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An Analysis of Tire Tread Wear Groove Patterns and the Effect of Heteroscedasticity on Tread Wear Statistics

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Final Report

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16. Abstract

This report examines the groove wear variability among tires subjected to the Uniform Tire Quality Grading (UTQC) test procedure for determining tire tread wear. The effects of heteroscedasticity (variable variance) on a previously reported statistical analysis were also examined. Two data sources were used: special tire tests performed by the Southwest Research Institute (SWRI) for NHTSA, and NHTSA's own compliance tests. The test concluded that groove wear variability exists during UTQG testing with the outside grooves generally wearing more than the inside grooves. The difference in wear between the inside and outside grooves varied from approximately 10 percent to 50 percent. This variability was different for different types but was uniform within the tire types during a test. However, in tests spaced apart in time, this within tire type groove variability will change and is probably influenced by environmental conditions. It was also concluded that heteroscedasticity would have no effect on previously reported statistical results but that this effect could be meaningful on an individual tire basis.

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PREFACE

The work was performed by the U.S. Department of Transportation, Transportation Systems Center (TSC) in support of the National Highway Traffic Safety Administration (NHTSA), Office of Research and Development as a continuing effort to better understand the sources of tread wear variability in the Uniform Tire Quality Grading (UTQG) test procedures. This report addresses two specific issues relating to the test variability: the variations in individual groove wear during a test, and the effects of heteroscedasticity on tread wear statistical analyses.

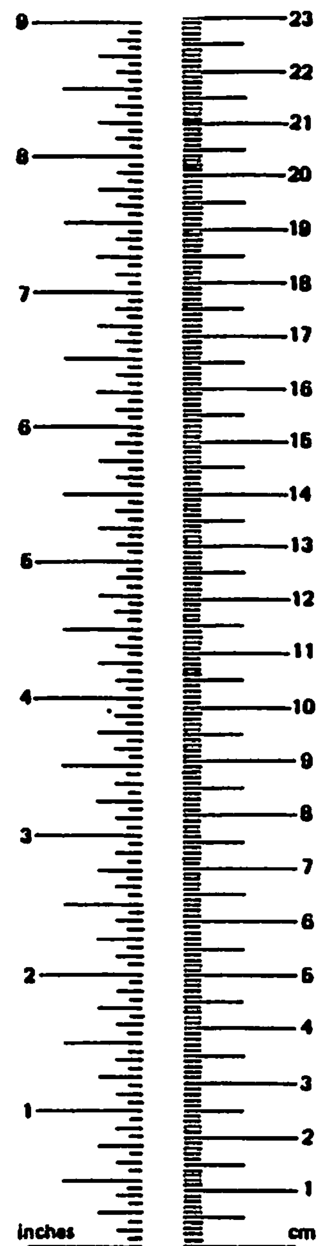
The authors gratefully acknowledge the assistance of those who made this report possible. The support and guidance of Robert Nicholson, Chief, Crash Avoidance Division, and Dr. Jose Bascunana of NHTSA's Office of Vehicle Research were invaluable. We would also like to thank Melodie Esterberg and Jonathon Belcher for computer analyses and figure preparation, and Robin Barnes for report preparation.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

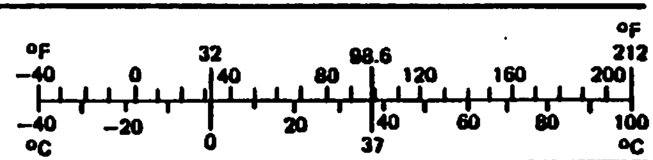
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in. = 2.54 cm (exactly). For other exact conversions and more detail tables see NBS Misc. Publ. 286. Units of Weight and Measures. Price $2.25 SD Catalog No. C13 10 286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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EXECUTIVE SUMMARY

BACKGROUND

This report documents an analysis that was completed by the Transportation Systems Center (TSC) in support of the National Highway Traffic Safety Administration's (NHTSA) efforts to reduce the variability during tread wear testing of radial tires subject to the Uniform Tire Quality Grading (UTQG) system. This work is a follow-on to a previous statistical analysis performed by TSC on tread wear and UTQG test variability (Reference 1). The reader is referred to that paper for a more complete discussion of the UTQG test procedures and history. This follow-on effort had two primary objectives:

1. Document and analyze the groove-to-groove wear variations in radial tires subject to the UTQG; and
2. Determine the effect of correcting for variable variance in groove depth measurements when calculating tire mileage using linear regression techniques and analyze if this effect was of sufficient magnitude to impact TSC's previous statistical analyses.

