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FINAL REPORT

AN INVESTIGATION OF A LOW-VARIABILITY TIRE TREADWEAR TEST PROCEDURE AND OF TREADWEAR ADJUSTMENT FOR AMBIENT TEMPERATURE. VOLUME I: THE TEST PROCEDURES, STATISTICAL ANALYSES, AND THE FINDINGS

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16. Abstract

The program was conducted to evaluate the variation in tire treadwear rates as experienced on identical vehicles during the various environmental exposure conditions of the winter, spring, and summer seasons. The diurnal/nocturnal effect on the treadwear rate was evaluated by running separate but similar test samples on the same four-car convoys.

A two-car convoy was utilized during the spring to extend the total mileage on two of the winter test sets to 24,000 miles. A summer test of 16 test sets in exactly the same test configuration as the previous winter test was conducted using the same vehicles and, where possible, the same drivers.

Tread loss was measured by determining the periodic loss in tread-groove depth and in total tire weight. Both methods were very carefully controlled.

Special investigations of (1) the effect of different drivers on treadwear results (measurement of absolute vehicle acceleration during normal test operations) and (2) a means of determining projected mileage by using tire weight loss rates.

The report contains a statistical analysis of the wear rates both in mils and grams per 1000 miles as they relate to the vehicle, season, environmental condition, driver, and how eight test sets each of four different manufacturer groups (total of 32 test sets) are variable within themselves. Volume II, 542 pages, contains data pertaining to the test effort. Volume III, 502 pages, contains data used in the statistical analysis effort.

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TERMINOLOGY AND ABBREVIATIONS USED WITH SwRI COMPUTERIZED DATA ACQUISITION AND REPORTING SYSTEM
(in reference to data presented in Appendices A and E)

a—Intercept of least mean square calculation of linear regression of the remaining tread.

b*CSAF—Wear Rate adjusted to course condition by multiplying by CSAF. The slope of the linear regression calculation (see "a").

BI—Break-in.

Calc WR—Calculated Wear Rate, the slope of the linear regression of the remaining tread measurements.

Circuit—The 400 miles required to completely cover the test course. Identified as either the first or second circuit of a specific run or 1-1, 1-2, 2-1, 2-2, etc.

CR%—Crown Radius, the determined average radius of the tire crown in term of the nominal cross section of the tire. The nominal CS of the P195/75R14 tire is 7.68 therefore the crown radius, in inches, is 7.68 increased by CR%.

CSAF—Course Severity Adjustment Factor (UTQG) established at unity, 1.000, for these tests.

CSW—Cross Section Width, excluding lettering of designs.

Data Codes—Variously for the tire groups, convoys, and sponsor designations.

Diff—The difference in depth (loss in rib height) between a current measurement and an immediately previous one.

Gauge—SwRI equipment code.

Groove Designations— SS: The tread groove nearest the Serial Side of the tire.
— Grooves A, B, C, etc. in order away from the SS toward the OSS groove.
OSS: The tread groove nearest the side of the tire which is *opposite* the Serial Side.

Group ID—Group Identification.

Hardness—The hardness of the tread rubber as determined by the Shore A Hardness Gauge.

Inner Grooves—The grooves other than the outer grooves, i.e., the A, B, C, etc. grooves.

Ins—Inspection.

Inspection Level—Categories range through VS, SL, MED, BAD, VBAD.

Inv No—The individual tire "Inventory Number" assigned for the life of the tire.

LS—Leg Setting used in adjusting shoulder drop measurement tool to a specified tread width.

MDF—Measurement Data File.

OSS—The side of the tire opposite the serial number.

TERMINOLOGY AND ABBREVIATIONS USED WITH SwRI COMPUTERIZED DATA ACQUISITION AND REPORTING SYSTEM (Cont'd)

OD—Outer Diameter.

Outer Groove—The two grooves nearest the tread shoulders—the SS groove and the OSS groove.

p—PM/300, the calculated PM relative to a 100 rated (UTQG) tire at 30,000 miles.

PM—Projected mileage = (Intercept - 62/b*CSAF) × 1000 + 800 to wear out at tread indicators, 0.062 inches.

POS—Removed from wheel position.

Rating—The calculated rating rounded to the next lower decrement.

Ref No—Client's Code.

Run—The 800 miles consisting of 2 circuits of the test course—the interval between tire inspections. Designated as BI (Break-In), runs 1, 2, 3, etc.

SD—Shoulder Drop, the difference between the crown radius and mean of two shoulder radii.

Size Factor—The sum of the OD and the mean CSW.

SN—The circumferential location where a radial line would pass through the serial number.

SpCode—Sponsor Code.

SS—The serial number side of the tire.

Std 001,002—Laboratory control standard tire.

TRR—Test Run Record.

Vehicle—Number, Code, Description, and Equipment.

Wear Rate—In *miles/0.001*—a form of presenting the rate of tread wear stated as miles per mil.

WR—Wear Rate, see "B*CSAF" and "Calc WR."

SUMMARY

Four convoys of four identical cars each were used to generate tire treadwear data for the purpose of evaluating certain low-variability test procedures and the effect on treadwear of certain environmental parameters. The test tires were a control group of Uniroyal tires, with Michelin, Goodyear and Bridgestone representing the other groups. These tires were chosen to be broadly representative of all-season tires available to the motoring public; no other significance should be placed on the brand choices. Figure 1 is a presentation of the treadwear loss rates in terms of both mils and grams per 1000 miles. The data shown are in terms of the testing subsequent to a 1600-mile break-in condition. These data are typical and relative to the other results.

The Phase I testing was conducted during February and March 1984, using two groups of four cars, each group running with two different sets of four tire brands, to result in 4 convoys testing a total of 64 tires for 8,000 miles each.

Phase II testing was done from May until early July 1984, using two cars from the first vehicle group to extend the testing of two tire sets which ran on those vehicles during the first test (4S0001) of Phase I. The extended tire groups, Uniroyal (X_1) and Michelin (M_1) were run an additional 16,000 miles during Phase II to provide 24,000 miles of testing on each of the eight tires involved.

Phase III testing duplicated the Phase I program, using new tire sets, but was conducted during the hot weather of July and August 1984.

- The Bridgestone tires had the highest estimated average wear rates, (mils/1000 miles) while the Uniroyal tires had the lowest. The average wear rates obtained from Phase III were greater than those obtained from Phase I for all brands. In terms of variability, Michelin had the highest while Uniroyal had the lowest.

- Relative to the Uniroyal tires, the Bridgestone tires had the highest estimated average wear rate and Michelin had the lowest; the variability was highest for the Michelin tires and similar for both the Bridgestone and Goodyear brands.

- The Bridgestone tires had the highest estimated weight loss rates (grams/1000 miles) and Uniroyal had the lowest. The variability was greatest for the Michelin tires and lowest for the Uniroyal. The variability was less, in all cases, using the estimated weight loss rates as compared to that using the estimated wear rates. Relative to the Uniroyal tires, Bridgestone had the highest average weight loss rates. The Michelin and Goodyear brands had low but similar averages. Variability was highest for the Michelin tires. The variability of the relative weight loss rates was less than the variability of the relative wear rates.

- All distributions of the estimated wear rate data (both in terms of mils/1000 miles and grams/1000 miles) appeared to be normally

Phase		TEST	GROUP X UNIROYAL MILS	GROUP X UNIROYAL GRAMS	GROUP M MICHELIN MILS	GROUP M MICHELIN GRAMS	GROUP G GOODYEAR MILS	GROUP G GOODYEAR GRAMS	GROUP B BRIDGESTONE MILS	GROUP B BRIDGESTONE GRAMS
Phase I WINTER	DAY	4S0001	2.25	17.98	2.61	18.88	3.25	19.25	5.25	22.08
		4S0002	2.18	17.75	2.48	18.50	2.90	18.00	5.04	22.40
	NIGHT	4S0003	2.42	17.08	2.73	18.80	3.31	18.23	4.83	20.20
		4S0004	2.30	16.43	2.75	19.23	3.20	18.00	4.78	19.90
Phase II SPRING	DAY	4S0005	2.70	17.78	3.02	20.03	----	-----	----	-----
Phase III SUMMER	DAY	4S0006	3.73	24.53	3.75	23.60	5.26	25.29	7.83	31.38
		4S0007	3.61	23.38	3.64	23.26	4.91	24.14	7.42	29.78
	NIGHT	4S0008	3.49	22.54	4.02	22.96	4.91	23.43	7.19	28.26
		4S0009	3.12	21.64	4.02	23.70	4.67	22.91	7.06	26.35

Phase II SPRING: Convoy 1 (450005) consisted of two cars from Vehicle Group 1 (1403, 1404). The data is for the extension (to 24,000 miles) of the 4S0001 test.

Phase III SUMMER:

Convoy 1 (4S0001 & 4S0006) and Convoy 3 (4S0003 & 4S0008) utilized Vehicle Group 1 (1401, 1402, 1403, 1404)

Convoy 2 (4S0002 & 4S0007) and Convoy 4 (4S0004 & 4S0009) utilized Vehicle Group 2 (1405, 1406, 1407, 1408)

FIGURE 1. SUMMARY OF GROUP RESULTS

TREADWEAR RATES/1,000 MILES

(1,600 Mile Break-In)

distributed except for the combined data of Phases I and II where two different distributions appeared, one for each phase.

- Temperature, wet miles, and convoy were significant predictors of the estimated wear rates (mils/1000 miles) for all tire brands, except Michelin and run R3 of the goodyear tires. Humidity was a nonsignificant predictor in all cases. The R^2 values exceeded 0.95 for the Uniroyal, Goodyear, and Bridgestone tires and exceeded 0.65 for the Michelin tires.

- Relative to the Uniroyal tires, the regression using estimated relative wear rates were inconclusive; the R^2 values were low for the Michelin tires and moderate for the Goodyear and Bridgestone tires.

- Temperature, wet miles, and convoy were significant predictors of the estimated weight loss rates (grams/1000 miles) for both the Uniroyal and Bridgestone brands but none of these were found to be significant for the Michelin tires. Wet miles and convoy were significant for the Goodyear tires and humidity was significant in two of the three run types of the Bridgestone tire and for R3 of the Uniroyal tires. The R^2 values were higher and the coefficients of variation were lower in most cases as compared to those obtained by using the estimated wear rate data.

- Relative to the Uniroyal tires, wet miles and convoy were not significant predictors of the weight loss rates (grams/1000 miles) for any of the tire brands. Temperature was significant for 2 out of 3 runs for the Bridgestone brand and humidity was significant for one run of the Bridgestone brand. These run types yielded lower coefficients of variation than those obtained for the relative wear rates.

- Rankings of the four convoys using the average estimated weight loss rates (grams/1000 miles) were different from those obtained using the estimated regression coefficients for each convoy in the fit of the estimated weight loss rates. For the Uniroyal, Goodyear and Bridgestone tires convoy 4 consistently had the lowest average weight loss rate while for all tire brands convoy 2 consistently had the smallest estimated regression coefficient relative to convoy 4.

- The R^2 values were higher and the standard errors of prediction and coefficients of variation were smaller using the R3 runs and the estimated wear rates as compared to those using the R1 and R2 runs.

- The ANOVA results, obtained from the actual weight loss rate (grams/mile) data of Phase III showed significant differences due to individual drivers, car positions, tire positions, humidity and miles. The effect due to wet miles and the temperature by wet miles interaction were significant for all brands except Michelin. Temperature was significant for all brands, and convoys were insignificant for all brands except the Bridgestone tires.

- The results obtained by a regression analysis of the actual weight loss rates (grams/mile) for each phase separately were not consistent across tire brands and the R^2 values were low. For the combined data of Phases I and III, the variables test, wet miles, mileage and the interaction of wet miles with temperature were found to be significant for all brands. Also, temperature was significant for both the Uniroyal and Goodyear tires and humidity was significant for the Uniroyal and Michelin tires. When a phase variable was added to the model for the combined data, it was found to be significant and the convoys became nonsignificant for all tire brands except Bridgestone.

- Three regression models (linear, quadratic and square root) were fit using tread depth (mils) and tire weight (grams) as a function of mileage for both the Phase I data and the combined Phase I and II data. Confidence intervals on the expected rates at 8,000 miles overlapped for the two sets of data for all models except the linear runs on tread depth. Comparisons across the three models for a given data set revealed several differences in the tread depth regressions but only one difference in the tire weight regressions. To determine in a more conclusive way the value of linear or non-linear regressions, a more extensive analysis, with more data, would be required.

- No corrections were made for temperature effects due to the inconsistencies in the results obtained using the actual weight loss rate data (grams/1000 miles) as well as the estimated wear rate (mils/1000 miles) and estimated weight loss rate (grams/1000 miles).

- ANOVA runs on the acceleration data showed that in 29 of the 32 comparisons the between-driver variability was not significant. Thus, the drivers, on the average, accelerated and decelerated in a similar manner over the test course.

- Rankings of the drivers according to the means of their acceleration data and to the magnitude of their estimated regression coefficients obtained in the analyses of the actual weight loss rates (grams/miles) for the Phase III data revealed no consistent patterns. Few differences were found among the drivers and, those that were found did not follow a consistent trend.

PREFACE

This is a report of the results of Southwest Research Institute Project 08-7928. The program was conducted under contract DTNH-22-84-C-07106 for the National Highway Traffic Safety Administration of the U. S. Department of Transportation. The project was carried out by the Tire Evaluation/Research Section of the Division of Engines, Fuels and Lubricants (Vice President, John A. Vitkovits) with Mr. R. N. Pierce serving as the Institute's program manager and principal investigator.

Dr. Robert L. Mason, Manager of the Institute's Statistical Design and Analysis Section, was a co-principal investigator and was responsible for the analysis of the data. Ms. K. E. Hudson was instrumental in development of the mathematics and procedures used in the statistical analyses. Mr. Robert Gauss was responsible for the fabrication and implementation of the acceleration measurement and recording equipment. Mr. John White of the Engines, Fuels and Lubricants Data Systems was instrumental in the preparation of the field data for the statistical analyses, especially in the case of the vehicular acceleration studies and the tire wear regression computations. Dr. H. E. Staph provided direction in the support of the project and acted as an immediate back-up to the project manager in the operational portion of the work. Messrs. J. E. Steele and E. F. Jones were responsible for the on-site direction of the field work.

Dr. Staph was also responsible for the coordination and editorial requirements of the final report. The preparation of the report was the result of combined efforts of the support personnel from the SwRI Statistical Design and Analysis Section and the Tire Evaluation/Research Section. Specifically, the accomplishments of Marilyn Smith, Shirley McDonald, Kim Barclay, and Gail Vollmer are especially appreciated.

Dr. Jose L. Bascunana was the Contract Technical Manager for the Office of Vehicle Research (OVR) of NHTSA. Mr. Harlan Galloway of the NHTSA Uniform Quality Tire Grading (UTQG) Test Center in San Angelo, Texas, was responsible to OVR for the observation and monitoring of the evaluation. Mr. James Auten was the Contracting Officer for the Government.

1. INTRODUCTION AND BACKGROUND

This program was initiated to meet a requirement presented by NHTSA to determine the variability of the tire treadwear rate during an evaluation which emphasizes stringent control of a refined test procedure in determining:

1. actual temperature response of tire treadwear rate and variability on the test course,

2. the veracity of projected results by extension of developed data,

3. the response of candidate brand tests in terms of variation of treadwear rates relative to selected samples of a product,

4. the seasonal influence on the environmentally related factors which are shown to influence tire treadwear,

5. means to further reduce variability of the adjusted treadwear rate by reduction of the control unit variability.

The testing was to be conducted in three phases. This report presents the analysis of the results of Phase I which considers the first, third and fifth of the objectives, Phase II which relates to the second objective through extended treadwear tests, and Phase III which was conducted during the hottest time of the year in contrast to the Phase I environment to develop the fourth objective. In addition, a special evaluation to provide for a basis of determining 100% tread-loss by weight was conducted.

The problem of establishing a practical and dependable means of evaluating tire treadwear has long been the subject of many studies. It is the subject of this effort. The more specific problem now involves the determination of procedural and operational variability in the interest of improved verification of the treadwear test result.

In 1966, the Congress of the United States enacted the National Traffic and Motor Safety Act which, in part, mandated that the Department of Transportation was to assume the responsibility for the development and implementation of the Uniform Tire Quality Grading System. The UTQGS is to provide for determining relative performance criteria of commercially available tires and to inform the consumer regarding the utility of the system.

The treadwear grading problem is an extremely complex one -- much more involved than that considered by even the most interested casual observer. Procedural statements must consider response differences of many tire tread materials and designs, tire structures and performance features, as they are operated in many environmental associations -- on unlimited surfaces and terrains by even a greater number of buyer/drivers in almost that many more vehicle/suspension/load circumstances. Several attempts to design systems to control enough variables to acquire a full understanding of the wear response have not been entirely successful. On the other hand, several million miles of testing have resulted in data which is indicative that controllable procedures are practical and within reach -- but that certain of the variances inherent in outdoor road testing must simply be nullified by reducing the reasons for data variation or by increasing the size of the data base.

Recent investigations have evaluated certain variances which are considered significant and subject to improved control influences in this type of testing. Given the utilization of a tire which is as close to being non-variable as any production tire can be, it was considered that the items of concern are the test vehicles, the test drivers, and the influences of the course, all of which are massive in their impact as a result.

The immediate requirement, previously stated, was begun on January 17, 1984, by initiating processes for acquiring test tires and test vehicles. The preparation for the Phase I testing required a month -- the first convoy deployment was on February 17, 1984, and the final data measurements were made on March 20, 1984.

A draft report of the analysis of the Phase I work was prepared and accepted preliminary to the start of the Phase II extended mileage work on May 7. During the interim some special studies of the course ambient temperatures and tire weighing processes were initiated. This report covers those efforts.

The Phase II mileage accumulation was completed at 24,000 miles on July 7, 1984, and the new tests were begun on convoys 6, 7, 8 and 9 on July 18, 1984 as Phase III. The Phase III mileage was completed on August 15, 1984, and final tire measurements established at that time.

The mileage accumulated during Phases I and III was 128,000 vehicle miles in each case; the Phase II mileage was 32,000 miles. The total program was run while accumulating 288,000 vehicle miles.

A modification of the original contract provided for certain additional tasks and expansion of some of the originally stated efforts. In particular, the statistical analyses was extended to the degree indicated in Section 3 of this report; a very special effort was made to evaluate a methodology for establishing 100% tread loss by weight; all of the numerical data accumulated was forwarded to the government for SAS analyses after being formated accordingly; tread loss was determined by tire weight loss each 400 miles rather than 800 miles during Phases II and III; and equipment was procured and implemented during Phase III to determine typical longitudinal and lateral acceleration profiles of the test vehicles as they were normally deployed in the convoys.

This report covers all aspects of the foregoing except for the determination of the 100% tread loss methodology which will be provided as a supplement to the report.

2. THE TEST

The program consists of three major phases, each made up of several tasks.

The Phase I work provided for much of the preparation portion of the program including the procurement and preparation of the test tires and vehicles. In addition, much of the new procedural investigation was carried out during this time. Phase I covered the conduct of four 4-car tests of 32,000 miles (8000 miles per vehicle). It required that the mechanical record of loading and alignment be validated prior to each 400-mile circuit of each vehicle. The tires were measured and weighed to determine tire tread loss at 800-mile intervals. Phase III was conducted in a like manner during the summer months of 1984. In addition, the tires were weighed each 400 miles to provide for additional precision in projection of the loss rate, but also to relate loss results to each 400-mile circuit (one day's run during a single driving shift).

Tire weighings at 400 mile intervals were made throughout Phase II which was the extension of the testing of Test Sets X_1 (Uniroyal) and M_1 Michelin) from the original convoy 1 (Test 4S0001). The testing was done on the cars 1403 (X_1) and 1404 (M_1) from the convoy 1 and employed the lead and fourth drivers from that convoy, Codes 01 and 04 respectively (refer to Drivers Codes, Appendix B). The Phase II test (4S0005) was run without rotating cars in the convoy or tire sets on the cars. The tires remained on the cars as initially assigned and were rotated in a forward-X pattern at 400-mile intervals.

Tire temperatures were determined during the mileage accumulation. Ambient and road temperatures were measured, and environmental control of the measurement area and control of the schedules was made a part of this procedure.

Data acquisition was partially automated. Usage of some new procedural steps precluded use of automated procedures in some cases, but will provide some opportunity for development of additional or revised data specifications.

One task of the first phase was a systematic procurement of the P195/75R 14 test tires. All of the tires in this program were selected to be representative of the all-season type that are readily available to the consumer; no other significance should be placed on the choice of brand. Three domestic brands and one foreign manufactured brand were chosen. The treads of the domestic brands were largely of synthetic rubber blends, the foreign tire treads contained a substantial quantity of natural rubber.

The control tires, designated X Group, were procured by the government. These were production tires, Uniroyal Tiger Paw brand which were followed in their material, manufacture and inspection specifically for this program. All of the Group X tires were manufactured in the Ardmore, Oklahoma Uniroyal plant and cured in the same mold on the same day of the first week of 1984.

The three groups of tires other than the control tires were sought from as many production weeks and production sources as possible. In that tires of a like size and brand are ordinarily produced in a single plant of a manufacturer, all of the tires of each of the three candidate groups came from a single manufacturing source. An effort was made to secure varied production dates and as many production mold code identities as possible to introduce a random variation in tires of a candidate group or set.

All of the Michelin XA4 tires (35 including spares) were produced in the Lexington, South Carolina plant and were purchased from one distributor at the same time. The tires were from five (5) production weeks between October 11, 1982 and December 13, 1983. They were cured in sixteen (16) different final molds, and there were two constructions (carcass/belt ply combinations). These combinations of dates, molds, and constructions, resulted in nine (9) sets of duplicates; seventeen (17) tires were not duplicated.

The Goodyear tires were of the Arriva brand. Sixteen (16) tires were procured from a single source at one time and twenty (20) others were purchased in groups of three or four from six different dealers throughout the United States. All of the Goodyear tires were produced in the Gadsen, Alabama tire production facility between September 19, 1983 and January 9, 1984. Eight (8) different production dates and twenty-two (22) different curing molds are represented. From this, four (4) pairs of Goodyear tires were duplicated; twenty-seven (27) were unique.

