0000      1.1     20 +XX
 5.0000       .5      9 +X
 6.0000       .3      5 +X
 . . .
 8.0000       .1      1 +X
 9.0000       .1
 . . .
 12.000       .1      1 +X

 Missing            193
 Total             2052
```

Figure C4

Histogram of the Coefficients of the First Order Term in the Equation for Tread Pattern

```
Midpoint   Percent  Count for 703.A2  (Each X= 18)

-2.2000       .1      1 +X
-2.0000       .1      1 +X
-1.8000       .1      1 +X
  . . .
-1.2000       .1      1 +X
-1.0000       .2      3 +X
-.80000       .4      7 +X
-.60000       .9     17 +X
-.40000      5.1     94 +XXXXXX
-.20000     10.3    192 +XXXXXXXXXXX
 .0         38.1    709 +XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 .20000     20.0    371 +XXXXXXXXXXXXXXXXXXXXX
 .40000      8.9    166 +XXXXXXXXXX
 .60000      6.8    127 +XXXXXXXX
 .80000      2.5     46 +XXX
 1.0000      3.0     55 +XXXX
 1.2000       .9     16 +X
 1.4000       .1      1 +   Notes: The width of each
 1.6000       .8     14 +          interval is 0.2.
 1.8000       .2      3 +
 2.0000       .3      6 +          435 cases equal exactly
 2.2000       .1      2 +          zero.  274 additional cases
  . . .                            range from -0.15 to +0.15.
 2.6000       .3      5 +
 2.8000       .1      2 +X
 3.0000       .2      3 +X
  . . .
 4.0000       .2      4 +X
  . . .
 4.6000       .1      1 +X
  . . .
 5.0000       .1      1 +X
  . . .
 5.6000       .1      1 +X
  . . .
 6.0000       .1      2 +X
  . . .
 6.6000       .1      2 +X
  . . .
 7.0000       .1      1 +X
  . . .
 7.6000       .2      3 +X
  . . .
 9.0000       .1      1 +X

 Missing           193
 Total            2052
```

Figure C5

Histogram of the Coefficients of the Second Order Term in the Equation for Tread Pattern inflation. Convex patterns result in negative values of a_2, while positive values indicate concave patterns. A measure of the concavity/convexity is the depth of "dishing" shown by C in Figure C1, where C is the maximum distance from a straight line through the predicted depths of the outer two grooves and the parabola between the outer grooves. The sign of C is arbitrarily chosen to be positive when the pattern is convex.

$$C = -a_2(N-1)^2/4$$

and is 3.39 in the example shown. The location of C (groove number) is

$$\text{Groove}_C = (N+1)/2$$

which is the center of the tread.

In the analysis reported in Section 3.4.3, the patterns were treated as a trichotomy, those that are concave, convex, or linear. The linear group was expanded to include cases in which

$$-1/32 \le C \le 1/32$$

since the measurements of depth have a resolution of 1/32, and such small deviations from linearity are probably irrelevant.

The other pattern characteristic examined is its lateral symmetry. If $a_2=0$, indicating a parabola, the wear is symmetrical if the vertical axis of the parabola is located in the center of the tread. If the axis is off-center, the wear is greater on one side--the classical wear pattern of improper toe or camber. The axis of the parabola is located at the point of maximum or minimum tread depth given as a groove number by

$$G_{M/M} = -a_1/2a_2 \qquad a_2=0,$$

or as the proportion of the distance from groove 1 to the inner groove, N by

$$\text{Location of } G_{M/M} = -(a_1/2a_2+1)/(N-1) \qquad a_2=0$$

The location of the maximum or minimum--greater or less than 0.5--in combination with the sign of a_2 indicating whether a maximum or minimum--can be used to determine whether the inside or outside has lower tread.

If $a_2=0$, the pattern is linear. In this case the sign of the slope (a_1) indicates the side with the greater wear. If $a_2=0$ and the location of the maximum or minimum is at 0.5, the pattern is symmetrical. If both $a_1=0$

and $a_2=0$, the pattern is uniform (flat) and hence also symmetrical.