With respect to the individual groove measurements, it has been postulated that, under conditions of uneven groove wear, groove depth measurements by gauging would not be indicative of the mass of rubber removed per unit distance, and tire weighing would produce a more meaningful indicator of tread loss. (See Reference 2.) In addition, uneven tire wear would increase the within-tire type variability during groove depth measurement.

The linear regression techniques performed according to the Code of Federal Regulations (CFR) for UTQG tests assume that the groove depth measurements at each mileage interval have the same variance (i.e. homoscedastic relationships). It has been observed that, in general, this is not the case. We, therefore, decided to examine this issue further and determine if this observed variable variance could impact TSC's previous statistical conclusions relative to the precision of the UTQG test.

Two sources of data were used to examine these issues. These sources were the results of special tests performed by Southwest Research Institute for NHTSA and NHTSA's 1980-1981 radial tire compliance test data. (SWRI, Reference 3) (Details on these tests can be found in the references.) The Statistical Analysis System (SAS) program was used for all analyses.

RESULTS

The results of these analyses can be summarized as follows:

Groove Wear Variations:

- All tires examined (224 total) exhibited uneven groove wear patterns. These differences in groove wear varied from less than 10 percent up to 60 percent when compared to the overall tire tread wear.
- In general, the outside grooves of a radial tire wore faster than the inside grooves.
- Some exceptions were noted in which the inside grooves wore faster than the outside grooves.
- The groove wear patterns were consistent within tire types and convoys exposed to the same environmental conditions. However, the within tire

type groove wear pattern changed between convoys widely spaced in time (as did the treadwear).

- The SWRI test tires had, in general, less groove-to-groove variation than the NHTSA compliance tires.
- The SWRI Phase III (hot weather) test results had more even tire tread wear than the Phase I (cool weather) test results.
- Sufficient data was not available from this analysis to substantiate the theory that uneven tire wear would contribute to increased test variability for gauging.

Comparisons of Grading by Groove Gauging and Weighing:

- Tire tread loss by weighing has less variability than tread loss by gauging; however, the ability to distinguish between tire types by wear rate is lessened when weighing is used.
- The ratios between SWRI phases of wear rate by gauging and weighing were relatively constant over tire types; however, the ratios for the two methods were different (.65 gauging vs .76 weighing).
- There are differences between the gauging and weighing methods between tire type variability. Further, the relative ranking of the tires is different depending on whether gauging and weighing is used and the ranking by weighing differs between Phase I and III.

Effects of Variable Variance on TSC's Statistical Analysis:

- The effects of correcting for variable variance on tire regression analyses using both SWRI and NHTSA data were minor, usually a few percent, and would have no impact on previously reported TSC statistical results. In the case of individual tires types, this correction made a difference of less than one percent to as much as eight percent (in one case). When we consider the magnitude of the variability due to other sources in the test, this is of little significance. However, on an individual tire type basis it is possible that heteroscedasticity could contribute to grade inversion.

Comparison of SWRI and NHTSA Compliance Data Test Results (see Appendix A):

- o The within tire type treadwear variability* of the combined Phase I and Phase III SWRI test results were 0.231 by gauging and 0.147 by weighing. The NHTSA compliance data test results for the treadwear variability was 0.122.**
- o When we adjusted the tread wear using one of the test tires as a CMT*** tire, the treadwear variability was reduced by factors of 2.7 and 3.2 (to .0858 and .0447) for gauging and weighing respectively. The CMT correction in the NHTSA compliance data reduced the variability by a factor of 1.5 to .081.
- o The attained grade variabilities by gauging were approximately equivalent for both the SWRI and NHTSA compliance data (.0803 and .083).

*By the variability here we mean more specifically the pooled (over tire types) standard error of the means of the four-tire sets (one set for each convoy) for each tire type. (Furthermore, because this is the standard error of log tread wear, its value multiplied by 100 equals approximately the pooled coefficient of variation of the mean tread wear of the four-tire sets for each tire type.)