The Bridgestone RD401 tires were produced in Saga-Ken, Japan. The thirty-five (35) tires were procured from eight different sources in eight sets of four and one group of three. It is indicated that the Bridgestone production was limited to four final mold installations. The tires were produced during eleven (11) different production weeks between January 24, 1983 and August 1, 1983. The Bridgestone production contained sixteen (16) unique mold/date combinations; there were two duplicate sets, two triplicate sets, and one each identical groups of four and five tires in the population.

As the tire procurement became complete, individual tires were assigned to the four tire sets to be used in the test. In the final assignment, the Phase I tires represented the following characteristics:

Group	Brand	Unique Production Dates	Unique Production Molds	Tire Sets (4 each)
X	Uniroyal	1	1	X_1, X_2, X_3, X_4
M	Michelin	4	10	M_1, M_2, M_3, M_4
G	Goodyear	6	13	G_1, G_2, G_3, G_4
B	Bridgestone	6	4	B_1, B_2, B_3, B_4

Three of the remaining tires of each group were assigned as spares and the remainder of the procurement assigned to Phase III as follows:

Group	Brand	Unique Production Dates	Unique Production Molds	Tire Sets (4 each)
X	Uniroyal	1	1	X_6, X_7, X_8, X_9
M	Michelin	3	14	M_6, M_7, M_8, M_9
G	Goodyear	4	13	G_6, G_7, G_8, G_9
B	Bridgestone	8	4	B_6, B_7, B_8, B_9

The Phase II tests were conducted on sets X_1 and M_1 from Phase I. These X_1 tires were produced in the same mold on the same day. The M_1 tires were cured in four different molds during the 41st and 45th weeks of 1982 (one tire each) and the 49th week of 1983 (two tires).

Appendix A provides a complete list of the tires procured for the program.

The test plan, as shown in Table 2.1, provided for the testing of four sets of each of the tire groups on four convoys made up of eight identical vehicles[(1)]. The four car convoys of Phases I and III each accumulated 8000 miles during the period of testing. The tires were measured at the conclusion of each 800 miles; the tires were rotated through the wheel positions and the vehicle within the convoy and the vehicular loads and alignments checked every 400 miles. The two cars of the Phase II convoy each accumulated 16000 miles during that Phase. They ran only during the day. In addition to the 800-mile tire groove depth measurements, each tire was thoroughly cleaned and weighed at the time of measurement during Phase I and at 400 mile intervals during Phases II and III.

With the exception of the Phase II convoy (Test 4S0005), the vehicles were advanced in the convoy after each 400-mile circuit. Drivers always remained in place. This provided for an observation of each driver/vehicle combination imposed upon each test group at regular intervals during Phases I and III. The on-vehicle tire rotations were in the forward-X pattern -- that is, to move the front wheels directly to the same-side rear positions, while the rear tires crossed diagonally to the front positions. This rotation was executed four times after a set was placed on a car to allow each tire to run 400 miles on each of the wheel positions; then when applicable the

[(1)] Identical vehicles are alike in respect to manufacturer, name and model, engine size, wheel base, drive train (which consists of transmission, shaft and differential), suspension (which includes identical springs, shock absorbers, dampers and torsion elements), and identical optional features which will influence the driveability or weight/power ratio of the vehicle. It also includes the same overall length of the vehicle.

TABLE 2.1

TEST PLAN FOR THE INVESTIGATION OF A LOW VARIABILITY TIRE TREADWEAR TEST PROCEDURE AND OF TREADWEAR ADJUSTMENT FOR AMBIENT TEMPERATURE TO EVALUATE TIRE TREADWEAR VARIABILITY IN TERMS OF -

- Tire Brands X vs M vs G vs B
- Time of Year
- Time of Day

	WINTER		SPRING	SUMMER	
	DAY	NIGHT	DAY	DAY	NIGHT
Vehicle Group 1 - Test No.:	4S0001	4S0003	-	4S0006	4S0008
Vehicle Group 2 - Test No.:	4S0002	4S0004	-	4S0007	4S0009
Vehicle Group 3 - Test No.:	-	-	4S0005	-	-

Phase	Time	Test	Convoy	Car	Driver	Tire Set
PHASE I (COOL WEATHER, FEBRUARY - MARCH 1984)	DAY	TEST 4S0001	CONVOY 1	1401	1	X_1
				1402	2	M_1
				1403	3	G_1
				1404	4	B_1
		TEST 4S0002	CONVOY 2	1405	5,19	X_2
				1406	6	M_2
				1407	7	G_2
				1408	8	B_2
	NIGHT	TEST 4S0003	CONVOY 3	1401	10	X_3
				1402	11	M_3
				1403	12	G_3
				1404	13,15,20	B_3
		TEST 4S0004	CONVOY 4	1405	14	X_4
				1406	16	M_4
				1407	17	G_4
				1408	18	B_4
PHASE II (MAY - JULY 1984)	DAY	TEST 4S0005	CONVOY 5	1403	1	X_1
				1404	4	M_1
PHASE III (HOT WEATHER, JULY - AUGUST 1984)	DAY	TEST 4S0006	CONVOY 6	1401	1	X_6
				1402	22	M_6
				1403	3	G_6
				1404	4	B_6
		TEST 4S0007	CONVOY 7	1405	19	X_7
				1406	23	M_7
				1407	24	G_7
				1408	8,29	B_7
	NIGHT	TEST 4S0008	CONVOY 8	1401	10	X_8
				1402	25	M_8
				1403	12	G_8
				1404	26,20,21 28,27	B_8
		TEST 4S0009	CONVOY 9	1405	16	X_9
				1406	30	M_9
				1407	9	G_9
				1408	15	B_9

1. Each tire set consists of 4 tires of the same brand. A spare tire for each brand is available in each convoy.
2. The vehicle/tire sets shown are at test start. Tire, tire sets, and vehicles rotate, except that tires only rotate during Phase II.
3. A spare vehicle, 1409 was stand by.
4. Driver positions DO NOT CHANGE.
5. Vehicle Group 1 (1401, 1402, 1403, 1404) was utilized in Convoy 1 (day) and Convoy 3 (night); Vehicle Group 2 (1405, 1406, 1407, 1408) was utilized in Convoy 2 (day) and Convoy 4 (night); Vehicle Group 3 (1403, 1404) ran Daytime Only as Convoy 5.

complete set was moved to the following vehicle to repeat the rotation pattern. The 1600-mile cycle was repeated five times during the 8000-mile Phase I and III tests and ten times during Phase II.

Nine 1984 Buick Regal 4-door sedans were procured and prepared for testing. An inventory of these vehicles is provided in Table 2.2. All vehicles were equipped with automatic transmissions, power steering, power brakes, air conditioning, and radio.

The vehicles were prepared for test by loading to provide for equal loads of 1031 $^{+10}_{-0}$ pounds at each of four wheel positions. The loading provided for a driver equivalent of 190 pounds; all drivers in the test carried extra ballast supplement to provide for that weight in the driver's place.

The vehicle alignments were set to the middle of the specification shown in Table 2.3.

TABLE 2.3
Alignment Specifications for 1984 Buick Regal Sedan from
Buick Service Manual, Section 3A, for G series Cars 1983 (1984)

	Caster	Camber	Toe-In	Adjustment
Front Wheels	+3° ±0.5°	0.5° ±0.5°	0.15° ±0.05°	Normally Adjustable Within Range Indicated
Cross Caster and Cross Camber will not exceed ½° side-to-side variation.				
Rear Wheels	Not Applicable	From -.3° To +.5°	0 to -.05° (Toe-Out)	Not Adjustable.
Settings are those established by General Motors for re-setting wheel alignment if required. Important - at curb load.				
Alignment will be set at test load and in accordance with manufacturer's procedure.				

Alignment adjustments of the front end of the vehicle required removal or replacement of varying thickness shims in each of four places in the suspension. This resulted in adjustments which were nearly continuous, but not quite. Therefore, in some instances, adjustments and resetting of alignments to the prior or initial setting were extremely close if not exact. The settings were determined at the conclusion of each 400-mile circuit and reset to the specified settings in each case. As previously experienced, the need to adjust became less and less demanding as the mileage was accumulated.

Appendix B consists of the Initial Calibration Data and Raw Field Data covering the alignment and weighing of the cars at 400-mile increments.

TABLE 2.2

VEHICLE LIST

VEHICLE NO.	DESCRIPTION				IDENTIFICATION		ASSIGNMENT	
	MFR.	MODEL	BODY	ENGINE	SERIAL NUMBER VIN-1G4AJ47A	LICENSE	CONVOY	POS.
1401	Buick	Regal	2-dr Sed.	3.8 Liter V6	3EH400565	186EGW	1 & 3	1
1402	"	"	"	"	8EH400531	403EGY	"	2
1403	"	"	"	"	5EH435768	405EGY	"	3
1404	"	"	"	"	1EH400533	468EGN	"	4
1405	"	"	"	"	XEH438925	240EGN	2 & 4	1
1406	"	"	"	"	XEH433790	406EGY	"	2
1407	"	"	"	"	7EH416123	840EGZ	"	3
1408	"	"	"	"	6EH400432	191EGW	"	4
1409	"	"	"	"	6EH434211	241EGW	Stand-by	

All vehicles are equipped with automatic transmissions, power steering, power brakes, air conditioning and radio.

The initially determined rear alignments with full test load were determined to be as shown in Table 2.4. These data differ from those shown in Table 2.3 which are specified for curb load.

TABLE 2.4

Initial Rear-Wheel Alignment Measurements at Test Load

Vehicle No.	Camber Left	Camber Right	Toe-Out Left	Toe-Out Right	Total Angle
1401	-.15°	-.15°	+.08°	-.15°	-.04°
1402	-.30°	-.15°	-.15°	0	-.08
1403	-.08°	-.15°	0	-.15°	-.08°
1404	-.25°	-.08°	+.15°	-.15°	0
1405	-.25°	-.15°	+.15°	0	+.08°
1406	-.30°	-.15°	0	-.08°	-.04°
1407	-.50°	-.25°	+.25°	-.15°	+.05°
1408	-.25°	-.15°	+.15°	-.5°	+.05°

Phase I testing was conducted in four convoys which were deployed on the same schedule during each of the twenty (20) test days. Convoy 1 (Test 4S0001) departed at 8:00 AM each day and Convoy 2 (Test 4S0002) left two hours later the same morning. The first convoy returned after the 400-mile circuit at the same time each afternoon and was serviced, weighed and aligned. The wheels were removed and replaced with the Test 4S0003 tires and the cars were re-deployed in the evening as Convoy 3. The vehicles used were the same as Convoy 1 but with a different group of drivers. Convoy 2, following Convoy 1 by two hours, was processed in exactly the same manner as Convoy 3 and was dispatched as Convoy 4 with Test 4S0004 two hours behind Convoy 3. In this way, each test ran 400 miles during each 24-hour period; the cars each ran 800 miles daily; the drivers were associated with the same test and tire sets always.

Phase III was conducted in like manner at the same times indicated for Phase I; i.e., Test 4S0006 (Convoy 1) departed at 8:00 AM, followed by Test 4S0007 (Convoy 2) two hours later; and the night Convoys 3 and 4 departed at 8:00 PM and 10:00 PM, with Tests 4S0008 and 4S0009, respectively.

Phase II Test 4S0005 (Convoy 1) was deployed each day at 8:00 AM. Typical preparation for test convoy departure is shown in Figure 2.1.

During all phases of the test, the drivers were responsible for noting any mechanical circumstances, wet miles, or conditions possibly influencing the vehicle performance. In an attempt to achieve a more uniform acceleration and braking behavior by the drivers, an accelerometer device was installed in each car to sense and indicate forward accelerations in excess of 0.1G. A signal alerted the driver to accelerations in excess of this value.

Two individuals in each convoy were responsible for measuring the temperatures of each tire tread and sidewall, the ambient temperature

FIGURE 2.1
Convoy Preparation

and the road surface temperature at each scheduled stop during a circuit. The measurements were all to be made with the Omega contact potentiometer and recorded as quickly as possible after the convoy halted -- always in the same order from the number four vehicle position forward. Figure 2.2 illustrates the temperature data acquisition.

During the Phase I testing, temperatures were measured at five points on the course. Data acquired were inadequate and sometimes not reliable. The subsequent temperature measurements (Phases II and III) were made more frequently. Permanent temperature stations were established at each of seven circuit positions, and improved instrumentation was acquired and utilized for the tire contact temperature measurements. Figure 2.3 indicates the course as it was segmented for temperature study. Fixed thermometers at each of the four designated points were read a total of seven times during each run and the ambient temperature was computed in terms of an indicated average over each segment. Tire and road surface temperatures were measured at each of the seven check points during Phases II and III. The five data points used for the Phase I temperature data were supported only by local area temperature readings when available. The complete record of the ambient weather conditions in the San Angelo, Texas, area during this program was compiled by the NOAA at Mathis Field, Texas, (7 miles SW of the test base). This record is a part of Appendix D. Figure 2.4 shows the drivers obtaining ambient temperature and road surface temperature measurements.

The tires, when removed after concluding an 800-mile run (two 400-mile circuits) were prepared for measurement. In that the tires ran 400 miles daily, tire tread measurement procedures were carried out every other test day. They were weighed every other day for Phase I and daily (each 400 miles) during Phases II and III.

All of the tires were removed and washed in an especially constructed tank containing water. Each tire and wheel was individually immersed to half-depth and rotated while being scrubbed. At the conclusion of the scrubbing, the tire was lifted from the tank and rotated rapidly and blown with air until dry. The equipment and the procedure is illustrated in Figure 2.5. Prior to the washing, the operator and an assistant had removed all stones and debris from the tread. The tires were then removed to the tire measurement room where they were stored under temperature controlled conditions for at least seven hours prior to measurement and weighing.

Prior to measurement of the sixteen (16) tires of a Test, the tire measurer, A, and the measurement supervisor, B, measured a standard control tire to initiate the procedures and to establish continuity of control in the room. Table 2.5 is a record of the pre-test standard tire measurements by Measurers A and B during Phase I. The same measurers and laboratory personnel were used throughout the program.

FIGURE 2.2
Tire Temperature
Measurements

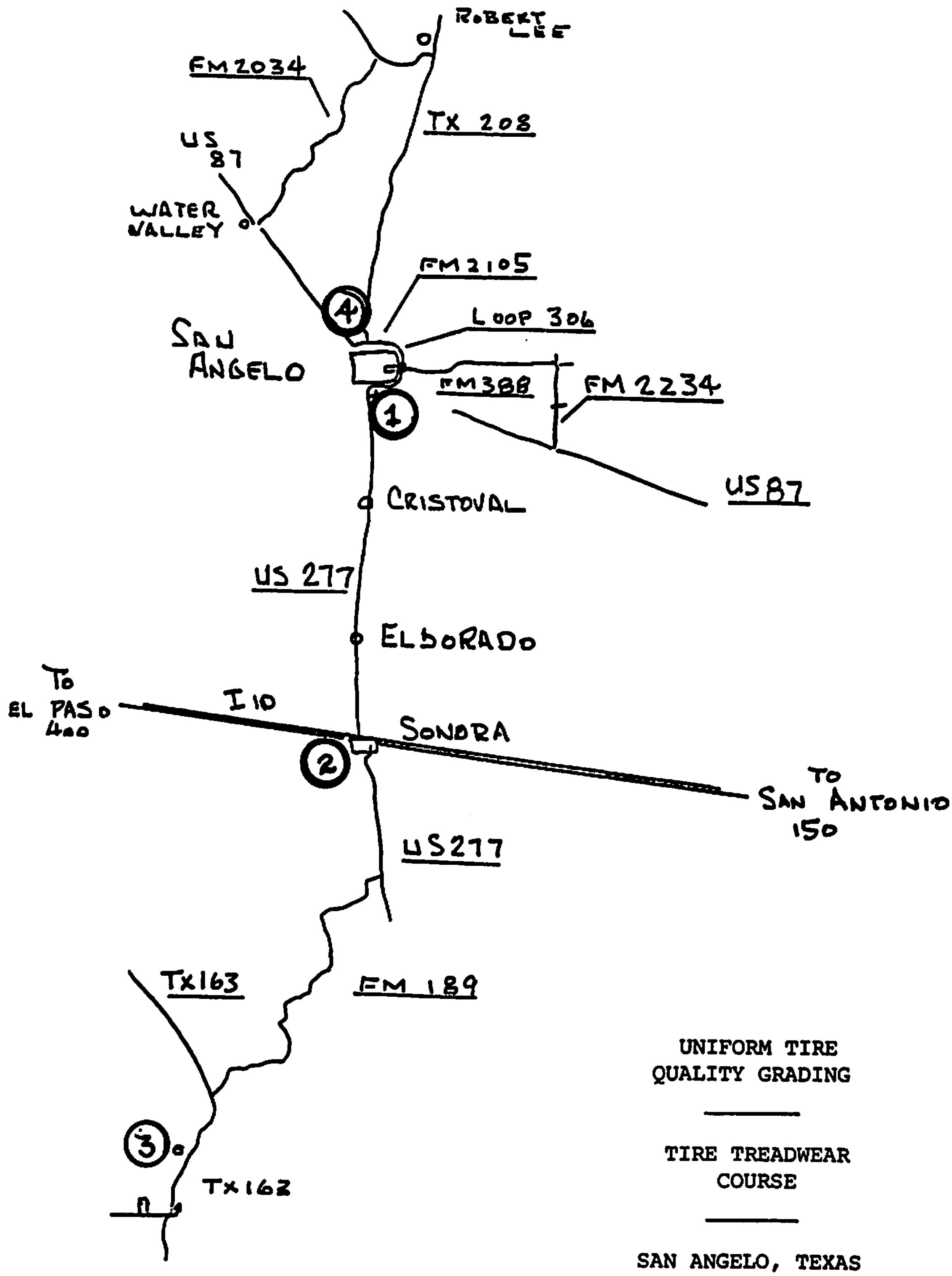
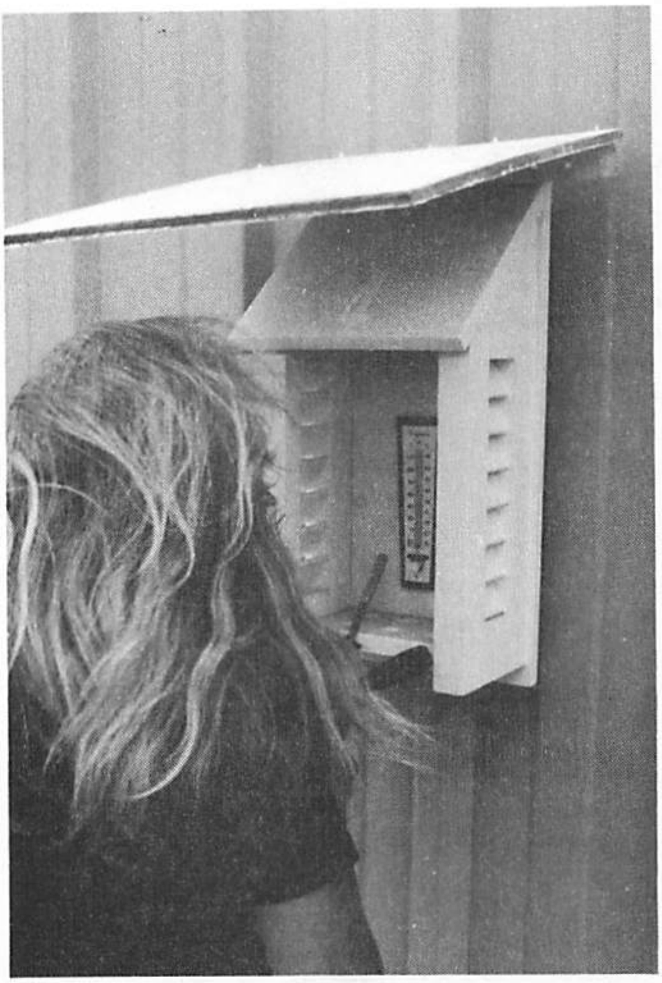
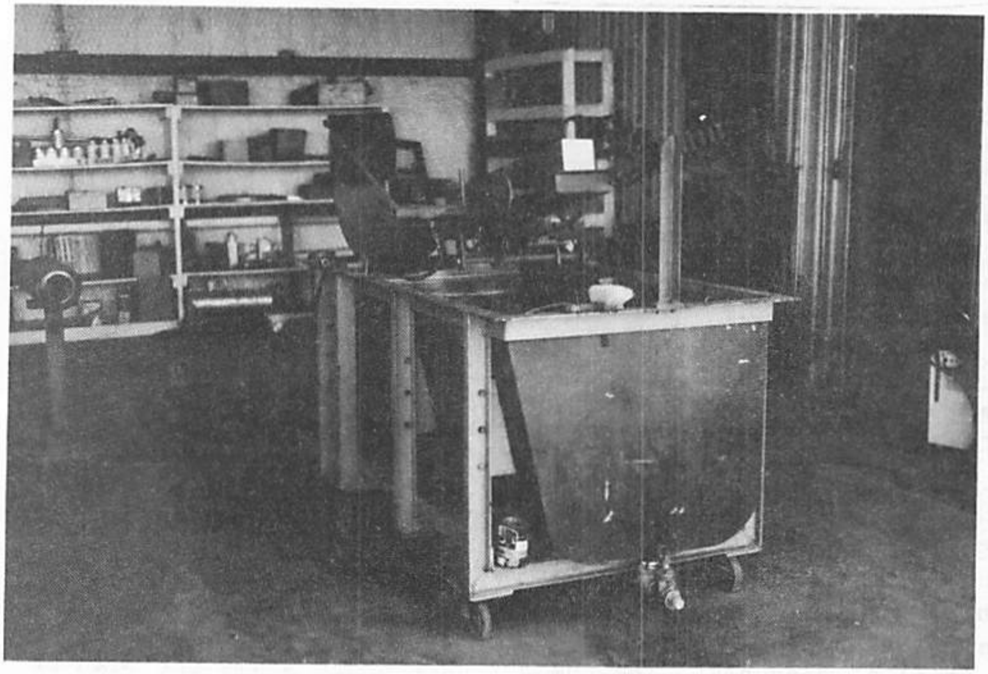


FIGURE 2.3
TIRE TREADWEAR COURSE

FIGURE 2.4
Ambient and Road
Temperature
Measurements





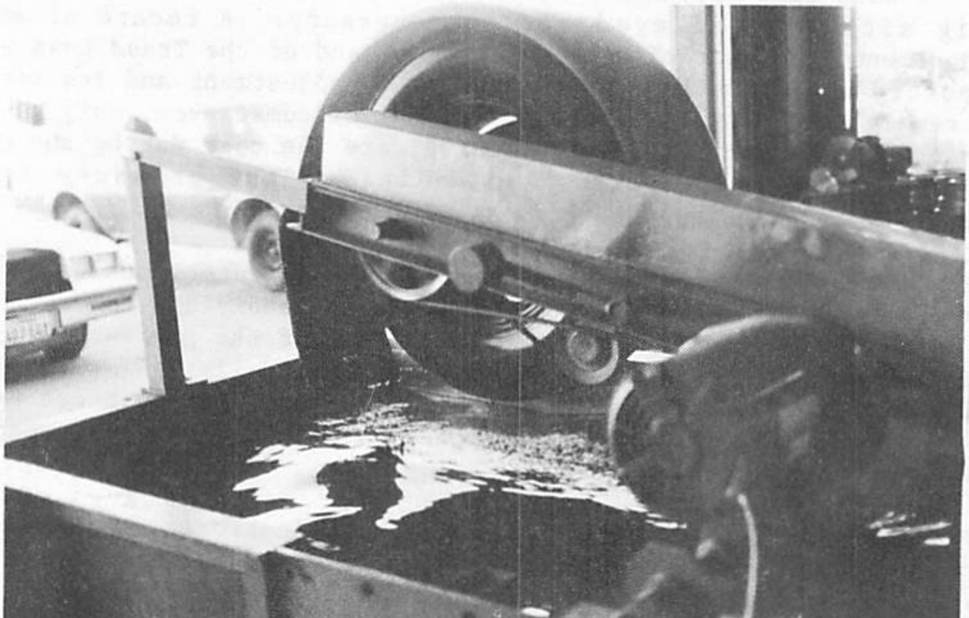


FIGURE 2.5
Tire Washing and Drying System

TABLE 2.5

MEASUREMENT OF STANDARD CONTROL TIRE
AVERAGE REMAINING GROOVE DEPTH, MILS

TEST NO.	4S0001		4S0002		4S0003		4S0004		ALL TESTS	
	Mean	s	Mean	s	Mean	s	Mean	s	Average	Cv, %
Measurer A	305.7	---	305.4	---	305.4	---	305.8	---	305.6	---
	---	.68	---	.77	---	.77	---	.31	of 4 Means	-.067
Measurer B	305.6	---	305.5	---	306.0	---	306.1	---	305.8	---
	---	.53	---	.64	---	.38	---	.40	of 4 Means	-.095
Difference	-0.1	---	+0.1	---	+0.6	---	+0.3	---		
							AVERAGE OF 8 MEANS		-305.7	
							C_v, %, OF 8 MEANS			-.086

The use of two measurers with a record of each of their abilities provided a statistical means for evaluating the quality of a replacement should such have been necessary. The mean and standard deviation of the replacement could have been compared to those of the remaining original measurer. The Phase I data which shows the mean of ten successive readings made by each measurer during each of four tests indicates resultant differences from -0.1 to +0.6 mils for the various tests -- an overall (4-test) mean of 305.6 mils and a 0.21 standard deviation by measurer B. Combining all of the measurements yields a 305.7 mil average and an overall (80 measurements) standard deviation of 0.264.

Before each tire was measured, the tire pressure was adjusted to 26 psig with dry filtered air as necessary. A record of such an adjustment is a part of each measurement and of the Tread Loss Summary reported at 800-mile increments. This adjustment and its record is extremely important because under normal circumstances, only pressure readings, and not further adjustments, are the case during the conduct of the test on the course. In addition, the pressure is very important in weighing the tires as will be seen.

The same pressure gauge was used in the laboratory and to check the final and starting convoy pressures. It is subdivided to indicate 0.5 psig and is accurate within one-half of 1% of the pressure read; this gauge was checked against a master gauge on a daily basis. These data and room temperature data as well as atmospheric pressure are required in conducting and validating the controlled laboratory environment and process.

The tire measurements were made with an electronic depth gauge in a very repetitive pattern and the groove depth measurements transmitted to the computer. The tire measurement probe was calibrated on the standard step-block prior to each tire measurement; the tread hardness was determined in the area of each groove depth measurement point and the tire inspected for any evidence of damage or abnormality. During the process of measuring, the tire inspected for any evidence of damage or abnormality. During the process of measuring, the measurer did not see a readout of a measurement result, but the measurement supervisor, or second measurer, observed the progressive individual readings in each groove and the subsequent mean value and groove coefficient (the coefficient of variation of the six groove measurements which is the standard deviation of those readings divided by the mean groove depth and converted to percent).

This program also provided data for determination of tread loss by weighing the tires at regular mileage intervals. A very precise electronic balance was used to weigh each tire to the nearest gram. This was done immediately after the measurement process (800-mile intervals) during Phase I and at 400-mile intervals (each rotation) thereafter. The weighing result was hand recorded. It was noted that the tires, weighing on the order of 17 to 18 kilograms (with the wheel), will lose between 12 and 24 grams during an 800-mile run.

During this program, every tire was weighed to the nearest gram at the stated mileage intervals to determine loss of tread. The weight loss determined in this way was small but significant. It was necessary to calculate the effect of atmospheric buoyancy on tire weight. A treatise presented by J. Bascunana[(1)] provides that the actual solid mass of the wheel/tire will be:

$$m_s = m - (P_g V_a M/RT) + (P_{atm} V_s M/RT)$$

where m = wheel mass as weighed, lb_m

P_g = tire inflation, gage pressure, psig

V_a = tire air volume, $ft.^3$

P_{atm} = atmospheric pressure, psia

V_s = solid wheel volume, $ft.^3$

M = air molecular weight, 28.97 lb_m/mole

R = Universal Gas Constant, 1545 lb_f ft/mole °R

T = air temperature, °R

In order that the computation could be carried out, the volumes of the various tires and the volumes of the rims were determined. The results are shown in Table 2.6.

TABLE 2.6

Volume of Tire/Wheel Components, cc

Tire Mfgr/Grp	Tire V_t	Rim V_r	Inflated Wheel $V = V_t + V_r + V_a$	Wheel Solids $V_s = V_t + V_r$	Tire Air $V_a = V - V_s$
Uniroyal/X	7768	1032	41515	8800	32715
Michelin/M	7725	1027	42759	8752	34007
Goodyear/G	7602	1019	41098	8621	32477
Bridgestone/B	7703	1030	40906	8732	32234

(1) Memo on Weighing of Tires/J. L. Bascunana/12/03/82 (See Appendix C).

The quantities V_t, V_r, and V were determined experimentally by measuring displaced water. For use in the equation, the volume in cubic centimeters was converted to cubic feet where 1 ft^3 = 28316.7.

The volume of the contained air, V_a, is also shown in the table. V_a was established by immersing a typical tire of each brand prior to and after mounting and determining the difference in volume of water displaced. Special equipment as shown in Figure 2.6 and special procedures were devised to overcome problems resultant from surface tension and flow of the displaced fluid. The volume of the rims was also measured by displacement of the fluid, but as a check, the weight of the rim and knowledge of the density of steel provided good correlation between the calculated volume and that measured.

The computation was then reduced to calculate the differences in weight to be expected at the case extremes during the Phase I testing.

From the formulas presented and the constant data provided for P_g, V_a, M, R, and V_s, it is seen that by implementation of the atmospheric pressure, P_{atm} and the room temperature T, a value for m_s can be determined when m is measured.

Simplified further to fit our purpose, the calculation can be utilized to provide corrections of the weight loss between measurement dependent on the pressure and temperatures at the times of measurement. It can be shown that corrections due to buoyancy can be applied to the measurement weights as follows:

When the pressure differs by	+1 Psia	+1 inch Hg
Adjust the weight by	-0.6 gms	-0.3 gms
When the temperature differs by	+1°F	+1°C
Adjust the weight by	-.09 gm	-.16 gm

The room temperatures during the Phase I testing were constantly within the bounds of 71°F and 78°F. The cleaned and inflated tires were "soaked" in the measurement room for a minimum of seven hours prior to weighing.

In applying the foregoing to the pressures and temperatures measured during the Phase I work, we can note the extreme to have occurred between late afternoon measurements on February 27 and February 29.

Date	Time	Temp	Pressure		P	Correction, gms		
	hrs	°F	P	°F	psi	t	P	Net
02-27-83	1700	77	14.774	---	---	---	---	---
02-28-83	2050	72	14.735	-5	-.039	+.45	+.023	+.473

The adjustment of the measured tire weights by +0.473 grams would be inconsequential in that the tire weights are resolved in one-gram increments. It must be noted, however, that if an extreme difference

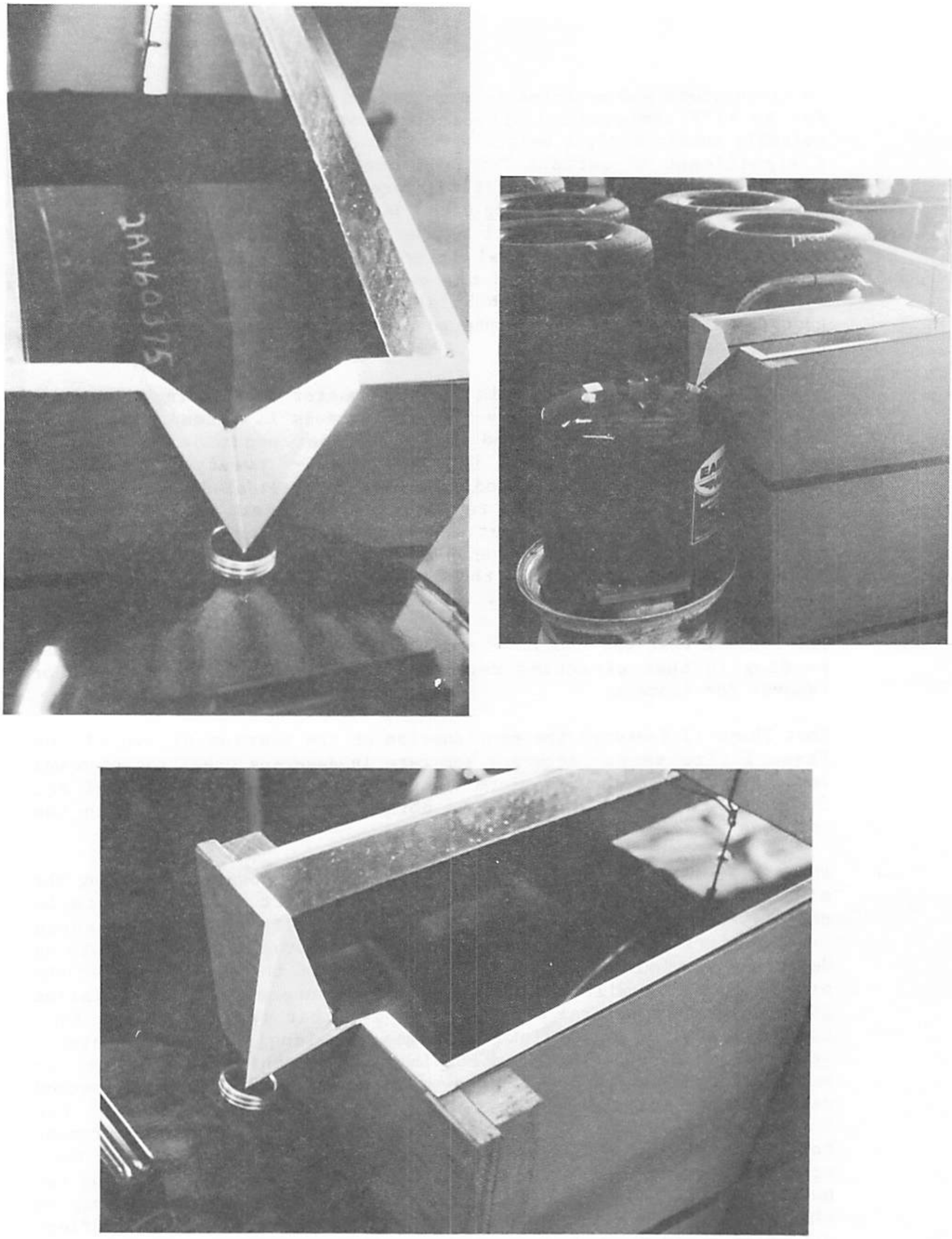


FIGURE 2.6
Volumetric Equipment
for Tire Buouyancy Determination

in temperature had occurred (a one-gram adjustment will be required for an 11°F temperature difference), or if the tires had not been suitably conditioned, a weight variation of consequence would occur. A significant adjustment for a barometric pressure variation would require a major differential in that pressure. Of significance, too, in the matter of determining tread loss, our ultimate objective -the temperature variation, as well as the barometric pressure variation, will act on the differential internal and external pressure of the tire in such a way to stress the measured components differently, resulting in increased "rib heights" or "non-wear" differences in groove depth. Everything points to extremely conscientious control of the laboratory atmosphere.

During an evaluation of this sort the matter of assuring the proper placement of each of the sixty-four (64) wheels is paramount. As an example, during Phase I and III the proper positioning was very demanding in that it differed each 400 miles -- twenty (20) changes for each tire must be directed, approved and validated during each of the 8000 mile tests. This requires experienced, practiced and knowledgeable personnel, but mostly exact and very clear direction. Figure 2.7 is an example of the charts prepared and checked prior to removal of the tires from the measurement area for delivery and placement in the service area.

The Phase I test was concluded and the mounted tires removed and held pending further direction regarding continued use on Phase II or removal for storage.

Test Phase II featured the continuation of the testing of two of the Phase I tire sets. Accuracy and care in assuring wheel position was important in that the procedure featured rotation on each car but not from car to car -- a change in normal procedure used during the previous phase.

Phase III was set up early in July with emphasis toward conducting the mileage accumulation during the hottest part of the year to be contrasted with the winter mileage during Phase I. Major differences in procedure were the concentration on improved temperature data as described previously, more frequent weighing of the test tires (at the end of each 400-mile shift), and the measurement of the relative longitudinal and lateral acceleration of a car in each of the four test convoys. Test equipment to measure longitudinal and lateral acceleration was installed and remained in the vehicle; thus, as the vehicle rotated through the convoy positions, each driver was observed relative to each of the other drivers in the convoy. Due to the vehicle-tire rotation plan, the data were collected from different convoy positions and different tire sets each shift. The two cars equipped with the acceleration data logging equipment were running two hours apart on the course during both the day and night deployments so that data obtained on the same portion of the test route will reflect different environmental conditions.

The plan to record the biaxial accelerations simultaneously with the velocity at a particular point on the road was generally successful.

Test No 45000 1

Run 1

Circuit 1

LF 1141 — RF 1142

Car 1401 — Driver E McCARTY

LR 1143 — RR 1144

LF 1111 — RF 1112

Car 1402 — Driver N. EGGEMEYER

LR 1113 — RR 1114

LF 1121 — RF 1122

Car 1403 — Driver J. TREVINO

LR 1123 — RR 1124

LF 1131 — RF 1132

Car 1404 — Driver B SHANNON

LR 1133 — RR 1134

Supervisor J STEELE Date 2/22/84

FIGURE 2.7

CONVOY SETUP AND TIRE PLACEMENT PLAN

The system was not fully automated and depended on operator initiation of the logger and the data storage system. The data were collected over four different 20-mile sectors which generally typify the complete test route.

1. From the Loop 306-US 277 South intersection, South 20 miles.

2. From Mayfield's Store on TX 163 South to turnaround at the monument and then North, 20 miles.

3. At the Loop 306 blinker at the entry of the Eastern Loop, to turnaround and return, 20 miles.

4. At the Water Valley entrance to FM 2034 toward Robert Lee, North 20 miles.

Most of the time, the data initiation was executed properly. The collection success rate from the standpoint of the operator efficiency was about 90%. Enough data were collected to provide a qualitative observation of each of the regular drivers. Several instances of substitute drivers precluded any good judgement of some individual runs.

The inaccuracy of precisely logging a point on the route and relating it to the accumulated mileage record was evident as the latter portions of the 400-mile course were encountered. Distances as measured by the two vehicle systems were not precisely the same, although they were well within a 1% distance recording tolerance. The rolling radius variations of different tire brands also effectively caused slight distance variations at the longer mileages. It was obvious, however, that an examination of the plotted lateral acceleration over the individual sectors could be used to coordinate the locations on the course. This was done. The longitudinal (acceleration and deceleration irregularities) were more indicative of the drivers' responses.

The CR7 data logger made by Campbell Scientific Inc. is a programmable microprocessor-controlled data acquisition system. The CR7 is compact and is capable of being powered by AC line voltage, external DC sources or its internal power supply; so, it is also portable. Data may be sampled at rates between 0.1 sec. and 6553 sec. to be selected by the user.

The CR7 has inputs for a pulse counter as well as analog inputs. Analog signals are converted into digital values.

The two data loggers had expanded memories which allowed them to store approximately 19,000 recorded data points. These data could be stored permanently on an ordinary cassette tape using a Panasonic RQ-8300 tape recorder modified by Campbell Scientific.

The accelerometers, made by Humphrey, are mechanical potentiometers working on a pendulum principle. Powered by the CR7, the accelerometers will output 5000 mV full scale if accelerations of 2gs are attained. Since the accelerometers were not on a gyro-stabilized platform, the readings were subject to the attitude of the car. The two (lateral and longitudinal) accelerometers were placed in a metal box fixed on the car's back tunnel. On the box was a bidirectional bubble level which was adjusted by two thumbscrews and was centered at the beginning of every circuit when the car with driver was on a known flat surface. External noise in the accelerometer signal was reduced by a lowpass 5 Hz (3db down) filter before it could reach the CR7's analog input.

A Hall effect transducer connected to the car's transmission allowed the CR7 to determine the instantaneous velocity and accumulated distance. These values were calculated in the users CR7 program given that the transmission sends out 15,000 pulses per mile and the sampling rate is known by the programmer.

An op-amp buffer placed before the pulse counter input prevented the transducer signal from dropping sharply before it reached the CR7. Cars 1401 and 1405 were prepared identically with the electronic hardware and data loggers. The test drivers were rotated through the cars in their respective convoys (one of the cars being either 1401 or 1405) every 400 miles so that after four circuits (1600 miles) all drivers of a given convoy would have ridden once with the data logger.

The drivers were instructed to start the data logger at four different points in the test course. The program in the CR7 would record velocity, the two accelerations, and distance every 0.4 sec. for twenty (20) miles after the start command was issued, then stop; but it would continually update the total miles traveled.

At the scheduled temperature and rest stops, the driver with the data logger would dump the previously recorded data points to a cassette tape. Starting the data logger and dumping data to tape is accomplished by simple keystroke sequences on the CR7's 16-key pad. A complete record of these data, including programming instructions, are in Appendix J.

Installation of the accelerometers and the data logger equipment is shown in Figure 2.8.

The variability of the driver's speed changes in response to road conditions were, for the most part, not significant. There were, however, three exceptions wherein some drivers at several locations experienced accelerations significantly different from the other drivers in the convoy. These results are described in Section 3.10.1 of the Statistical Analysis. The determination of the drivers' responses during Phase III is based on the data transmitted from the cassette tape recording by way of a Campbell Scientific C-20 cassette interface to a program which will develop the following statistics for each run:

- Absolute Mean and Standard Deviation of the whole sample.

- Mean and Standard Deviation of the positive data.

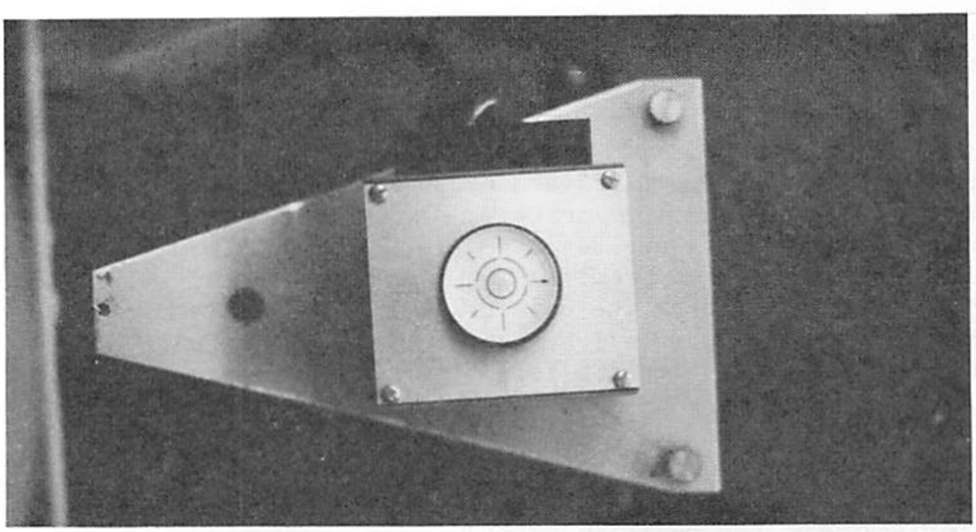


FIGURE 2.8a
Accelerometer
and
Data Logger
Installation

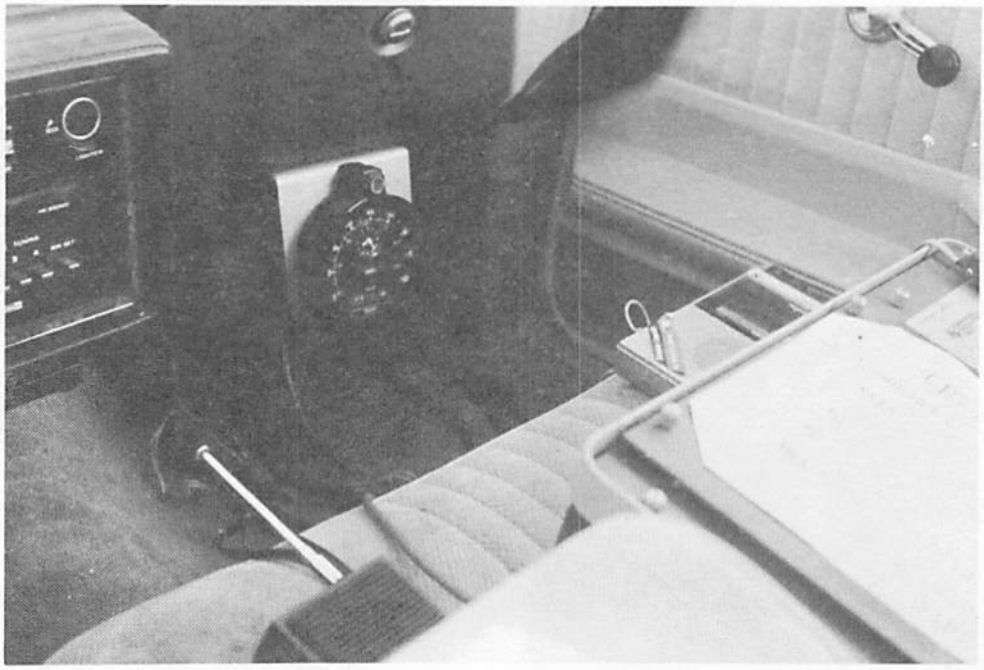


FIGURE 2.8b
Data Logger Installation

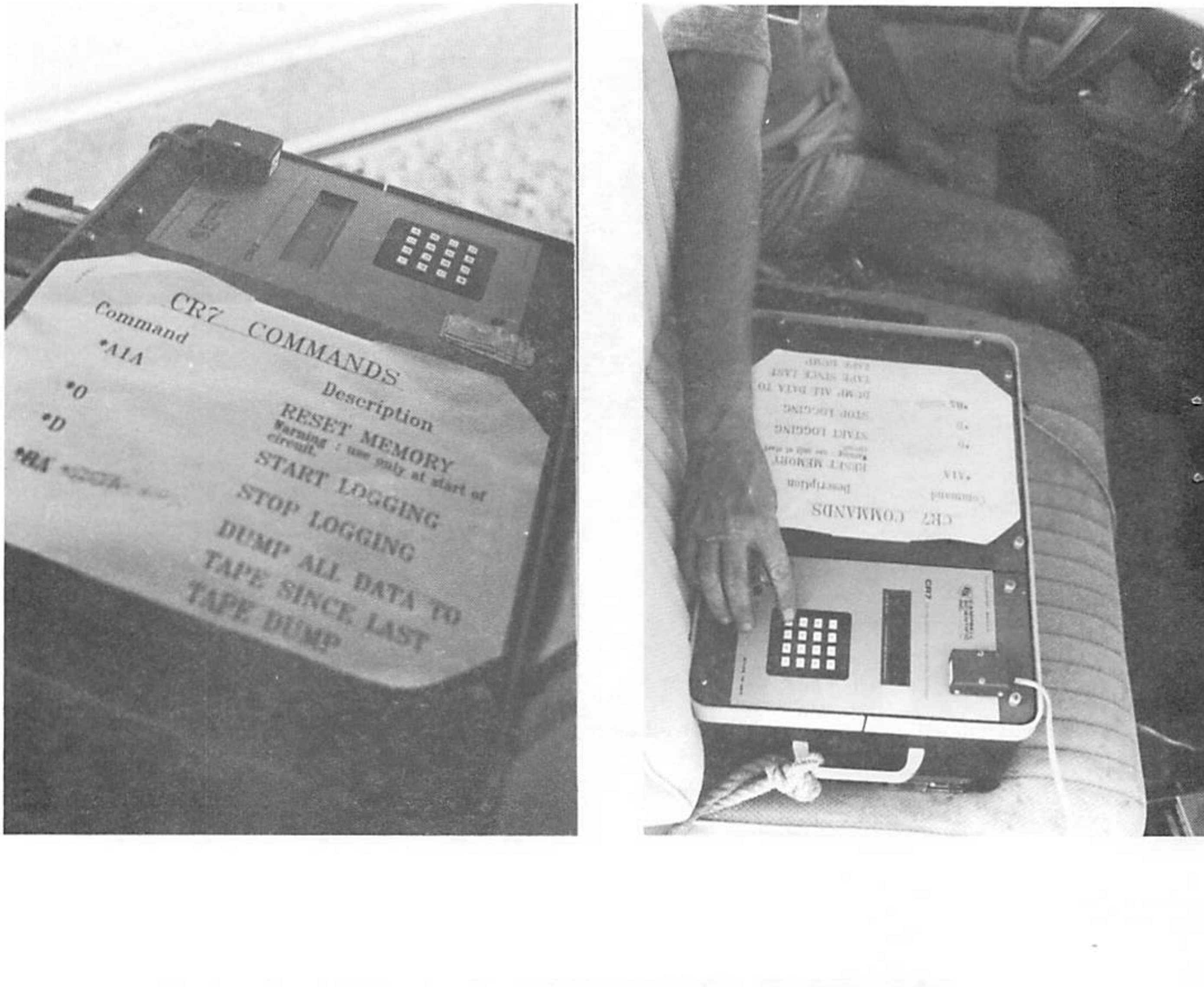


FIGURE 2.8c
Data Logger
Operation

- Maximum Value of the positive data.

- Mean and Standard Deviation of the negative data.

- Minimum Value of the negative date.

In addition, the relationship of these data, indicative of each driver's response, were studied in terms of the tire wear rate during the relevant test circuit. These analyses are described in Section 3 of this report.

3. STATISTICAL ANALYSIS

This chapter contains a discussion of the statistical analyses that were run on the tire treadwear data of Phases I, II and III. The analyses include:

- Descriptive summaries of the estimated tire wear rate data (mils/1000 miles) and the estimated tire weight rate (grams/1000 miles) data obtained from the UTQG regression procedure.
- Analysis of variance to determine the effects of selected factors on the estimated wear rate data (both in terms of mil loss and weight loss in grams).
- Regression analysis to establish relationships between estimated wear rate and ambient conditions and between weight loss rate and ambient conditions.
- Analysis of actual weight loss rate variation as a function of ambient conditions and as a function of extended mileage.
- Comparison of driver effects both as related to acceleration data and as related to tire wear rate.

Unless otherwise indicated, the test data were considered to be statistically significant if the probability level of the hypothesis test did not exceed 0.05 (i.e., $p \leq 0.05$). The results of these analyses are detailed below. All tables and figures labelled with a letter prefix are contained in the corresponding lettered appendices.

3.1 Wear Rates for Individual Tires

The estimated average wear rate (mils/1000 miles), b_{ij}, for the four identical tires (i.e., for $i = 1, 2, 3, 4$) of a given tire brand in each convoy was calculated according to the UTQG regression procedure. This was done for each test run* during the winter phase or Phase I (i.e., $j = 1, 2, 3, 4$), the summer phase or Phase III (i.e., $j = 5, 6, 7, 8$), and for the combined data of Phases I and III (i.e., $j = 1, 2, ..., 8$). Hence, there were 16 measurements for each of the four tire brands in each separate phase (i.e., Phase I or Phase III).

These procedures were repeated in three different ways in order to account for the variation in break-in time for the tires. The three run types are described as follows:

R1 - regression data contained nine average groove depths per tire including those from both break-in periods (800 miles and 1600 miles) and all succeeding periods except the 8,000 miles results.

* The subscript $j=1,2,..,8$ in this chapter is used strictly as a count of the number of tests run in each phase of this study and should not be confused with the actual test numbers described in chapter 2; i.e., tests 1,2,..,9.

R2 - regression data contained ten average groove depths per tire including all runs from 800 miles to 8,000 miles.

R3 - regression data contained nine average groove depths per tire excluding the 800 mile break-in period but including all data from 1600 miles to 8,000 miles.

The estimated wear rates obtained from both Phase I and Phase III for R1, R2, and R3 are given in Table F.1 along with the corresponding estimated weight loss rate (grams/1000 miles) data, weighted ambient temperatures (°F), counts of wet miles (per 400 or 800 miles), and humidity readings (grains/lb. dry air). These are categorized by test (1-4, 6-9), tire brand (1=Uniroyal, 2=Michelin, 3=Goodyear, 4=Bridgestone), and tire number (1-4).

3.1.1 Winter Weather (Phase I)

Table 3.1 contains a summary of the estimated wear rate means, standard deviations and coefficients of variation from Phase I. This is categorized by tire brand, test number, and run type. Overall, the Uniroyal tires had the lowest average wear rates while the Bridgestone tires had the highest average rates; the Michelin tires had the second lowest average rates while the Goodyear tires had the second highest average rates. Variability was greatest among the Michelin tires, with the composite coefficient of variation exceeding 13% for all three run types. The lowest variability was among the Bridgestone and Uniroyal tires, followed closely by the Goodyear tires.

The frequency histograms of each of the 16 estimated wear rate values for each tire brand and run type are contained in Figure F.1. They visually display the patterns seen in Table 3.1. The center of the Uniroyal wear rate distribution is at the low end of the scale while the center of the Bridgestone wear rate distribution is at the high end of the scale. In the middle region between these two are the distributions of the Michelin and Goodyear wear rates.

Each of the above distributions was compared to a normal distribution having a mean and standard deviation similar to the sample means and standard deviations given in the appropriate category in Table 3.1. This was done graphically by plotting the data on a normal probability plot and statistically using a Kolmogorov-Smirnov goodness-of-fit test. The normal probability plots for the three run types are given in Figure F.2. Since the curves in all of the graphs are similar to straight lines, it appears each distribution is a normal one.

This is reinforced by the Kolmogorov-Smirnov test results given in Table 3.2. None of the calculated test statistics are statistically significant indicating that the data support the hypothesis that the distributions are similar to normal distributions with the corresponding sample means and standard deviations given in Table 3.1.

A final comparison was made of the distribution of the wear rates for the Uniroyal tires to those of the other three tire brands. Visually, the histograms indicate that the Uniroyal curve is centered about such a small average wear rate

TABLE 3.1
PHASE I SUMMARY STATISTICS*
Wear Rates** by Tire Brand and Test Run

	TIRE BRAND		TEST 1	TEST 2	TEST 3	TEST 4	COMPOSITE***
			2.04	2.17	2.26	2.28	2.19
1.	UNIROYAL	R1	.064	.076	.074	.091	.077
			3.14	3.50	3.27	3.99	3.51
			2.20	2.25	2.36	2.33	2.29
		R2	.042	.064	.114	.084	.080
			1.91	2.84	4.83	3.60	3.51
			2.25	2.18	2.42	2.30	2.28
		R3	.054	.062	.138	.046	.084
			2.40	2.85	5.71	2.00	3.66
			2.60	2.56	2.71	2.75	2.66
2.	MICHELIN	R1	.336	.494	.340	.391	.395
			12.92	19.18	12.56	14.23	14.87
			2.69	2.60	2.72	2.75	2.69
		R2	.359	.418	.304	.359	.362
			13.36	16.11	11.16	13.08	13.47
			2.61	2.45	2.73	2.75	2.64
		R3	.324	.444	.262	.335	.347
			12.40	18.14	9.59	12.19	13.16
			3.29	3.23	3.57	3.37	3.36
3.	GOODYEAR	R1	.170	.044	.325	.114	.193
			5.17	1.36	9.11	3.38	5.75
			3.35	3.17	3.49	3.36	3.34
		R2	.188	.063	.296	.127	.189
			5.62	1.99	8.49	3.78	5.66
			3.25	2.90	3.31	3.20	3.17
		R3	.189	.089	.239	.077	.163
			5.81	3.07	7.21	2.41	5.15
			5.38	5.48	5.25	5.15	5.31
4.	BRIDGESTONE	R1	.124	.131	.339	.301	.244
			2.30	2.39	6.46	5.85	4.59
			5.35	5.37	5.10	5.02	5.21
		R2	.097	.094	.274	.285	.209
			1.81	1.75	5.37	5.68	4.01
			5.12	5.04	4.83	4.78	4.94
		R3	.101	.111	.211	.241	.177
			1.97	2.20	4.37	5.04	3.58

* 1st entry - mean
2nd entry = standard deviation
3rd entry - coefficient of variation
** mils/1000 miles
*** 1st entry = mean
2nd entry = pooled standard deviation
3rd entry - coefficient of variation

TABLE 3.2
PHASE I KOLMOGOROV-SMIRNOV TEST SUMMARY
Wear Rates* by Tire Brand

TIRE BRAND		Normal Curve Comparison		Uniroyal Curve Comparison	
		K-S Statistic	p-value	K-S Statistic	p-value
1. UNIROYAL	R1	0.522	0.948		
	R2	0.553	0.920		
	R3	0.888	0.408		
2. MICHELIN	R1	0.516	0.953	1.945	0.001
	R2	0.615	0.844	1.945	0.001
	R3	0.670	0.761	1.945	0.001
3. GOODYEAR	R1	0.884	0.415	2.828	0.000
	R2	0.752	0.624	2.828	0.000
	R3	0.455	0.986	2.828	0.000
4. BRIDGESTONE	R1	0.981	0.291	2.828	0.000
	R2	1.009	0.261	2.828	0.000
	R3	0.811	0.526	2.828	0.000

*mils/1000 miles

that it should be different from the Bridgestone and Goodyear curves. Also, since the Michelin curve has such a large standard deviation it, too, should differ from the Uniroyal curve. This is supported in the two-sample Kolmogorov-Smirnov test statistics given in the last column of Table 3.2. In all comparisons, the three tire wear rate curves are significantly different from the Uniroyal distribution curve.

3.1.2 Summer Weather (Phase III)

Contained in Table 3.3 is a summary of the Phase III estimated wear rate means, standard deviations and coefficients of variation. In all cases the averages obtained from the Phase III data were greater than those obtained from the Phase I data. However, the rankings among brands remained the same. Uniroyal tires had the lowest average wear rates and Bridgestone had the highest; the Michelin tires had the second lowest and Goodyear had the second highest. As also was seen in Phase I, the variability in the Phase III data was greatest among the Michelin tires (i.e., composite coefficient of variation exceeds 15%), while the Uniroyal tires had the lowest variability followed by Bridgestone and Goodyear.

The frequency histograms of each tire brand and run type contained in Figure F.3, reflect the relationships seen in Table 3.3. The Uniroyal brand is at the low end of the scale for all run types while Bridgestone is at the high end; Michelin and Goodyear are in the middle region.

As also was done in Phase I, each of the Phase III distributions was compared to a normal distribution having a similar mean and standard deviation to those given in Table 3.3. All the data appear to be normally distributed based on observing the normal probability plots contained in Figure F.4. This assumption is further supported by the Kolmogorov-Smirnov tests results shown in Table 3.4.

When comparing the distribution of each tire brand to the Uniroyal distribution using the two-sample Kolmogorov-Smirnov test (last column of Table 3.4), the results were the same as those found in Phase I. All comparisons were found to be statistically significant which indicates all three of the tire-brand wear rate distributions are different from the Uniroyal distribution.

3.1.3 Winter-Summer Combined (Phase I and Phase III)

To compare the average estimated wear rate data obtained from two different temperature ranges, the winter data obtained from Phase I and the summer data obtained from Phase III were combined to yield 32 values for each tire brand and run type. Table 3.5 shows the overall means, standard deviations, and coefficients of variation for the combined data. As expected, the wear rate rankings among the brands are the same as those obtained for the separate Phase I and Phase III data. However, the distributions are different. The Uniroyal, Goodyear and Bridgestone data distributions appear to have two separate peaks for all three run types; this can be seen in both the histograms and the corresponding normal probability plots given in Figures F.5 and F.6. This shape is not as apparent for the Michelin distribution.

The Kolmogorov-Smirnov test results shown in Table 3.6 also support this observation. The Uniroyal, Goodyear, and Bridgestone brands have significant (p .12) test statistics indicating nonnormality for their wear rate distribution

TABLE 3.3
PHASE III SUMMARY STATISTICS*
Wear Rates** By Tire Brand and Test Run

	TIRE BRAND		TEST 6	TEST 7	TEST 8	TEST 9	COMPOSITE***
1.	UNIROYAL	R1	3.81 .102 2.68	3.73 .131 3.51	3.38 .124 3.67	3.38 .059 1.75	3.58 .108 3.01
		R2	3.76 .104 2.77	3.62 .108 2.98	3.44 .086 2.50	3.32 .078 2.35	3.53 .095 2.69
		R3	3.73 .098 2.63	3.61 .094 2.60	3.39 .109 3.22	3.12 .119 3.81	3.46 .105 3.05
2.	MICHELIN	R1	3.85 .737 19.14	3.77 .872 23.13	4.01 .695 17.33	4.36 .273 6.26	4.00 .682 17.05
		R2	3.77 .694 18.41	3.64 .792 21.76	3.99 .682 17.09	4.27 .253 5.93	3.92 .640 16.32
		R3	3.75 .670 17.87	3.63 .751 20.69	4.02 .605 15.05	4.02 .194 4.83	3.86 .595 15.42
3.	GOODYEAR	R1	5.64 .105 1.86	5.13 .159 3.10	5.19 .102 1.96	4.90 .098 2.00	5.21 .119 2.28
		R2	5.45 .130 2.39	5.00 .132 2.64	5.08 .090 1.77	4.82 .134 2.78	5.09 .123 2.41
		R3	5.26 .188 3.57	4.91 .154 3.14	4.91 .064 1.30	4.67 .155 3.32	4.93 .148 2.99
4.	BRIDGESTONE	R1	8.40 .364 4.33	7.84 .474 6.05	7.47 .342 4.58	7.49 .144 1.92	7.80 .352 4.51
		R2	8.09 .314 3.88	7.60 .432 5.68	7.29 .309 4.24	7.27 .112 1.54	7.56 .314 4.15
		R3	7.83 .264 3.37	7.42 .326 4.39	7.19 .195 2.71	7.06 .127 1.80	7.37 .240 3.25

*1st entry = mean
2nd entry = standard deviation
3rd entry = coefficient of variation
**mils/1000 miles
***1st entry = mean
2nd entry = pooled standard deviation
3rd entry = coefficient of variation

TABLE 3.4
PHASE III KOLMOGOROV-SMIRNOV TEST SUMMARY
Wear Rates* By Tire Brand

TIRE BRAND		Normal Curve Comparison K-S Statistic	Normal Curve Comparison p-Value	Uniroyal Curve Comparison K-S Statistic	Uniroyal Curve Comparison p-Value
1. UNIROYAL	R1	0.607	0.855		
	R2	0.586	0.883		
	R3	0.481	0.975		
2. MICHELIN	R1	0.503	0.962	1.591	0.013
	R2	0.561	0.912	1.591	0.013
	R3	0.599	0.866	1.414	0.037
3. GOODYEAR	R1	0.630	0.823	2.828	0.000
	R2	0.537	0.935	2.828	0.000
	R3	0.401	0.997	2.828	0.000
4. BRIDGESTONE	R1	0.872	0.432	2.828	0.000
	R2	0.862	0.448	2.828	0.000
	R3	0.975	0.297	2.828	0.000

*mils/1000 miles

TABLE 3.5

SUMMARY STATISTICS *
PHASE I AND PHASE III COMBINED

WEAR RATE (MILS/1000 MILES)

TIRE BRAND	R1	R2	R3
1. Uniroyal	2.88 .728 25.27	2.91 .651 22.37	2.87 .630 21.95
2. Michelin	3.33 .855 25.68	3.30 .794 24.06	3.25 .769 23.66
3. Goodyear	4.29 .974 22.70	4.21 .916 21.76	4.05 .928 22.91
4. Bridgestone	6.56 1.321 20.14	6.38 1.246 19.53	6.16 1.271 20.63

* 1st entry = mean
2nd entry = standard deviation
3rd entry = coefficient of variation

TABLE 3.6

KOLMOGOROV-SMIRNOV TEST SUMMARY
Wear Rates* By Tire Brand
Phase I and Phase III Combined

TIRE BRAND		Normal Curve Comparison		Uniroyal Curve Comparison	
		K-S Statistic	p-Value	K-S Statistic	p-Value
1. UNIROYAL	R1	1.389	0.042		
	R2	1.327	0.059		
	R3	1.375	0.046		
2. MICHELIN	R1	0.870	0.435	1.375	0.046
	R2	0.857	0.455	1.375	0.046
	R3	0.714	0.687	1.375	0.046
3. GOODYEAR	R1	1.349	0.052	2.125	0.000
	R2	1.226	0.099	2.125	0.000
	R3	1.200	0.112	2.000	0.001
4. BRIDGESTONE	R1	1.489	0.024	4.000	0.000
	R2	1.500	0.022	4.000	0.000
	R3	1.472	0.026	4.000	0.000

*mils/1000 miles

curves. The test statistics for the Michelin tires, however, were not found to be significant for any of the three run types.

When each of the tire brands were compared to the Uniroyal brand (Table 3.6) all test statistics were found to be significant and indicate that all three distributions differ from that of the Uniroyal brand.

3.2 Relative Wear Rates for Individual Tires

Estimated relative wear rates were calculated for each of the three brands of tires (i.e., Michelin, Goodyear and Bridgestone) using Uniroyal as the course monitoring tires. Initially, the average wear rate, $\bar{c_j}$, of the four Uniroyal tires used in a given test of Phase I (i.e., j = 1, 2, 3, 4) and of Phase III (i.e., j = 5, 6, 7, 8) was determined. The relative wear rate values, $b_{ij}/\bar{c_j}$, then were calculated for the four identical tires (i.e., for i = 1, 2, 3, 4) for each of the three comparison tire brands in each test. This was done separately for each of the three run types. Hence, each separate phase consisted of 16 measurements. These data are given in Table F.2.

3.2.1 Winter Weather (Phase I)

Descriptive statistics calculated for Phase I include the mean, standard deviation, and coefficient of variation of the relative estimated wear rates by test run and run type. The results are contained in the first four columns of Table 3.7. Overall, the Bridgestone tires had the highest average relative wear rates across the test runs while the Michelin tires had the lowest average relative wear rates. Also, the variability was greatest for the Michelin tires while it was lowest for the Bridgestone tires; the Goodyear tires had similar variability to the Bridgestone brand. The coefficients of variation ranged from 9.64% to 19.21% for the Michelin tires, 1.35% to 9.12% for the Goodyear tires, and 1.76% to 5.85% for the Bridgestone tires.

The frequency histograms and normal probability plots (Figures F.7 - F.8) of the 16 relative wear rates for each brand type and run type visually display the patterns seen in Table 3.7. The Michelin relative wear rate distribution is centered at the low end of the scale on the plots while the Bridgestone relative wear rate distribution is centered at the high end of the scale on the plots. In the middle region is the Goodyear distribution.

The fact that the normal probability plots in Figure F.8 indicate that the distributions are normal (the curves are similar to straight lines) is confirmed by the Kolmogorov-Smirnov goodness-of-fit test results given in Table 3.8. All of the calculated test statistics are nonsignificant indicating that the data support the hypothesis that the distributions are similar to normal distributions with sample means and standard deviations corresponding to those given in Table 3.7.

3.2.2 Summer Weather (Phase III)

Contained in Table 3.9 is a summary of the Phase III relative wear rate means, standard deviations and coefficients of variation. Overall, as in Phase I, the Bridgestone tires had the highest average relative wear rates followed by

TABLE 3.7
PHASE I SUMMARY STATISTICS*
Relative Wear Rates** by Tire Brand and Test Run

	TIRE BRAND		TEST 1	TEST 2	TEST 3	TEST 4	COMPOSITE***
			1.00	1.00	1.00	1.00	1.00
1.	UNIROYAL	R1	.031	.035	.033	.04	.035
			3.10	3.50	3.30	4.00	3.49
			1.00	1.00	1.00	1.00	1.00
		R2	.019	.028	.048	.036	.034
			1.90	2.80	4.80	3.60	3.44
			1.00	1.00	1.00	1.00	1.00
		R3	.024	.028	.057	.020	.035
			2.40	2.80	5.70	2.00	3.54
			1.28	1.19	1.20	1.21	1.22
2.	MICHELIN	R1	.165	.228	.150	.171	.181
			12.93	19.21	12.52	14.19	14.83
			1.22	1.15	1.15	1.18	1.18
		R2	.164	.186	.129	.154	.160
			13.40	16.13	11.18	13.10	13.52
			1.16	1.12	1.13	1.20	1.15
		R3	.144	.204	.109	.146	.155
			12.39	18.15	9.64	12.21	13.44
			1.61	1.49	1.58	1.48	1.54
3.	GOODYEAR	R1	.083	.020	.144	.050	.087
			5.14	1.35	9.12	3.38	5.67
			1.52	1.41	1.48	1.44	1.46
		R2	.086	.028	.126	.054	.082
			5.64	1.99	8.53	3.75	5.62
			1.48	1.33	1.37	1.39	1.39
		R3	.084	.041	.099	.033	.070
			5.69	3.08	7.22	2.37	5.04
			2.64	2.53	2.32	2.26	2.44
4.	BRIDGESTONE	R1	.061	.060	.150	.132	.109
			2.31	2.38	6.46	5.85	4.45
			2.44	2.38	2.16	2.15	2.28
		R2	.044	.042	.116	.122	.089
			1.81	1.76	5.37	5.68	3.93
			2.28	2.31	2.00	2.08	2.17
		R3	.045	.051	.087	.105	.076
			1.97	2.20	4.35	5.05	3.51

* 1st entry = mean
2nd entry = standard deviation
3rd entry = coefficient of variation
** relative wear rates (mils/1000 miles)
*** 1st entry = mean
2nd entry = pooled standard deviation
3rd entry = coefficient of variation

TABLE 3.8
PHASE I KOLMOGOROV-SMIRNOV TEST SUMMARY
Relative Wear Rate* by Tire Brand

TIRE BRAND		Normal Curve Comparison	
		K-S Statistic	p-value
2. MICHELIN	R1	0.732	0.658
	R2	0.658	0.779
	R3	0.571	0.901
3. GOODYEAR	R1	0.658	0.779
	R2	0.745	0.636
	R3	0.546	0.926
4. BRIDGESTONE	R1	0.560	0.912
	R2	0.608	0.853
	R3	0.659	0.778

*mils/1000 miles

TABLE 3.9

PHASE III SUMMARY STATISTICS*
Relative Wear Rates** By Tire Brand and Test Run

	TIRE BRAND		TEST 6	TEST 7	TEST 8	TEST 9	COMPOSITE***
1.	UNIROYAL	R1	1.00 .027 2.70	1.00 .035 3.50	1.00 .037 3.70	1.00 .017 1.70	1.00 .030 3.00
		R2	1.00 .028 2.80	1.00 .030 3.00	1.00 .025 2.50	1.00 .023 2.30	1.00 .027 2.70
		R3	1.00 .026 2.60	1.00 .026 2.60	1.00 .032 3.20	1.00 .038 3.80	1.00 .031 3.10
2.	MICHELIN	R1	1.01 .193 19.11	1.01 .234 23.17	1.19 .206 17.31	1.29 .081 6.28	1.12 .188 16.76
		R2	1.00 .185 18.50	1.01 .219 21.68	1.16 .198 17.07	1.29 .076 5.89	1.11 .178 16.06
		R3	1.00 .180 18.00	1.01 .208 20.59	1.19 .178 14.96	1.29 .062 4.81	1.12 .167 14.89
3.	GOODYEAR	R1	1.48 .027 1.82	1.38 .043 3.12	1.54 .030 1.95	1.45 .029 2.00	1.46 .033 2.25
		R2	1.45 .034 2.34	1.38 .036 2.61	1.48 .026 1.76	1.45 .040 2.76	1.44 .034 2.39
		R3	1.41 .050 3.55	1.36 .043 3.16	1.45 .019 1.31	1.50 .050 3.33	1.43 .042 2.97
4.	BRIDGESTONE	R1	2.20 .095 4.32	2.10 .127 6.05	2.21 .101 4.57	2.22 .043 1.94	2.18 .096 4.42
		R2	2.15 .083 3.86	2.10 .119 5.67	2.12 .090 4.25	2.19 .034 1.55	2.14 .087 4.07
		R3	2.10 .071 3.38	2.05 .090 4.39	2.12 .058 2.74	2.26 .041 1.81	2.13 .067 3.17

*1st entry = mean
2nd entry = standard deviation
3rd entry = coefficient of variation
**miles/1000 miles
***1st entry = mean
2nd entry = pooled standard deviation
3rd entry = coefficient of variation

Goodyear and Michelin. The variability was greatest for the Michelin tires and lowest for the Goodyear tires. This contrasts with the results given in Table 3.7 where Bridgestone tires had the lowest variability. In general, all tabled entries within a given brand appear to be consistent across test and run types.

Figure F.9 contains the frequency histograms of each tire brand and run type. As seen in Table 3.9 Michelin is at the low end of the scale, Goodyear is in the middle region, and Bridgestone is at the high end of the scale. The data of all three brands appear to be normally distributed based on the normal probability plots contained in Figure F.10, although the Michelin curve is disjoint and reflects the slight two-peak curve seen in the histogram of Figure F.9. The Kolmogorov-Smirnov test results in Table 3.10 indicate that the data are distributed normally for all tire brands and run types.

3.2.3 Winter-Summer Combined (Phase I and Phase III)

The average relative wear rate data obtained from both Phase I and Phase III were combined as in subsection 3.1.3. Descriptive statistics including the means, standard deviations, and coefficients of variation are contained in Table 3.11. The results are similar to those seen in the separate analyses of the Phase I and Phase III data. The Bridgestone tires had the highest average relative wear rates across the test runs while the Michelin had the lowest average rates. The variability was greatest for Michelin tires while lowest for the Goodyear tires.

The frequency histograms of the 32 values for each brand and run type (Figure F.11) show that the combined relative wear rate distributions do not appear to be as disjoint as the combined distributions of the raw average wear rates. Also, the relationship between brands remains the same with Michelin at the low end of the scale followed by Goodyear and Bridgestone.

Each of these combined distributions were tested for normality using both graphical and statistical procedures. Figure F.12 contains the normal probability plots; all curves indicate that the distributions are normal. The Kolmogorov-Smirnov test results in Table 3.12 also support this result.

3.3 Relative Wear Rates for Identical Tires in a Test Run

The relative estimated wear rates (mils/1000 miles) were averaged across the four identical tires within a given test to form

$$a_j = (b_{ij}/\bar{c}_j)/4 \quad ,$$

where j=1,2,3,4 for Phase I and j=5,6,7,8 for Phase III. This was done for each of the three tire brands (i.e., Michelin, Goodyear and Bridgestone) and for each run type.

3.3.1 Winter Weather (Phase I)

The fifth column (i.e., labelled composite) of Table 3.7 contains a summary of the pooled mean, standard deviation, and coefficient of variation of each set of a_j values from Phase I. The results are similar to those given in subsection 3.2.1. Overall, the Michelin tires had the lowest average relative wear

TABLE 3.10
PHASE III KOLMOGOROV-SMIRNOV TEST SUMMARY
Relative Wear Rates* By Tire Brand

TIRE BRAND		Normal Curve Comparison K-S Statistic	Normal Curve Comparison p-Value
2. MICHELIN	R1	0.913	0.375
	R2	0.987	0.284
	R3	1.110	0.170
3. GOODYEAR	R1	0.506	0.960
	R2	0.738	0.647
	R3	0.604	0.859
4. BRIDGESTONE	R1	0.433	0.992
	R2	0.687	0.733
	R3	0.492	0.969

*mils/1000 miles

TABLE 3.11

SUMMARY STATISTICS *
PHASE I AND PHASE III COMBINED

RELATIVE WEAR RATE (MILS/1000 MILES)

TIRE BRAND	R1	R2	R3
1. Uniroyal	1.00 .029 2.90	1.00 .027 2.70	1.00 .029 2.90
2. Michelin	1.17 .191 16.32	1.15 .175 15.22	1.14 .168 14.74
3. Goodyear	1.50 .092 6.13	1.45 .069 4.76	1.41 .072 5.11
4. Bridgestone	2.31 .196 8.48	2.21 .143 6.47	2.15 .128 5.95

* 1st entry = mean
2nd entry = standard deviation
3rd entry = coefficient of variation

TABLE 3.12

KOLMOGOROV-SMIRNOV TEST SUMMARY
Relative Wear Rate* By Tire Brand
Phase I and Phase III Combined

	TIRE BRAND		Normal Curve Comparison K-S Statistic	Normal Curve Comparison p-Value
2.	MICHELIN	R1	0.778	0.580
		R2	0.697	0.716
		R3	1.053	0.218
3.	GOODYEAR	R1	0.652	0.790
		R2	0.701	0.710
		R3	0.458	0.985
4.	BRIDGESTONE	R1	0.761	0.609
		R2	0.681	0.743
		R3	0.575	0.895

*mils/1000 miles

rates while the Bridgestone tires had the highest average relative wear rates; the Goodyear average wear rate was between these two but closer to the Michelin average. Also, the variability was low but similar for the Goodyear and Bridgestone tires and high for the Michelin tires.

3.3.2 Summer Weather (Phase III)

The fifth column of Table 3.9 contains the summary statistics of Phase III for the relative wear rates. Again, the Michelin tires had the lowest average relative wear rates closely followed by Goodyear. The Bridgestone brand had the highest averages. Variability also was found to be consistent with previous results. The Michelin data had the highest variability, followed by Bridgestone and Goodyear.

3.3.3 Winter-Summer Combined (Phase I and Phase III)

The average relative wear rates of the combined data of Phase I and Phase III are given in Table 3.11 along with the standard deviations and coefficients of variation for all brands and run types. These mean values are consistent with the results seen in Tables 3.7 and 3.9. However, with respect to variability, Goodyear was lower than Bridgestone although both were similar. The variability of the Michelin data remained the highest.

3.4 Weight Loss Rates for Individual Tires

The estimated average weight loss rate (grams/1000 miles), w_{ij}, for the four identical tires (i.e., for i = 1, 2, 3, 4) of a given brand in each convoy was calculated according to the UTQG regression procedure. This was done, as in Section 3.1, for each test run during the winter phase or Phase I (i.e., j = 1, 2, 3, 4), the summer phase or Phase III (i.e., j = 5, 6, 7, 8), and for the combined data of Phases I and III (i.e., j = 1, 2, ..., 8). Hence, for every estimated wear rate (b_{ij}) of Section 3.1 a corresponding estimated weight loss rate (w_{ij}) was calculated. These procedures were repeated three different ways to account for the variation in break-in time (i.e., R1, R2, R3 from Section 3.1). Likewise, the descriptive summaries, frequency histograms, normal probability plots, and Kolmogorov-Smirnov goodness-of-fit tests were repeated for each of Phase I, Phase III, and Phases I and III combined. The details are presented and discussed below.

3.4.1 Winter Weather (Phase I)

Table 3.13 contains a summary of the estimated weight loss rate means, standard deviations and coefficients of variation of Phase I. This is categorized by tire brand, test number and run type. Overall, the Uniroyal tires had the lowest average weight loss rates while the Bridgestone tires had the highest average rates; the Goodyear tires had the second lowest average rates while the Michelin tires had the second highest average rates. Variability was smallest for the Uniroyal tires and very similar for the Michelin, Goodyear, and Bridgestone brand tires (see Figure F.13 for the frequency histograms).

The conclusions on the variability of the weight loss rate data vary somewhat from those obtained by analyzing the average wear rate results given in Table 3.1. Hence, the coefficients of variation for these two measurement

TABLE 3.13
PHASE I SUMMARY STATISTICS*
Weight Loss** by Tire Brand and Test Run

	TIRE BRAND		TEST 1	TEST 2	TEST 3	TEST 4	COMPOSITE***
1.	UNIROYAL	R1	18.23 .250 1.37	17.93 .222 1.24	17.48 .150 .86	17.23 .465 2.70	17.71 .296 1.67
		R2	18.08 .299 1.65	17.93 .206 1.15	17.30 .141 .81	16.98 .450 2.65	17.57 .298 1.69
		R3	17.98 .340 1.89	17.75 .252 1.42	17.08 .126 .74	16.43 .150 .91	17.31 .233 1.35
2.	MICHELIN	R1	19.13 .978 5.11	18.83 .519 2.76	19.37 .808 4.17	19.93 .665 3.34	19.31 .757 3.92
		R2	19.05 .954 5.01	18.63 .532 2.85	19.20 .781 4.07	19.65 .532 2.71	19.13 .717 3.75
		R3	18.88 .873 4.62	18.50 .503 2.72	18.80 .781 4.15	19.23 .457 2.38	18.85 .667 3.54
3.	GOODYEAR	R1	19.30 .535 2.77	18.68 .435 2.33	19.03 .932 4.90	18.60 .510 2.74	18.90 .633 3.35
		R2	19.23 .506 2.63	18.45 .507 2.75	18.80 .879 4.67	18.43 .492 2.67	18.73 .647 3.45
		R3	19.25 .592 3.07	18.00 .523 2.90	18.23 .750 4.11	18.00 .432 2.40	18.37 .586 3.19
4.	BRIDGESTONE	R1	22.08 .574 2.60	23.18 .395 1.70	20.55 .911 4.43	20.30 1.236 6.09	21.53 .843 3.92
		R2	22.15 .619 2.79	22.83 .350 1.53	20.43 .834 4.08	20.13 1.024 5.09	21.38 .750 3.51
		R3	22.08 .665 3.01	22.40 .356 1.59	20.20 .898 4.44	19.90 1.042 5.24	21.14 .784 3.71

* 1st entry = mean
2nd entry = standard deviation
3rd entry = coefficient of variation
** gram/1000 miles
*** 1st entry = mean
2nd entry = pooled standard deviation
3rd entry = coefficient of variation

techniques were compared to determine which was smallest. The treadwear variability using the estimated weight loss rate was smaller than that obtained using the estimated wear rate for the Uniroyal, Michelin and Goodyear tires. For the Bridgestone brand, mixed results were obtained; however, the noted differences were small for the two treadwear methods.

Both the normal probability plots (Figure F.14) and the Kolmogorov-Smirnov tests results (Table 3.14) indicate that the distributions of wear rates for all tire brands are similar to normal distributions with the corresponding means and standard deviations given in Table 3.13. Also, the two-sample Kolmogorov-Smirnov test results in the last column of Table 3.14, reveal that each of the Michelin, Goodyear, and Bridgestone distributions differ significantly from the Uniroyal distribution.

3.4.2 Summer Weather (Phase III)

Table 3.15 contains the descriptive statistics for the estimated weight loss rates obtained from Phase III. The average weight loss rates were lowest for the Uniroyal tires followed closely by the Michelin and Goodyear tires. This relationship among brands is the same as that seen for the estimated average wear rate data of Phase III discussed in subsection 3.1.2. The frequency histograms in Figure F.15 visually display this pattern.

The variability was least for the Uniroyal brand followed by Goodyear and Bridgestone; Michelin had the greatest variability. As was the case in the Phase I data, the comparisons of the coefficients of variation showed the variability of the estimated weight loss rates to be less, in general, than those obtained using the mil loss measuring technique.

The data for all brands and run types appear to be normally distributed based on the probability plots (Figure F.16) and Kolmogorov-Smirnov test results (Table 3.16). The two-sample Kolmogorov-Smirnov tests for comparing the Uniroyal brand with each of the other three brands indicate no difference between Uniroyal and the Michelin and Goodyear distributions. However, the Uniroyal and Bridgestone curves were found to be significantly different from each other.

3.4.3 Winter-Summer Combined (Phase I and Phase III)

Table 3.17 contains the descriptive statistics of the combined estimated weight loss rate data from Phases I and III. As expected, the rankings for all brands are similar to those obtained in the analysis of each individual phase. However, the combined frequency histograms (Figure F.17) show clear separations in the distributions of all three run types for all four brands. This result is similar to that obtained in Section 3.1.3 for the combined estimated wear rates. Variability was greatest for the Bridgestone tires followed by Uniroyal, Goodyear and Michelin, although, in general, the variability was similar in size for all the brands. The coefficients of variation were smaller in all cases than those obtained for the estimated wear rates.

The normal probability plots (Figure F.18) and the Kolmogorov-Smirnov test results (Table 3.18) show that the Uniroyal and Goodyear distributions and the R2 Michelin distribution differ significantly ($p<.15$) from a normal distribution with

TABLE 3.14

PHASE I KOLMOGOROV-SMIRNOV TEST SUMMARY
Weight Loss Rates* by Tire Brand

Tire Brand		Normal Curve Comparison		Uniroyal Curve Comparison	
		K-S Statistic	p-value	K-S Statistic	p-value
1. Uniroyal	R1	0.529	0.943		
	R2	0.407	0.996		
	R3	0.590	0.877		
2. Michelin	R1	0.626	0.828	2.423	0.000
	R2	0.531	0.941	2.249	0.000
	R3	0.864	0.444	2.249	0.000
3. Goodyear	R1	0.507	0.959	2.121	0.000
	R2	0.444	0.989	2.121	0.000
	R3	0.434	0.992	1.591	0.013
5. Bridgestone	R1	0.722	0.675	2.828	0.000
	R2	0.678	0.747	2.828	0.000
	R3	0.549	0.924	2.828	0.000

* gms/1000 miles

TABLE 3.15

PHASE III SUMMARY STATISTICS*
Weight Loss** By Tire Brand and Test Run

	TIRE BRAND		TEST 6	TEST 7	TEST 8	TEST 9	COMPOSITE***
1.	UNIROYAL	R1	25.08 .574 2.29	24.33 .222 0.91	23.18 .096 0.41	22.10 .374 1.69	23.67 .363 1.53
		R2	24.73 .479 1.94	23.88 .189 0.79	22.93 .096 0.42	21.93 .287 1.31	23.36 .299 1.28
		R3	24.55 .500 2.04	23.40 .163 0.70	22.55 .129 0.57	21.63 .250 1.16	23.03 .298 1.29
2.	MICHELIN	R1	23.98 1.991 8.30	23.93 2.854 11.93	23.53 1.974 8.39	24.25 .173 0.71	23.92 2.002 8.37
		R2	23.85 1.996 8.37	23.68 2.608 11.01	23.25 2.004 8.62	24.05 .208 0.86	23.71 1.926 8.13
		R3	23.60 2.017 8.55	23.25 2.409 10.36	22.98 2.014 8.76	23.70 .245 1.03	23.38 1.870 8.00
3.	GOODYEAR	R1	26.25 .332 1.26	25.08 .727 2.90	24.38 .525 2.15	23.35 .835 3.58	24.76 .635 2.56
		R2	25.80 .283 1.10	24.65 .695 2.82	24.00 .548 2.28	23.23 .789 3.40	24.42 .609 2.50
		R3	25.30 .216 0.85	24.15 .681 2.82	23.45 .500 2.13	22.93 .780 3.40	23.96 .585 2.44
4.	BRIDGESTONE	R1	32.30 1.042 3.23	30.60 1.299 4.25	28.80 .589 2.05	26.73 .655 2.45	29.61 .942 3.18
		R2	31.95 1.025 3.21	30.23 1.276 4.22	28.68 .699 2.44	26.60 .668 2.51	29.36 .950 3.24
		R3	31.38 1.014 3.23	29.78 1.184 3.98	28.25 .532 1.88	26.33 .718 2.73	28.93 .898 3.11

*1st entry = mean
2nd entry = standard deviation
3rd entry = coefficient of variation
**grams/1000 miles
***1st entry = mean
2nd entry = pooled standard deviation
3rd entry = coefficient of variation

TABLE 3.16

PHASE III KOLMOGOROV-SMIRNOV TEST SUMMARY
Weight Loss Rates* by Tire Brand

Tire Brand		Normal Curve Comparison		Uniroyal Curve Comparison	
		K-S Statistic	p-value	K-S Statistic	p-value
1. Uniroyal	R1	0.657	0.781		
	R2	0.511	0.956		
	R3	0.455	0.986		
2. Michelin	R1	0.970	0.303	0.884	0.415
	R2	0.995	0.276	0.884	0.415
	R3	1.018	0.251	0.884	0.415
3. Goodyear	R1	0.452	0.987	1.061	0.211
	R2	0.450	0.987	1.237	0.094
	R3	0.442	0.990	1.237	0.094
4. Bridgestone	R1	0.435	0.992	2.828	0.000
	R2	0.420	0.995	2.828	0.000
	R3	0.447	0.988	2.828	0.000

* gms/1000 miles

TABLE 3.17

SUMMARY STATISTICS *
PHASE I AND PHASE III COMBINED

WEIGHT LOSS (GRAMS/1000 MILES)

TIRE BRAND	R1	R2	R3
1. Uniroyal	20.69 3.159 15.27	20.47 3.066 14.98	20.17 3.050 15.12
2. Michelin	21.69 2.725 12.56	21.49 2.684 12.49	21.19 2.633 12.43
3. Goodyear	21.83 3.130 14.34	21.57 3.028 14.04	21.16 2.978 14.07
4. Bridgestone	25.57 4.516 17.66	25.37 4.436 17.49	25.04 4.316 17.24

* 1st entry = mean
2nd entry = standard deviation
3rd entry = coefficient of variation

TABLE 3.18

KOLMOGOROV-SMIRNOV TEST SUMMARY
Weight Loss Rates* By Tire Brand
Phase I and Phase III Combined

TIRE BRAND		Normal Curve Comparison		Uniroyal Curve Comparison	
		K-S Statistic	p-Value	K-S Statistic	p-Value
1. UNIROYAL	R1	1.447	0.030		
	R2	1.414	0.037		
	R3	1.290	0.072		
2. MICHELIN	R1	1.038	0.232	1.750	0.004
	R2	1.149	0.143	1.608	0.011
	R3	1.086	0.189	1.608	0.011
3. GOODYEAR	R1	1.248	0.089	1.500	0.022
	R2	1.247	0.089	1.500	0.022
	R3	1.150	0.142	1.125	0.159
4. BRIDGESTONE	R1	0.998	0.272	2.000	0.001
	R2	1.061	0.211	2.000	0.001
	R3	1.027	0.242	2.000	0.001

* grams/1000 miles

similar means and standard deviations as those given in Table 3.17. Nonsignificant results were obtained for the Michelin rate data in run types R1 and R3 and all three run types of the Bridgestone tires.

Distributions of the weight loss rate data for all brands were compared to that of the Uniroyal brand using the two-sample Kolmogorov-Smirnov test. The results, found in the last column of Table 3.18, indicate that the three distributions differ significantly from the Uniroyal distribution except for run type R3 of the Goodyear brand.

3.5 Relative Weight Loss Rates for Individual Tires

Estimated relative weight loss rates were calculated for each of the tire brands (i.e., Michelin, Goodyear and Bridgestone) using the Uniroyal tires as the course monitoring tire. This was done using the same procedure as discussed in Section 3.2 by replacing each b_{ij} with its corresponding w_{ij}. Likewise, the descriptive summaries, frequency histograms, normal probability plots, and Kolmogorov-Smirnov tests were repeated for the data of Phase I, Phase II and the combined Phase I and III. The details of these analyses are presented and discussed below.

3.5.1 Winter Weather (Phase I)

The descriptive statistics for the Phase I estimated relative weight loss rates are contained in Table 3.19. Overall, the Bridgestone tires had the highest average relative weight loss rates across the test runs while the Michelin and Goodyear tires had lower but similar rates. Variability was highest for the Michelin tires and lowest for the Goodyear tires; however, the variability for all brands was similar.

The coefficients of variation in Table 3.19 were compared to those of Table 3.7 to determine which unit of measurement had the smallest relative variability. The treadwear variability using relative weight loss rate generally was smaller than that obtained using relative wear rate. On a test comparison basis six of the twelve test-by-run type combinations of the Bridgestone tire showed higher coefficients of variation in Table 3.19 relative to Table 3.7 versus only 2 of 12 for the Goodyear tires and 1 of 12 for the Michelin tires. Hence, relative weight loss rate appears to be a less variable measure than relative wear rate.

The frequency histograms of the 16 relative weight loss rates for each brand type and run type are given in Figure F.19. They visually display the patterns seen in Table 3.19. The Bridgestone distributions are centered at the high end of the scale in the plots while the Michelin and Goodyear are centered at the low end of the scale.

Each of the above distributions was compared to a normal distribution having a mean and standard deviation similar to the sample values given in Table 3.19. This was done graphically by plotting the data on a normal probability plot and statistically using a Kolmogorov-Smirnov goodness-of-fit. The normal probability plots are given in Figure F.20. In all of the plots the curves are similar to straight lines indicating that the distributions are normal.

TABLE 3.19
PHASE I SUMMARY STATISTICS*
Relative Weight Loss** by Tire Brand and Test Run

	TIRE BRAND		TEST 1	TEST 2	TEST 3	TEST 4	COMPOSITE***
			1.00	1.00	1.00	1.00	1.00
1.	UNIROYAL	R1	.014	.012	.009	.027	.017
			1.40	1.20	.90	2.70	1.70
			1.00	1.00	1.00	1.00	1.00
		R2	.017	.012	.008	.027	.017
			1.70	1.20	.80	2.70	1.70
			1.00	1.00	1.00	1.00	1.00
		R3	.019	.014	.007	.009	.013
			1.90	1.40	.70	.90	1.31
			1.05	1.05	1.11	1.16	1.09
2.	MICHELIN	R1	.034	.020	.147	.060	.073
			3.14	1.90	13.24	5.17	6.70
			1.05	1.04	1.11	1.16	1.09
		R2	.053	.030	.045	.031	.097
			5.05	2.88	4.05	2.67	8.92
			1.05	1.04	1.10	1.17	1.09
		R3	.049	.028	.046	.028	.038
			4.67	2.69	4.18	2.39	3.51
			1.06	1.04	1.09	1.08	1.07
3.	GOODYEAR	R1	.028	.028	.051	.029	.035
			2.64	2.69	4.68	2.68	3.31
			1.06	1.03	1.09	1.09	1.07
		R2	.028	.028	.051	.029	.035
			2.64	2.72	4.68	2.66	3.31
			1.07	1.01	1.07	1.10	1.06
		R3	.033	.029	.044	.026	.034
			3.08	2.87	4.11	2.36	3.18
			1.21	1.29	1.18	1.18	1.22
4.	BRIDGESTONE	R1	.031	.022	.052	.072	.048
			2.56	1.70	4.41	6.10	3.96
			1.22	1.27	1.18	1.19	1.22
		R2	.034	.020	.048	.060	.043
			2.79	1.57	4.07	5.04	3.54
			1.23	1.26	1.18	1.212	1.22
		R3	.037	.020	.053	.063	.046
			3.01	1.59	4.49	5.20	3.79

* 1st entry = mean
2nd entry = standard deviation
3rd entry = coefficient of variation
** grams/1000 miles
*** 1st entry = mean
2nd entry = pooled standard deviation
3rd entry = coefficient of variation

This is confirmed by the Kolmogorov-Smirnov test results given in Table 3.20. All of the calculated test statistics are nonsignificant indicating that the data support the hypothesis that the distributions are similar to normal distributions with the corresponding sample means and standard deviations.

3.5.2 Summer Weather (Phase III)

Table 3.21 contains the summary statistics for the estimated relative weight loss rates obtained during the summer phase (i.e., Phase III). Overall, Michelin had the lowest average rates followed closely by Goodyear and Bridgestone. This ranking is similar to the ranking seen for the relative wear rate in subsection 3.2.2. The frequency histograms in Figure F.21 visually display this pattern.

With respect to variability, Michelin tires were highest followed by Bridgestone; the variability was lowest for the Goodyear brand. Also, the coefficients of variation were lower than those based on mil loss. This parallels the results of subsection 3.2.2.

The data for all tire brands and run types follow a normal distribution. This result is based on the normal probability plots (Figure F.22) and Kolmogorov-Smirnov test results (Table 3.22). The plotted curves are similar to straight lines and the Kolmogorov-Smirnov test statistics were found to be nonsignificant in all cases.

3.5.3 Winter-Summer Combined (Phase I and Phase III)

Table 3.23 contains the descriptive statistics for the combined relative weight loss rates of Phase I and Phase III. Michelin had the lowest average followed by Goodyear and Bridgestone. Also, variability was highest for the Michelin brand followed by Bridgestone and Goodyear (see Figure F.23 for frequency histograms). The coefficients of variation, when compared to those obtained by using the mil loss measuring technique, were lower for every brand and run type. The normal probability plots (Figure F.24) and the Kolmogorov-Smirnov test results (Table 3.24) indicate that all tire brand distributions follow a normal distribution, at the .05 significance level.

3.6 Analysis of Estimated Wear Rates

Multiple regression analyses were performed on the estimated wear rate data (both in mils/1000 miles and grams/1000 miles) obtained from Phase I, Phase III, and the combined Phase I and III. These analyses were used to determine the effects of ambient conditions and convoy variability on tire treadwear. The estimated wear rates (b_{ij}), relative wear rates ($b_{ij}/\bar{c}_j$), estimated weight loss rates (w_{ij}), and the relative weight loss rates ($w_{ij}/\bar{d}_j$ where $\bar{d}_j$ refers to the average weight rate of the corresponding four control tires) for each run type (i.e., R1, R2, and R3) were used as the response variables. These analyses were performed on each brand separately; thus, there were a total of forty-eight regressions (12 for each brand) for each phase (both separate and combined).

TABLE 3.20
PHASE I KOLMOGOROV-SMIRNOV TEST SUMMARY
Relative Weight Loss* by Tire Brand

TIRE BRAND			Normal Curve Comparison	
			K-S Statistic	p-value
		R1	0.534	0.938
2.	MICHELIN	R2	0.613	0.847
		R3	0.587	0.881
		R1	0.690	0.728
3.	GOODYEAR	R2	0.607	0.855
		R3	0.732	0.657
		R1	0.556	0.916
4.	BRIDGESTONE	R2	0.488	0.971
		R3	0.476	0.977

*grams/1000 miles

TABLE 3.21

PHASE III SUMMARY STATISTICS*
Relative Weight Loss** By Tire Brand and Test Run

	TIRE BRAND		TEST 6	TEST 7	TEST 8	TEST 9	COMPOSITE***
			1.00	1.00	1.00	1.00	1.00
1.	UNIROYAL	R1	.023	.009	.004	.017	.015
			2.30	0.90	0.40	1.70	1.50
			1.00	1.00	1.00	1.00	1.00
		R2	.019	.008	.004	.013	.012
			1.90	0.80	0.40	1.30	1.20
			1.00	1.00	1.00	1.00	1.00
		R3	.020	.007	.006	.012	.013
			2.00	0.70	0.60	1.20	1.30
			0.96	0.98	1.02	1.10	1.01
2.	MICHELIN	R1	.079	.117	.085	.008	.082
			8.23	11.94	8.33	0.73	8.12
			0.97	0.99	1.01	1.10	1.02
		R2	.081	.109	.087	.009	.081
			8.35	11.01	8.61	0.82	7.94
			0.96	0.99	1.02	1.10	1.02
		R3	.082	.103	.089	.011	.080
			8.54	10.40	8.73	1.00	7.84
			1.05	1.03	1.05	1.06	1.05
3.	GOODYEAR	R1	.013	.030	.023	.038	.028
			1.24	2.91	2.19	3.58	2.67
			1.04	1.03	1.05	1.06	1.05
		R2	.011	.029	.024	.036	.027
			1.06	2.82	2.29	3.40	2.57
			1.03	1.03	1.04	1.06	1.04
		R3	.009	.029	.022	.036	.026
			0.87	2.82	2.12	3.40	2.50
			1.29	1.26	1.24	1.21	1.25
4.	BRIDGESTONE	R1	.042	.053	.025	.030	.039
			3.26	4.21	2.02	2.48	3.12
			1.29	1.27	1.25	1.21	1.27
		R2	.041	.053	.031	.030	.040
			3.18	4.17	2.48	2.48	3.15
			1.28	1.27	1.25	1.22	1.26
		R3	.041	.051	.024	.033	.039
			3.20	4.02	1.92	2.70	3.10

*1st entry = mean
2nd entry = standard deviation
3rd entry = coefficient of variation
**grams/1000 miles
***1st entry = mean
2nd entry = pooled standard deviation
3rd entry = coefficient of variation

TABLE 3.22
PHASE III KOLMOGOROV-SMIRNOV TEST SUMMARY
Relative Weight Loss* By Tire Brand

TIRE BRAND		Normal Curve Comparison	
		K-S Statistic	p-Value
2. MICHELIN	R1	0.645	0.800
	R2	0.614	0.845
	R3	0.622	0.834
3. GOODYEAR	R1	0.700	0.711
	R2	0.722	0.674
	R3	0.531	0.941
4. BRIDGESTONE	R1	0.630	0.822
	R2	0.572	0.899
	R3	0.582	0.887

*grams/1000 miles

TABLE 3.23

SUMMARY STATISTICS *
PHASE I AND PHASE III COMBINED

RELATIVE WEIGHT LOSS (GRAMS/1000 MILES)

TIRE BRAND	R1	R2	R3
1. Uniroyal	1.00 .014 1.40	1.00 .013 1.30	1.01 .025 2.50
2. Michelin	1.05 .087 8.29	1.05 .084 8.00	1.06 .101 9.53
3. Goodyear	1.06 .034 3.21	1.06 .035 3.30	1.06 .052 4.91
4. Bridgestone	1.23 .058 4.72	1.24 .054 4.35	1.25 .051 4.08

* 1st entry = mean
2nd entry = standard deviation
3rd entry = coefficient of variation

TABLE 3.24

KOLMOGOROV-SMIRNOV TEST SUMMARY
Relative Weight Loss Rates* By Tire Brand
Phase I and Phase III Combined

	TIRE BRAND		Normal Curve Comparison K-S Statistic	p-Value
2.	MICHELIN	R1	0.863	0.445
		R2	0.889	0.407
		R3	0.613	0.846
3.	GOODYEAR	R1	1.046	0.224
		R2	1.150	0.142
		R3	1.269	0.080
4.	BRIDGESTONE	R1	0.713	0.689
		R2	0.545	0.928
		R3	0.883	0.416

* grams/1000 Miles

For each response variable the following were used as the predictor variables:

- o Average weighted ambient temperature (^{o}F)
- o Average absolute humidity (grains/lb. dry air)
- o Total number of wet miles
- o Convoy indicator for either tests 1-4 or tests 6-9

The convoy variables consisted of three categorical variables (coded 0 or 1) indicating the presence or absence of a particular group of cars and/or drivers for each test.

When the Phase I and Phase III data were analyzed separately, the regression coefficients could not be estimated. This was a result of the fact that there were high correlations between linear combinations of the convoy variables and each of the other predictor variables and between temperature and wet miles. This collinearity was so extreme that only single-variable models could be constructed; hence, the analysis was limited to that conducted for the combined data of Phases I and III.

Table 3.25 contains the correlation matrices for each run type and phase. For all three run types of both Phase I and III, temperature is highly correlated with wet miles with correlation coefficients ranging from -0.988 to 0.999. The relationship between temperature and humidity is not nearly as strong with correlation coefficients ranging from a low of 0.046 for run type R3 of the Phase III data to a high of 0.546 for run type R1, also of Phase III. This low correlation for R3 is probably due to the small sample size (i.e., n=4), since slight fluctuations in the data produce large differences in the correlation coefficients.

In order to remove the collinearities present in each individual data set, the convoy variables were merged for the combined data of Phases I and III in the following manner:

- o Convoy 1 - Test 1 (Phase I) with Test 6 (Phase III)
- o Convoy 2 - Test 2 (Phase I) with Test 7 (Phase III)
- o Convoy 3 - Test 3 (Phase I) with Test 8 (Phase III)
- o Convoy 4 - Test 4 (Phase I) with Test 9 (Phase III)

These groups or convoys were chosen so that each one contained the same vehicles and the same drivers except for those changes noted in Table 2.1. Thus, the only differences within a given convoy were due to the ambient conditions resulting from either summer or winter driving. To account for these effects, the remaining predictor variables included temperature (^{o}F), humidity (grains/lb. dry air), and wet miles.

Table 3.25

CORRELATION COEFFICIENTS
BY PHASE

		TEMP			WET MILES			HUMIDITY			
		R1	R2	R3	R1	R2	R3	R1	R2	R3	
TEMP	R1	1.000			-0.988			-0.423			
	R2		1.000			-0.990			0.495		
	R3			1.000			-0.999			0.182	
WET MILES	R1	-0.988			1.000			0.515			
	R2		-0.990			1.000			-0.441		PHASE I
	R3			-0.999			1.000			-0.195	
HUMIDITY	R1	-0.423			0.515			1.000			
	R2		0.495			-0.441			1.000		
	R3			0.182			-0.195			1.000	
TEMP	R1	1.000			0.991			0.546			
	R2		1.000			0.994			0.499		
	R3			1.000			0.999			0.046	
WET	R1	.0991			1.000			0.611			
	R2		.0994			1.000			.0572		PHASE III
	R3			0.999			1.000			0.100	
HUMIDITY	R1	0.546			0.611			1.000			
	R2		0.499			0.572			1.000		
	R3			0.046			0.100			1.000	

A summary of the results, for all brands and run types, is displayed in Table 3.26 and discussed in the following subsections. Stars (*) are used to indicate the effects that are significant at the .05 level. Appendix G** contains the actual test results for each response variable, a detailed list of the estimated regression coefficients, and plots of the residuals versus the predicted values.

Additional regression analyses were performed for run type R3 by adding into the above models an interaction term for temperature with wet miles. These analyses were made for the purpose of comparing the results with those obtained from the actual weight loss rate analysis (for the special case of the R3 runs) of subsection 3.7.2. These new analyses were made using as response variables the estimated wear rates and estimated weight loss rates of the Uniroyal tires and the estimated relative wear rates and estimated relative weight loss rates for each of the other three tire brands. Because of the high correlation between temperature and wet miles (i.e., see Table 3.25) the inclusion of this interaction term in the regression model yielded drastic changes in the coefficients. For this reason, the analyses are not included in this discussion.

3.6.1 Wear Rates (Mils/1000 Miles)

The regression results using estimated wear rate as the response variable indicate that temperature, wet miles, and the convoy variables are significant for all run types and tire brands except run R3 of the Goodyear tires and all run types of the Michelin tires. Humidity was nonsignificant in all cases. The nonsignificant Michelin results were probably due to the large variation in the data for this tire brand (see Section 3.1 above). In general, the R^2 values exceeded 0.95 for the Uniroyal, Goodyear and Bridgestone tires and exceeded 0.65 for the Michelin tires.

3.6.2 Relative Wear Rates

The results obtained from the regressions using the estimated relative wear rates (i.e., relative to the Uniroyal tires) as the response variable were inconclusive in general. As indicated in Table 3.26, the R^2 values were low ($R^2 < 0.35$) for the Michelin tires and moderate ($R^2 < 0.62$) for the Goodyear and ($R^2 < .83$) for the Bridgestone tires.

3.6.3 Weight Loss Rate (Grams/1000 Miles)

When the estimated weight loss rate was used as the response variable in the regression analyses, the results were somewhat similar to those obtained using the estimated wear rate. None of the predictor variables were found to have

** The estimated regression coefficients in Appendix G have been calculated using a generalized inverse to solve the normal equations. This results from the fact that the four convoy effects (i.e., convoy 1-4) have been represented using only three categorical variables (coded 0 or 1). Because there is no unique way to accomplish this, the coefficients related to these variables are labelled B in the tables and designated as biased estimates of the true coefficients. This designation merely indicates that the convoy coefficients that are nonzero must be interpreted relative to the convoy effect that has the zero coefficient. Hence, the scale is relative and depends on which convoy has no defining variable in the equation.

TABLE 3.26

REGRESSION SUMMARY PHASE I & III COMBINED
BY TIRE BRAND AND RUN TYPE

		TIRE BRAND		TEMP	HUMID	WET MILES	CONVOY	R^2	STD. ERROR	C.V.**
Estimated Wear Rate (mils per 1000 miles)	1.	UNIROYAL	R1	*		*	*	.985	.099	3.44
			R2	*		*	*	.985	.088	3.03
			R3	*		*	*	.982	.095	3.01
	2.	MICHELIN	R1					.666	.550	16.54
			R2					.665	.512	15.50
			R3					.689	.478	14.72
	3.	GOODYEAR	R1	*		*	*	.977	.164	3.82
			R2	*		*	*	.976	.158	3.75
			R3			*	*	.978	.153	3.78
	4.	BRIDGESTONE	R1	*		*	*	.954	.315	4.80
			R2	*		*	*	.962	.271	4.24
			R3	*		*	*	.979	.207	3.35
Estimated Relative Wear Rate	1.	UNIROYAL	R1	-	-	-	-	-		-
			R2	-	-	-	-	-		-
			R3	-	-	-	-	-		-
	2.	MICHELIN	R1					.279	.181	15.44
			R2			*		.339	.167	14.45
			R3					.293	.158	13.85
	3.	GOODYEAR	R1				*	.602	.065	4.32
			R2	*	*	*	*	.618	.064	4.38
			R3			*	*	.499	.057	4.04
	4.	BRIDGESTONE	R1			*		.785	.101	4.36
			R2	*	*	*	*	.826	.087	3.92
			R3			*	*	.752	.071	3.31
Estimated Weight Loss Rate (gms per 1000 miles)	1.	UNIROYAL	R1	*		*	*	.991	.326	1.58
			R2	*		*	*	.993	.292	1.43
			R3	*	*	*	*	.994	.263	1.30
	2.	MICHELIN	R1					.750	1.496	6.91
			R2					.767	1.450	6.74
			R3					.774	1.399	6.60
	3.	GOODYEAR	R1			*	*	.968	.622	2.85
			R2			*	*	.968	.602	2.79
			R3			*	*	.970	.574	2.71
	4.	BRIDGESTONE	R1	*	*	*	*	.970	.876	3.43
			R2	*	*	*	*	.971	.840	3.31
			R3	*		*	*	.969	.852	3.40
Estimated Relative Weight Loss Rate	1.	UNIROYAL	R1	-	-	-	-	-		-
			R2	-	-	-	-	-		-
			R3	-	-	-	-	-		-
	2.	MICHELIN	R1					.556	.065	6.20
			R2					.541	.063	6.04
			R3					.570	.062	5.89
	3.	GOODYEAR	R1					.292	.031	2.98
			R2					.365	.031	2.91
			R3					.470	.030	2.84
	4.	BRIDGESTONE	R1	*	*			.555	.043	3.50
			R2	*				.530	.041	3.32
			R3					.378	.043	3.49

* Indicates $p \leq 0.05$

\- Does not apply

** Coefficient of variation

a significant effect on the Michelin tires; wet miles and the convoy effect were significant for all run types of the three remaining brands; and temperature was significant for both the Uniroyal and Bridgestone brands. Humidity was found to be significant in two of the three run types of the Bridgestone tires and for R3 of the Uniroyal tires. The R^2 values for the regressions were higher and the coefficients of variation were lower in most cases as compared to those obtained using the estimated wear rate (see Table 3.26).

3.6.4 Relative Weight Loss Rate

The results obtained from the regressions using the estimated relative weight loss rate as the response variable show temperature and humidity as having a significant effect for different run types of the Bridgestone brand. The remaining predictors were not found to be significant for any of the three tire brands. In general, these run types yielded lower coefficients of variation than those obtained in subsection 3.6.2 for the relative wear rate (see Table 3.26).

3.6.5 Test For Homogeneity

Levene's test* for homogeneity was used to check the assumption of constant variances in the above regression analyses. This test was performed only on the estimated wear rate data since the variability appeared more heterogeneous for this variable as compared to that using the estimated weight loss data. Each test was performed across all eight tests (of Phases I and III) for each brand and run type. All test statistics (i.e., see Table 3.27) were found to be nonsignificant and, therefore, supportive of the constant variance assumption.

3.6.6 Convoy Comparison

Because the combined convoy effect was found to be a significant factor in the above regression analyses, further comparisons were made of the average wear values and estimated regression coefficients for each convoy to determine which convoys had the highest wear rates. These comparisons were made only on the estimated weight loss rates for run type R3 since these values were most stable in terms of variability. Table 3.28 contains a summary of the estimated average weight loss rates, and estimated regression coefficients associated with each convoy and tire brand.

For the Uniroyal, Goodyear, and Bridgestone brands, convoy 4 (i.e., test 4 combined with test 9) consistently had the lowest average weight loss followed by convoy 3, with the second lowest. Convoys 1 and 2 had the highest averages. For the Michelin tires, convoy 2 had the lowest average followed by convoys 3, 1, and 4.

The estimated regression coefficient associated with each convoy were also ranked and compared (see Table 3.28). It should be noted that the coefficients

* H. Levene (1960). Robust tests for equality of variance. In Contributions to Probability and Statistics, I. Olkin, ed, Stanford University Pres: Palo Alto, CA, 278-42

TABLE 3.27

LEVENE'S TEST SUMMARY
Wear Rates* By Tire Brand
Phase I and Phase III

TIRE BRAND			F Statistic	p-Value
1.	UNIROYAL	R1	1.41	.2473
		R2	0.88	.5366
		R3	1.10	.3923
2.	MICHELIN	R1	1.02	.4435
		R2	0.96	.4847
		R3	1.15	.3662
3.	GOODYEAR	R1	1.58	.1902
		R2	1.69	.1581
		R3	1.81	.1318
4.	BRIDGESTONE	R1	2.04	.0907
		R2	2.28	.0624
		R3	1.58	.1894

*mils/1000 miles

TABLE 3.28

R3 AVERAGE WEIGHT LOSS RATES* AND REGRESSION COEFFICIENTS
BY TIRE BRAND AND CONVOY

Phase I and Phase III Combined

	TIRE BRAND		CONVOY 1	CONVOY 2	CONVOY 3	CONVOY 4
1.	UNIROYAL	COEFFICIENT	-2.68	-4.40	0.39	0
		Rank	2	1	4	3
		MEAN	21.26	20.58	19.81	19.03
		Rank	4	3	2	1
2.	MICHELIN	COEFFICIENT	-1.27	-1.95	-0.48	0
		Rank	2	1	3	4
		MEAN	21.24	20.88	21.19	21.46
		Rank	3	1	2	4
3.	GOODYEAR	COEFFICIENT	0.05	-1.61	0.44	0
		Rank	3	1	4	2
		MEAN	22.28	21.08	20.84	20.46
		Rank	4	3	2	1
4.	BRIDGESTONE	COEFFICIENT	-6.00	-8.57	0.14	0
		Rank	2	1	4	3
		MEAN	26.73	26.09	24.23	23.11
		Rank	4	3	2	1

* grams/1000 miles

associated with convoy 4 have been assigned a value of zero. This is a result of the reparametrization (0 or 1 coding scheme) which was necessary for inclusion of this categorical variable in the regression model.

For all tire brands, convoy 2 consistently had the smallest estimated coefficient relative to convoy 4. For the Uniroyal, Michelin, and Bridgestone brands convoy 1 ranked second; and convoy 3 and convoy 4 had the largest coefficients. The coefficients associated with the Goodyear tires were largest for convoy 3 followed by those for convoys 1 and 4.

Although the rankings of the average weight loss rates were not the same as the rankings of the corresponding regression coefficients, there was some consistency in the rankings of the means across tire brands and the rankings of the coefficients across tire brands. This result can be expected since the regression coefficients reflect convoy rankings after adjusting for the effects of temperature, wet miles, and humidity while the means are indicative of rankings of unadjusted data.

3.6.7 Comparison of Run Types

Three different run types, R1, R2 and R3 were described in Section 3.1 for usage in analyzing the estimated wear rate and weight loss data. A comparison of these run types were made using the regression analyses in Table 3.26 with ambient conditions and convoy variability as the predictor variables. The summary values given in the last three columns of this table include the squared correlation coefficients, the standard errors of prediction and the coefficients of variation. Statistical comparisons of these values were not made due to the fact that the observations in each run were strongly correlated with those in the remaining runs. However, in general, the R^2 values were higher and the standard errors of prediction and coefficients of variations were smaller using the R3 runs and the estimated rates as compared to those using the R1 and R2 runs. Further, in all the cases examined, the R1 runs has the highest coefficients of variations and highest standard errors of prediction.

3.7 Analysis of Actual Weight Loss Rate

As already discussed in Sections 3.4 and 3.6 and seen in the regression summary of Table 3.26, the variability in terms of estimated weight loss is smaller than the variability in terms of mil loss. This is true for all brands and run types. Also, the R^2 values obtained from the weight loss regressions are higher than those obtained from the mil loss regressions. Finally, as seen in subsection 3.6.7 the variability in the regression data after a 1,600 mile break-in period (i.e., R3) was less, and the R^2 values higher, than that obtained with either of run types R1 and R2. For these reasons, the weight loss data from run type R3 was chosen for use in further and more detailed analyses of the effects of ambient conditions and convoy on tire wear. The actual weight loss rates (grams/mile) were obtained by calculating the individual tire weight differences (in grams) between each consecutive tire inspection, and dividing by the number of miles.

3.7.1 Analysis of Variance Results

Analysis of variance (ANOVA) techniques were used to analyze the effects of several factors on the actual weight loss rate. These factors included the following:

- TEST -1-4 (Phase I); 6-9 (Phase III); 1-4, 6-9 (Phase I & III)
- DVR (TEST) - individual driver in a given test
- CPOS - car position in a test (1=lead, 2=second, 3=third, 4=last)
- POS - tire position on a car (1=LF, 2=RF, 3=LR, 4=RR)
- TEMP - average weighted ambient temperature (^{o}F)
- WET - number of wet miles (per 400 or 800 mile leg)
- TEMP*WET - cross product of temperature with wet miles
- HUMID - average absolute humidity (grains/lb. dry air)
- MILE - index of number of miles travelled (miles/800)

Analyses of these factors were attempted using the separate and combined data of Phases I and III. However, only the Phase III data allowed analysis of all the variables. This was a result of the fact that each tire in Phase I was measured every 800 miles but the vehicles and tires were rotated every 400 miles. Hence, for each 800-mile period, each tire was exposed to two different drivers and two different tire positions. The tires of Phase III, however, were weighed every 400 miles. Thus, it was possible to account for the various individual effects of convoys, drivers, tires, tire positions, and car positions in Phase III but not in the Phase I or Phase I and III data.

The ANOVA tables and residual plots of each brand for Phase III are contained in Appendix H; similar results are not given for the Phase I data or the combined Phase I and III data due to the problems discussed above. For all four tire brands the effects on weight loss rate due to individual drivers, car positions, tire positions, humidity, and miles were found to be significant. The effect due to wet.miles and the interaction of temperature with wet miles were significant for all brands except Michelin. Temperature was insignificant for all brands and test was insignificant for all brands except the Bridgestone tires.

3.7.2 Regression Results

In an attempt to obtain a model useful for predicting the actual weight loss rate as a function of temperature, wet miles, and humidity, regression analyses were performed on the weight loss rate data of each tire brand for Phase I, Phase III, and the combined Phase I and III data using the following predictor variables:

- TEST - 1-4 (Phase I); 6-9 (Phase III); 1-4, 6-9 (Phase I&III)
- TEMP - average weighted ambient temperature (^oF)
- WET - number of wet miles (per 400 or 800 miles)
- TEMP*WET - cross product of temperature with wet miles
- HUMID - average absolute humidity (grains/lbs of dry air)
- MILE - index of number of miles travelled (miles/800)

The results obtained from the regression analyses are summarized in Table 3.29. Stars (*) are used to indicate significant effects at the .05 level. Tables H.5 - H.17 contain the actual test results for each predictor variable and a detailed list of the estimated regression coefficients and residual plots for each tire brand.

The results obtained by analyzing each phase separately were not consistent across tire brands. For example, temperature was found to be significant in three of the tire brands for the Phase I data and was nonsignificant in the Phase III data. Also, mileage was significant for all tire brands using the Phase III data but was insignificant for the Uniroyal and Bridgestone tires in the Phase I data. Similar results were seen for the other predictor variables. In general, the R^2 values were low and this may have accounted for the inconsistent results.

For the combined data of Phases I and III, the variables test, wet miles, mileage, and the interaction of wet miles with temperature were found to be significant for all tire brands. Temperature was significant for both the Uniroyal and Goodyear tires, and humidity was significant for the Uniroyal and Michelin tires.

An additional regression analysis was made on the combined data of Phases I and III by including an additional categorical variable (i.e., PHASE = 0 if Phase I and 1 if Phase III) to account for a seasonal effect. The results of this analyses are summarized in Table 3.29 and are enclosed in parentheses. When PHASE was included in the model it was found to be significant for all tire brands; and TEST was nonsignificant for all tire brands except Bridgestone. All other results remained the same as those obtained without the PHASE variable. A similar analysis was attempted for comparison purposes using the estimated weight loss as the response variable. However, due to the fact that convoys had to be combined across the phases in this approach (i.e., see Section 3.6) the attempt proved futile.

3.8 Phase II Analysis

A major reason for conducting the Phase II test was to determine if the functional relationship between tire wear and mileage changes as the number of miles is extended from 8,000 miles (Phase I) to 24,000 miles (Phase II). Four Phase I tires from each of the Uniroyal and Michelin brands were selected and run an additional 16,000 miles during the Phase II test.

TABLE 3.29

R3 WEIGHT LOSS RATES** REGRESSION SUMMARY
BY TIRE BRAND

TIRE BRAND	PHASE	TEST	TEMP	WET MILES	HUMIDITY	MILEAGE	TxW	R^2	COEFFICIENT OF VARIATION
1. UNIROYAL	I		*		*			.196	16.62
	III					*		.167	18.74
	I & III	* ( )	*	*	*	*	*	.628	12.89
1. MICHELIN	I	*	*		*	*		.293	15.03
	III				*	*		.123	20.16
	I & III	* ( )		*	*	*	*	.528	12.60
3. GOODYEAR	I		*	*		*	*	.370	14.80
	III					*		.148	20.64
	I & III	* ( )	*	*		*	*	.582	13.40
4. BRIDGESTONE	I							.174	16.53
	III	*		*	*	*	*	.247	18.43
	I & III	* (*)		*		*	*	.673	13.29

* indicates $p \leq 0.05$
** gms/mile

3.8.1 Mileage Effects

Regression analyses were performed on the combined Phase I and II data using tread depth (mils) and tire weight (grams) as the response variables and mileage (miles) as the predictor variable. Linear, quadratic, and square-root models were used to determine the best fit to the data. Table 3.30 contains a summary of the predicted rates at 8,000 miles for each of the three regression fits for each tire of the Uniroyal and Michelin brands. Also given is the corresponding predicted rates using only the Phase I data for run type R3. Note that the predicted rates were obtained by differentiating the corresponding expected tread loss or weight loss value with respect to mileage and expressing it as loss per 1000 miles. Tables I.1 to I.12 in Appendix I contain the results for the Phase I data and the combined Phase I and II data including the estimated coefficients, their standard errors, the predicted rates at 8,000 miles, and 95% confidence bounds on the average rates at 8,000 miles.

A comparison of the expected rates at 8,000 miles using the Phase I data versus those using the combined Phase I and II data was made by utilizing the 95% confidence bounds given in Tables I.1 - I.12. In all but one of the linear runs on tread depth, the confidence bounds for the Phase I data were not contained within the confidence bands for the combined data. The one exception was for the Uniroyal tire 4. However, the confidence intervals for the two sets of data were overlapping for the quadratic and square-root fits on tread depth. Similarly, in all the fits of the tire weights, the two confidence intervals were overlapping.

A second comparison was made to determine if the constructed confidence bands for a given data set overlapped for the three models of a given tire. In the tread depth regressions for the combined data, the Uniroyal tires 3 and 4 showed differences between the linear and quadratic models as did the Michelin tires 2 and 3. The bounds in the square-root model overlapped those for the linear and quadratic models in all cases except for the Uniroyal tire 3. In the tire weight regressions for the combined data, the only difference was between the linear and square-root models for the Michelin tire 4. In the analysis of the Phase I data, there were no differences except between the linear and quadratic models for the tread depth data of the Uniroyal tire 4.

3.8.2 Ambient Effects

A second reason for conducting the Phase II test was to investigate the effects of ambient conditions such as temperature, wet miles, and humidity on tire treadwear while holding the effects due to individual drivers, cars, and car positions constant in the convoys. All tests were run during the day time and the position of the cars remained constant. Although the tires remained on the same car throughout this phase, the tire position was rotated every 400 miles.

A multiple regression analysis was performed for each brand, using the actual weight loss rates (calculated every 400 miles) as the response variable. The predictor variables included three indicator variables (coded 0 or 1) for the four tires of a given brand, three indicator variables (coded 0 or 1) for the four tire positions (i.e., LF, RF, LR, RR), a mileage index (miles/800), the number of wet miles (per 400 miles), the average ambient temperature (^{o}F), the average absolute humidity (grains/lb. dry air), and a cross-product term of the number of wet miles with the average humidity.

TABLE 3.30
COMPARISONS OF PREDICTED RATES* AT 8,000 MILES
Phase I versus Phase I and II

TIRE BRAND	ID	PREDICTED RATES LINEAR** I	LINEAR** I & II	QUADRATIC** I	QUADRATIC** I & II	SQUARE ROOT** I	SQUARE ROOT** I & II	RATE
UNIROYAL	1	-2.18	-2.67	-2.68	-2.58	-2.41	-2.61	
	2	-2.31	-2.72	-2.66	-2.63	-2.52	-2.66	
	3	-2.24	-2.67	-3.14	-2.49	-2.77	-2.57	
	4	-2.26	-2.68	-3.09	-2.55	-2.79	-2.60	TREAD LOSS (mils/1000 mi)
MICHELIN	1	-2.38	-2.75	-2.41	-2.64	-2.38	-2.69	
	2	-2.80	-3.31	-3.19	-3.16	-2.98	-3.25	
	3	-2.30	-2.64	-2.49	-2.48	-2.34	-2.57	
	4	-2.97	-3.34	-3.81	-3.23	-3.44	-3.29	
UNIROYAL	1	-18.3	-17.9	-17.5	-17.8	-17.7	-17.9	
	2	-18.0	-17.6	-16.6	-17.5	-16.9	-17.7	
	3	-17.5	-17.3	-16.1	-17.2	-16.5	-17.3	
	4	-18.1	-17.6	-17.6	-17.5	-17.7	-17.6	WEIGHT LOSS (grams/1000 mi)
MICHELIN	1	-18.2	-18.5	-17.4	-18.3	-17.6	-18.6	
	2	-19.3	-20.0	-18.0	-19.9	-18.3	-20.2	
	3	-18.1	-18.5	-17.4	-18.4	-17.4	-18.6	
	4	-19.9	-20.2	-19.0	-20.1	-19.1	-20.4	

* Phase I data is for run type R3 only.

** Linear = $a+bx$; quadratic = $a+bx+cx^2$; square root = $a+bx+cx^{1/2}$;

Linear rate = b; quadratic rate = $b+2cx$; square root rate = $b+c/2x^{1/2}$.

The results (see Tables I.13 and I.14) for the Uniroyal brand showed that all the predictor variables, except the tire variable and the average ambient temperature, had a significant effect on weight loss rate. For the Michelin brand, all the variables were significant predictors. However, in both cases, the R^2 values were very low (R^2=0.33) indicating that there may be other variables in addition to those above that influence weight loss rate.

3.9 Temperature Correction

As previously presented and discussed in Sections 3.7 and 3.8, the effects of ambient conditions including temperature, wet miles and humidity were not consistent for any one tire brand across each phase of the study. For example, temperature was a statistically significant effect in the regression analyses for the Uniroyal tires in Phase I; however, for Phases II and III it was not statistically significant.

Tables 3.31 and 3.32 contain a summary of the estimated regression coefficients and the associated p-values for temperature for each tire brand and phase using the actual weight loss rate data as well as the estimated wear rate and weight loss rate data. The inconsistencies in the temperature effect for the actual weight loss rate data in Table 3.31 are noted by the changes in the magnitude and the signs (either positive or negative) of the estimated coefficients from phase to phase. The coefficients for the Uniroyal tires range from -0.024 for Phase III to 0.156 for Phase I; the p-values range from .001 for the combined data of Phases I and III to .816 for the data of Phase III alone.

Similar inconsistencies in the regression coefficients are noted in the results contained in Table 3.32 for the estimated data. Also, the p-values are inconsistent with those given for the combined Phase I and III data of Table 3.31. Due to these results, no corrections were made for temperature effects. Any adjustment would need to be not only a function of temperature, but also a function of tire brand and related environmental conditions.

3.10 Acceleration Data Analysis

As part of the Phase III test, special equipment was installed on two cars in order to measure and record the longitudinal and lateral acceleration of the various drivers. One car was used in tests 6 and 8 while the other was used in tests 7 and 9. Within each test the car was rotated among the four positions in the convoy to insure that each driver was given the opportunity to drive the instrumented vehicle.

Data were collected along four different legs of approximately 20 miles in length during the course of each 400-mile circuit. These consisted of the following:

- o Leg 1 - flat road segment with few stops and no intersections.
- o Leg 2 - road segment with sharp curves and many dips.
- o Leg 3 - flat road segment many stops and several intersections
- o Leg 4 - road segment with long hills and gentle curves.

TABLE 3.31
ESTIMATED TEMPERATURE COEFFICIENTS*
FOR ACTUAL WEIGHT LOSS RATE (R3)
By Tire Brand and Phase

	PHASE			
TIRE BRAND	I	III	I & III	II
UNIROYAL	0.156 (.003)	-0.024 (.816)	0.132 (.001)	-0.104 (.122)
MICHELIN	0.142 (.007)	-0.264 (.403)	0.080 (.057)	-0.281 (.000)
GOODYEAR	0.492 (.000)	0.019 (.868)	0.107 (.017)	
BRIDGESTONE	0.045 (.474)	-0.136 (.284)	0.033 (.533)	

* 1st entry = estimated coefficient (grms/1000 miles/^{o}F)
2nd entry = p-value

TABLE 3.32
ESTIMATED TEMPERATURE COEFFICIENTS*
FOR ESTIMATED WEAR AND WEIGHT LOSS RATES
By Tire Brand - Phases I and III Combined

TIRE BRAND		Estimated Wear Rate (mils/1000 mi)	Estimated Relative Wear Rates	Estimated Weight Loss Rate (gms/1000 mi)	Estimated Relative Weight Loss Rate
UNIROYAL	R1	.085 (.004)		.305 (.002)	
	R2	.083 (.001)		.333 (.000)	
	R3	.071 (.008)		.410 (.000)	
MICHELIN	R1	-.013 (.933)	-.041 (.411)	-.041 (.920)	-.013 (.466)
	R2	-.007 (.955)	-.057 (.173)	.003 (.992)	-.013 (.397)
	R3	.007 (.956)	-.024 (.569)	.098 (.790)	-.012 (.479)
GOODYEAR	R1	.153 (.002)	-.011 (.533)	.311 (.075)	-.002 (.859)
	R2	.112 (.007)	-.042 (.012)	.245 (.104)	-.006 (.422)
	R3	.066 (.110)	-.022 (.150)	.161 (.292)	-.014 (.088)
BRIDGESTONE	R1	.185 (.039)	-.024 (.388)	1.017 (.000)	.031 (.014)
	R2	.148 (.032)	-.063 (.006)	.851 (.000)	.020 (.049)
	R3	.151 (.010)	-.002 (.911)	.790 (.001)	.013 (.242)

* Coefficient unit is mils/1000 miles/°F or grms/1000 miles/°F; p-values are in parentheses.

These measurements allowed for each driver in Phase III to experience each leg a total of five times. However, due to mechanical difficulties, this amount of replication was not achieved for every driver.

Measurements were taken on both the longitudinal and lateral acceleration as well as on the velocity and displacement. Readings were made on all accelerations to an accuracy of 0.1G. Velocity was measured to the nearest 0.1 miles per hour while displacement was recorded to the nearest 0.1 mile. The resulting acceleration data are summarized in the tables in Appendix J. Descriptive data include the means, standard deviations, and sample sizes for both the longitudinal and lateral accelerations of a given driver for a given test, leg and replicate.

3.10.1 Acceleration Comparisons

Analyses were run to determine if the acceleration variability between the drivers for a given test and leg exceeded the variability within the replicates for the drivers. This was accomplished by performing a one-way analysis of variance (ANOVA) on the mean accelerations (i.e., mean of the absolute values) of a specific driver for a given test leg and replicate. The F-statistics from the ANOVAs are summarized in Table 3.33 while the complete ANOVA tables are given in Appendix K.

In 29 of the 32 comparisons the between-driver variability was not significant. This implies that the drivers, on the average, accelerated in a similar manner over the test course. The three exceptions were for the longitudinal acceleration data of the drivers during leg 1 of test 6, leg 1 of test 8 and leg 4 of test 8. In leg 1 of test 6, driver 22 had a significantly lower mean acceleration than drivers 1 and 3. In leg 1 of test 8, driver 28 had a significantly higher mean acceleration than drivers 10, 12 and 25. Finally, in leg 4 of test 8, drivers 10 and 28 had a significantly higher mean acceleration than drivers 12 and 25.

3.10.2 Driver Comparisons

A major purpose for instrumenting two cars in this study was to allow a comparison between the acceleration data and the tire wear rate data for a given driver. For example, it would be of interest to know if tire wear is related to a person's driving habits. Hence, an analysis was conducted using both the acceleration data and the actual weight loss data from the R3 runs of Phase III.

Drivers were rank-ordered according to the means of their acceleration data for a given test and leg. The results for the lateral accelerations are given in Table 3.34 while those for the longitudinal accelerations are summarized in Table 3.35. Similarly, drivers were rank ordered according to the magnitude of their estimated regression coefficients obtained in the analyses of the actual weight loss rates for Phase III (i.e., see Tables H.1-H.4). The results of the coefficient rankings are summarized in Table 3.36 by brand and test number.

No consistencies evolve when a comparison is made across the rankings in Tables 3.34 - 3.36. Also, within each table there is little agreement across test legs or across tire brands within a test. This result implies that there are few differences among the drivers and that, when there are significant differences, the results are not consistent.

TABLE 3.33 F-STATISTICS FROM COMPARISON OF DRIVER ACCELERATION MEANS

TEST	ACCELERATION TYPE	F-STATISTICS			
		LEG1	LEG2	LEG3	LEG4
6	LATERAL	1.33	1.34	0.94	0.94
	LONGITUDINAL	4.99*	1.27	0.22	0.11
7	LATERAL	2.09	1.25	2.44	2.38
	LONGITUDINAL	0.86	1.44	0.44	0.86
8	LATERAL	0.48	1.48	0.16	3.05
	LONGITUDINAL	7.33*	1.71	2.50	6.82*
9	LATERAL	1.43	0.94	0.20	1.74
	LONGITUDINAL	1.67	0.62	1.25	3.10

*Indicates significant at .05 level

TABLE 3.34 RANK ORDERING* OF DRIVERS USING
LATERAL ACCELERATION MEANS

TEST	LEG1	LEG2	LEG3	LEG4
	3(.0177)	3(.0387)	4(.0166)	3(.0201)
6	22(.0186)	22(.0404)	3(.0174)	22(.0203)
	1(.0197)	4(.0407)	22(.0183)	1(.0214)
	4(.0206)	1(.0427)	1(.0186)	4(.0223)
	29(.0182)+	29(.0354)+	19(.0167)	19(.0192)
	24(.0195)	19(.0366)	8(.0172)	8(.0200)
7	8(.0202)	8(.0383)	24(.0174)	29(.0202)+
	19(.0203)	24(.0387)	23(.0187)	24(.0202)
	23(.0226)	23(.0400)	29(.0195)+	23(.0220)
	26(.0166)+	10(.0388)	26(.0156)	26(.0169)+
	25(.0181)	27(.0399)+	10(.0161)	10(.0182)
	12(.0188)	12(.0404)	25(.0162)	28(.0184)
8	10(.0191)	25(.0441)	28(.0168)	12(.0184)
	28(.0199)		12(.0172)	27(.0205)+
	27(.0213)+		27(.0222)+	25(.0213)
	30(.0193)	15(.0397)	30(.0178)	30(.0208)
	15(.0204)	9(.0400)	15(.0181)	15(.0210)
9	9(.0209)	30(.0401)	9(.0182)	9(.0217)
	16(.0217)	16(.0432)	16(.0187)	16(.0229)

* Driver numbers are given as ranked from smallest (top) to largest (bottom) within each test and leg; acceleration means are in parenthesis.

\+ These drivers were recorded for only one run in the given leg and thus were not included in the comparison analyses in Table 3.33.

TABLE 3.35 RANK ORDERING* OF DRIVERS
USING LONGITUDINAL ACCELERATION MEANS

TEST	LEG1	LEG2	LEG3	LEG4
6	22(.0112)	3(.0300)	1(.0225)	4(.0158)
	4(.0119)	22(.0321)	3(.0228)	22(.0160)
	1(.0131)	4(.0326)	4(.0235)	3(.0161)
	3(.0133)	1(.0341)	22(.0240)	1(.0166)
7	24(.0134)	24(.0337)	24(.0228)	24(.0166)
	19(.0142)	8(.0370)	19(.0228)	19(.0174)
	29(.0156)+	23(.0370)	29(.0253)+	8(.0183)
	8(.0167)	19(.0373)	23(.0257)	29(.0193)+
	23(.0186)	29(.0398)+	8(.0265)	23(.0205)
8	27(.0116)+	25(.0300)	27(.0179)+	27(.0145)+
	12(.0121)	10(.0301)	25(.0215)	12(.0153)
	10(.0130)	27(.0306)+	10(.0222)	25(.0163)
	25(.0135)	12(.0326)	12(.0229)	26(.0165)+
	26(.0136)+		26(.0238)	10(.0195)
	28(.0181)		28(.0283	28(.0207)
9	30(.0131)	30(.0321)	9(.0208)	30(.0160)
	9(.0136)	16(.0327)	30(.0223)	9(.0161)
	16(.0146)	15(.0330)	16(.0228)	15(.0170)
	15(.0155)	9(.0334)	15(.0235)	16(.0179)

* Driver numbers are given as ranked from smallest (top) to largest (bottom) within each test and leg.

\+ These drivers were recorded for only one run in the given leg and thus were not included in the comparison analyses in Table 3.33.

TABLE 3.36 RANK ORDERING* OF DRIVERS USING ESTIMATED REGRESSION COEFFICIENTS OF PHASE III

	TEST 6		TEST 7		TEST 8		TEST 9	
	3	(.489)	19	(.001)	12	(.061)	9	(.113)
UNIROYAL	1	(.655)	24	(.066)	10	(.078)	15	(.209)
	22		8	(.357)	27	(.447)	16	(.286)
	4	(.429)	23	(.918)	28		30	
			29		25	(.937)		
					21	(.010)		
	3	(.125)	23	(.701)	27	(.067)	30	
	1	(.724)	29		25	(.019)	9	(.002)
MICHELIN	22		24	(.871)	10	(.529)	16	(.014)
	4	(.211)	19	(.816)	12	(.617)	15	(.270)
			8	(.692)	21	(.795)		
					28			
	3	(.871)	24	(.074)	12	(.002)	9	(.696)
	22		23	(.595)	27	(.066)	30	
GOODYEAR	1	(.833)	8	(.837)	25	(.002)	15	(.517)
	4	(.098)	29		10	(.113)	16	(.387)
			19	(.755)	28			
	3	(.132)	8	(.840)	28		15	(.433)
	1	(.173)	24		12	(.579)	30	
BRIDGESTONE	4	(.790)	19	(.068)	27	(.566)	9	(.123)
	22		23	(.066)	10	(.348)	16	(.015)
					25	(.164)		

* Driver numbers are given as ranked from smallest (top) to largest (bottom); p-values of coefficients are in parentheses and represent significance relative to the numbered driver within a test without a p-value.

4. FINDINGS

4.1 Procedural Considerations

- The procedure for weighing the tire was established and shown to be effective in accurately determining weight loss. It was found to be essential that the measurement laboratory control be very closely monitored; that pressure and temperature data be well documented; and that adequate time be allowed for the tire pressure/temperature condition to stabilize prior to the measuring or weighing.

- The tires were weighed at 800-mile intervals during Phase I. The Phase II and III tires were weighed after each 400-mile circuit. An improvement in the accuracy of the results was realized when the weight loss procedure was used. Good resolution of 10 gram losses was possible and this is the magnitude of the loss to be expected in 400 miles. Therefore, more frequent "weighings" than determination of tread loss by measurement can be done because the average "mil" loss of a radial tire on the UTQG course in 400 miles will probably be somewhat less than the experimental error of the process; however, the weight-loss procedure will be valid only when laboratory controls and adequate schedules are established. At this point, the matter of practicality in terms of cleaning, handling and conditioning must be considered in terms of data improvement.

- The 400-mile rotation cycle, the emphasis on mechanical reliability (weight and alignment) of the vehicles at 400-mile intervals, and the rotation of the tires and tire sets throughout the convoy were causes for minimizing the effects of the vehicles, drivers, wheel positions, etc. These items have been examined previously as reasons for variance. The statistical analysis applied to the data of this program serves to examine further these causes in the light of the increased frequency of the rotations and/or mechanical examinations. The testing was completed with no problems involving the tire or vehicle rotations.

- An effort was made to utilize the same drivers in the same relative convoy positions during the Phase III test (summer) as during the Phase I tests (winter). In that the delay of several weeks between phases disrupted the employment of most of the initial group of drivers, it was necessary to replace eight of the original 16 as Phase III was initiated. Except for Convoy 4 (Tests 4S0004 and 4S0009), all lead drivers remained unchanged . In that case, an experienced, dependable driver from the first Phase was moved to lead in the same convoy for phase III. During Phase I, driver substitutions were necessary on three occasions. Fourteen of the 16 positions ran 20 times each without changes. Fourteen of the 16 positions were filled by the same drivers during the Phase III tests. One position of the Test 4S0008 (Convoy 3 of Phas III) was filled by five different drivers during the testing.

  The analytical portion of this report, Section 3.10, indicates differences in the drivers as measured by the accelerometers. Substitution of drivers when required appeared to have no measurable affect on tire wear response according to that analysis. Table 4.1 lists the drivers assigned to the tests during each of the three phases together with reasons for substitution when required.

- In plotting the regressed data, it is noted that the tendency for early "rapid" losses or high wear-rates is not as prevalent in the weight loss data as in the groove depth measurement procedure. It is theorized but not proven that this is due to a tread-rib compression as well as material removal when groove reduction is measured, while the weighing process would indicate the actual mass of the material removed.

- A disadvantage in the use of weight measurement is that the projected mileage to worn out is undeterminable unless there is a means of establishing a "100% tread-loss" condition for the projection of the data to the Tread Wear Indicators. An effort has been made to provide a means of determining the 100% tread loss condition of a given tire brand-design. A report of that task will supplement this report.

- During the course of the testing, temperature of the tires and the ambient course temperatures were taken. The data obtained during Phases II and III were taken at more frequent intervals than the Phase I temperature measurements. The data used in the analysis were generated by normalizing the temperature of the course relative to mileage segments between scheduled break and stop points on the 400-mile circuit. Appendix D contains a summary of the data as measured at each of the points, the averages of the two circuit temperatures as run temperatures, and the average of the 10-run temperatures as a test average.

- Outdoor atmospheric temperature, relative humidity, and barometric pressure at the test facility were logged at the time of each convoy departure and return.

4.2 Tread Loss Result

- The primary objective of this work was to determine wear rates in terms of average groove depth reduction (mil loss) and in terms of weight of tread rubber removed by abrasion (gram loss) during each of several tests. In many respects, these tests were replicative but in several other ways there were differences to be utilized in the analysis of the many computed wear results.

Tables 4.2, 4.3, and 4.4 present the computed wear rates of each tire set and the respective coefficient of variation of each set. The calculations are stated for Phases I, II, and III as discussed in the procedural portion of the report. These tabular summaries provide for comparison of the wear results within each Phase.

The same data are presented in Tables 3.1, 3.3, 3.13, and 3.15 of Section 3 wherein the results are used for analyses of variation considering the many variants between each of the tests to establish the result pertinent to the tire in each case.

TABLE 4.1

DRIVER ASSIGNMENTS AND REPLACEMENTS

Phase	Test	Driver Code, By Convoy Position 1	2	3	4
I	4S0001	01	02	03	04
	4S0002	05 (a) 19 (b)	06	07	08
	4S0003	10	11	12	13 (c) 15 (d) 20 (e)
	4S0004	14	16	17	18
II	4S0005	01	04	--	--
III	4S0006	01	22 (m)	03	04
	4S0007	19	23 (m)	24 (m)	08 (f) 29 (g)
	4S0008	10	25 (m)	12	26(m)(h) 20 (i) 21 (j) 28 (k) 27 (l)
	4S0009	16 (m)	30 (m)	09 (m)	15 (m)

(a) Through Run 4/1, Medical
(b) From Run 4/2 to test end; then to Phase III
(c) Through Run 3/2, New Employment
(d) Filled in Run 4/1 only; then permanent Phase III
(e) From Run 4/2 to test end
(f) Through Run 7/1, Medical
(g) From Run 7/2 to test end
(h) Through BI 1/2, Dependability
(i) Filled in Run BI 2/1 only; Not available
(j) From Run BI 2/2 through Run 1.2; Medical
(k) From Run 2.1 through Run 6.2, Dependability
(l) From Run 7.1 to test end
(m) Replacement because Phase I personnel no longer available

TABLE 4.2

SUMMARY OF TREADWEAR AND TIRE WEIGHT LOSS RATES

DURING PHASE I - WINTER TESTING

-The mean of 4 tires in each set; the Coefficient of Variation, % for the set.
-Treadwear in inches - 0.001 inch is a MIL.
-Tire weight loss in grams, G.

TEST GROUP	TREADWEAR MILS/1000 MILES ① $\bar{x}$	Cv %	② $\bar{x}$	Cv %	TIRE WEIGHT LOSS G/1000 MILES ① $\bar{x}$	Cv %	② $\bar{x}$	Cv %	NOTES
TEST 4S0001									
X 1	2.04	3.14	2.25	2.40	18.23	1.37	17.98	1.89	
M 1	2.60	12.92	2.61	12.40	19.13	5.11	18.88	4.62	
G 1	3.29	5.17	3.25	5.81	19.30	2.77	19.25	3.07	
B 1	5.38	2.30	5.12	1.97	22.08	2.60	22.08	3.01	
TEST 4S0002									
X 2	2.17	3.50	2.18	2.85	17.93	1.24	17.75	1.42	
M 2	2.56	19.18	2.45	18.14	18.83	2.76	18.50	2.72	
G 2	3.23	1.36	2.90	3.07	18.68	2.33	18.00	2.90	
B 2	5.48	2.39	5.04	2.20	23.18	1.70	22.40	1.59	
TEST 4S0003									
X 3	2.26	3.27	2.42	5.71	17.48	0.86	17.08	0.74	
M 3	2.71	12.56	2.73	9.59	19.37	4.17	18.80	4.15	(a)
G 3	3.57	9.11	3.31	7.21	19.03	4.90	18.23	4.11	
B 3	5.25	6.46	4.83	4.37	20.55	4.43	20.20	4.44	
TEST 4S0004									
X 4	2.28	3.99	2.30	2.00	17.23	2.70	16.43	0.91	
M 4	2.75	14.23	2.75	12.19	19.93	3.34	19.23	2.38	
G 4	3.37	3.38	3.20	2.41	18.60	2.74	18.00	2.40	
B 4	5.15	5.85	4.78	5.04	20.30	6.09	19.90	5.24	

(a) Tire number 1322 failed and was removed from test at 6925 miles. The data shown are the 3 remaining tires of this group.

NOTE: The 8000 mile tests were conducted in 800 mile intervals and the tires were inspected/measured at the conclusion of each interval. Each tire was measured 10 times to determine the remaining tread and the tire weight. The treadwear rates and the tire weight loss rates were computed as the slopes of the linear regression of the data points at 800 mile increments. There were two considerations:

① The first 9 of 10 points were used establishing an 800 mile break-in.
② The last 9 of the 10 points were used, assuming a 1600 mile break-in.

TABLE 4.3

SUMMARY OF TREADWEAR AND TIRE WEIGHT LOSS RATES

DURING PHASE II - MAY, JUNE, JULY 1984

-The mean of 4 tires in each set; the Coefficient of Variation, % for the set.
-Tread wear in inches - 0.001 inch is a MIL.
-Tire weight loss in grams, G.

TEST GROUP	TREAD WEAR MILS/1000 MILES				TIRE WEIGHT LOSS G/1000 MILES				NOTES
	① $\bar{x}$	Cv %	② $\bar{x}$	Cv %	① $\bar{x}$	Cv %	② $\bar{x}$	Cv %	
TEST 4S0005									
X 1	2.68 2.76	1.06 1.53	2.70 ----	0.76 ----	17.78 18.08	0.71 0.53	17.78 ----	0.71 ----	(a) (b)
M 1	3.01 3.13	12.18 11.08	3.02 ----	12.05 ----	19.93 20.80	4.80 4.73	20.03 ----	4.78 ----	(a) (b)

(a) The test is a continuation of that shown in Table 4.2 for the same groups. The mileage was extended from 8000 to 24000 at the rate of 400 miles/day (day only); the tires were cleaned, conditioned and weighed every 400 miles from 8000 miles on. The tire tread measurements were made every other day at 800 mile intervals. The tread wear rates indicated were computed as the slopes of the linear regression of the data points at each of the pertinent measurement increments including the initial test (reference Table 4.2). There were two considerations:

① The measurement points from 800 miles through 24000 miles.
② The measurement points from 1600 miles through 24000 miles.

(b) The test data assuming an 8000 mile break-in and regressed rates from points 8000 through 24000 miles inclusive.

TABLE 4.4

SUMMARY OF TREADWEAR AND TIRE WEIGHT LOSS RATES

DURING PHASE III-SUMMER TESTING

-The mean of 4 tires in each set; the Coefficient of Variation, % for the set.
-Treadwear in inches - 0.001 inch is a MIL.
-Tire weight loss in grams, G.

TEST GROUP	TREADWEAR MILS/1000 MILES ① $\bar{x}$	Cv %	② $\bar{x}$	Cv %	TIRE WEIGHT LOSS G/1000 MILES ① $\bar{x}$	Cv %	② $\bar{x}$	Cv %	NOTES
TEST 4S0006									
X 6	3.81	2.68	3.73	2.63	25.08	2.29	24.55	2.04	
M 6	3.85	19.14	3.75	17.87	23.98	8.30	23.60	8.55	
G 6	5.64	1.86	5.26	3.57	26.25	1.26	25.30	0.85	
B 6	8.40	4.33	7.83	3.37	32.30	3.23	31.38	3.23	
TEST 4S0007									
X 7	3.73	3.51	3.61	2.60	24.33	0.91	23.40	0.70	
M 7	3.77	23.13	3.63	20.69	23.93	11.93	23.25	10.36	
G 7	5.13	3.10	4.91	3.14	25.08	2.90	24.15	2.82	
B 7	7.84	6.05	7.42	4.39	30.60	4.25	29.78	3.98	
TEST 4S0008									
X 8	3.38	3.67	3.39	3.22	23.18	0.41	22.55	0.57	
M 8	4.01	17.33	4.02	15.05	23.53	8.39	22.98	8.76	
G 8	5.19	1.96	4.91	1.30	24.38	2.15	23.45	2.13	
B 8	7.47	4.58	7.19	2.71	28.80	2.05	28.25	1.88	
TEST 4S0009									
X 9	3.38	1.75	3.12	3.81	22.10	1.69	21.63	1.16	
M 9	4.36	6.26	4.02	4.83	24.25	0.71	23.70	1.03	
G 9	4.90	2.00	4.67	3.32	23.35	3.58	22.93	3.40	
B 9	7.49	1.92	7.06	1.80	26.73	2.45	26.33	2.73	

NOTE: The 8000 mile tests were conducted in 800 mile intervals and the tread groove depths of the tires were measured at the conclusion of each interval. Each tire was measured 10 times to determine the average remaining tread depth. Each 800-mile run was divided into two 400 mile circuits of the test course during each driver shift. The weight loss in grams was determined for each tire at the conclusion of each 400-mile circuit. The tire tread mil loss rates and the tire weight loss rates were computed as the slopes of the linear regression of the data points at 800 mile and 400 mile increments respectively. There were two considerations in each case:

① The first 9 of 10 points were used establishing an 800 mile break-in.
② The last 9 of 10 points were used, assuming a 1600 mile break-in.

The Phase II data are shown as extended through the 24000 mile test in Table 4.3 but the comparable results at 8000 miles for the finalized (Phase I) and extended (Phase II) tests are indicated in Table 3.30 and discussed in Paragraph 3.8.

In essence, the Statistical Analysis and Tables presents the result of a study of the variants stated; the tabular data of Section 4 is a comparative presentation of wear rate results during the work.

4.3 Temperature Effects on Treadwear

Another test objective was to monitor closely the ambient test course temperatures as well as the responsive tire temperatures and to relate the data to the tire wear rates. This study was especially emphasized during Phase II when the tire, vehicle, driver and convoy positional effects remained unchanged. Section 3.8.2 of the Statistical Analysis states that all of the predictor variables, except for the tire and the ambient temperatures, were significant in the case of the Uniroyal tire group (Phase II) but that all of the variables including those for the tire and average ambient temperature were indicated to be significant in the case of the Michelin tires during the same testing. The correlation coefficient being very low indicated that there were probably other variants, not considered, in the process studied.

One aspect of all of the testing provided for the development of a wear-temperature relationship so that coefficients reflective of the average ambient temperature might be utilized for treadwear rate correction. Inconsistencies in the response of the temperature, humidity, and wet-miles variations (those designated as environmental) on treadwear of the different tire groups precluded establishment of such a correction factor. The estimated regression coefficients and the associated probabilities for temperature effect are shown in the Tables 3.31 and 3.32.

4.4 Determination of Treadwear by A Weight Loss Method

It was pointed out in the discussion of the procedures that the determination of tire wear rate by measurement of weight loss is an extremely effective and accurate method when the proper equipment and precautionary test processes are utilized. The determination of the total tire utilization by projection of the wear rate to worn out becomes problematical when the determination of "worn-out" in terms of tire weight is required. A special effort was made to find a "worn-out" condition for each of the four tire brands and sizes tested. This task is presented in detail in a supplement to this report. It was shown that the tires could be fairly well establihed in a "worn-out" mode by mechanical removal of the tread with relatively crude equipment; and it is suggested that employment of more precise equipment, will enhance the process in terms of specific tires. The problem still remains to generalize a process to be utilized in the establishment of a treadless tire weight for use in a tire tread-life projection.

4.5 Determination of Driver Differences on Treadwear

Although it is understood that different vehicle operators will contribute to differences in tire wear on a normal basis, drivers are regularly oriented and advised on the technique to be used during this test procedure. Efforts are made to establish consistency among drivers. It is known that the various convoy positions require various responses in drivers but that most of all differences in driver habits and personality contribute most to any differences noted.

In an attempt to evaluate the driver effect on wear, the accelerometer equipment was installed during certain portions of the testing and the different driver responses measured over four course segments. The driver to driver differences were then noted and the result analyzed statistically as reported in Section 3. Tables 3.34 and 3.35 imply that on the average, there was little, if any, influence on treadwear differences due to the way different drivers accelerated over the course.

It was the purpose of the acceleration study to establish differences in test drivers, thereby, a perceptible variable in treadwear. A comparison of the acceleration rankings and wear regression coefficients (by weight-loss in Phase III) is shown in Table 3.36.

Upon observing each of the tabular presentations 3.34 through 3.36, it is concluded that, on the average, there was very little individual driver affected difference in treadwear in a trained convoy.

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