**Phase I and II were separated by five months, whereas the compliance tests for identical tire types were normally run within two weeks of each other.

***The CMT or "course monitoring tire" is used to factor the tread wear of the other tires, thus correcting for envirionmental or "course" conditions.

- Therefore, TSC's original conclusion that with a 95 percent confidence level, the average attained grade of four gauged identical tires tested twice would not shift by more than 23 percent, is valid for both the NHTSA and SWRI data. However, we can conjecture that that this estimate would be reduced to 13 percent if the tires were weighed.

1.0 INTRODUCTION

NHTSA's Office of Crash Avoidance (NRD-11) has been investigating the variability in the treadwear results from UTQG testing at San Angelo, Texas. TSC has assisted NRD-11 in this investigation. TSC performed statistical analysis of the tread wear using data from NHTSA's 1980-81 radial tire compliance tests and data supplied by the manufacturers. (Reference 1) NHTSA has also been supporting tests performed at San Angelo by Southwest Research Institute (SWRI) to investigate methods of reducing tread wear variability. These methods included the use of identical vehicles, rotating tires between all vehicles of a convoy and weighing the tires to determine tread wear loss. These techniques appear to reduce the variability when compared to NHTSA's compliance results. The technique of weighing the tire, although it has other drawbacks, appeared to reduce the coefficient of variability (COV) within tire types by as much as 50 percent. Dr. José Bascunana formulated an explanation as to why the weighing technique should more accurately measure the actual mass of rubber lost during testing and the potential inaccuracies inherent in the groove depth measurement <u>if</u> the tire tread wear is uneven, i.e., some grooves wear more than other grooves. (See Reference 2.)

The analysis in this report examines the individual groove meaurements and their impact on tread wear and attained grade using both SWRI and NHTSA compliance data. Additionally, it was noted during TSC's previous analysis that the variance of the tread wear groove measurements at different mileage intervals was variable (heteroscedastic). A regression such as that specified in 49 CFR 575.104 for determining tread wear in tire testing, assumes homoscedastic relationships. Therefore, it was decided to examine both SWRI and the NHTSA compliance data to determine the extent of this heteroscedasticity and its impact on the previously reported statistical results.

2.0 OBJECTIVE

The objectives of this effort are threefold:

1. Document and quantify the tread wear variation on a groove-by-groove basis;
2. Examine the effects of correcting for heteroscedasticity on the previously reported ANOVA results; and
3. Perform other statistical analyses, specifically ANOVAs, as required to examine the weight method of tread wear loss and any effects of tread wear groove patterns.

3.0 APPROACH

In order to accomplish the aforementioned objectives, TSC analyzed tire tread wear data from two sources. The first source was data provided by SWRI on special tests performed for NHTSA to evaluate techniques to lower the variability in tread wear grading. These tests were performed in three phases -- a cool weather test (Phase I) an extended mileage test (Phase II), and a warm weather test (Phase III). The reader is referred to the SWRI report for details on these tests (Reference 3). For this analysis, only the Phase I and III results were used. The second source of data that we used was the NHTSA compliance tests performed in 1980 and 1981 for radial tires. This data was previously analyzed and reported by TSC in a NHTSA report. (Reference 1) The same basic approach was used for treating the data from both sources.

The SWRI data and the NTHSA compliance data were available in a machine-readable tape form. The necessary elements were identified and structured into a SAS data set for analysis. The typical elements of the data sets are shown in Table 1. In general, these elements consisted of an identification of the tire type and its number (a unique identifier), the convoy and circuit in which the tire was tested, the tread depth groove measurement on a circuit-by-circuit (800 mile) basis, and for the SWRI data, the tire weight loss data. For the first part of the analysis,the tread wear was calculated on an individual groove basis using the standard regression techniques as prescribed in 49 CFR 575.104. The ratio of each individual groove's tread wear to the overall tire tread wear was then calculated. In addition, the attained grade of the tire was calculated using various groove combinations and again compared to the overall tire attained grade. Further comparisons were made based upon the coefficients of variation (COV) and, where appropriate, analysis of variance (ANOVA). The SWRI data contained three four-groove tires and one three-groove tire. Only four-groove tires were selected for analysis from the NHTSA compliance data.

In order to perform the corrections for variable variance (heteroscedasticity), the variance of the groove depth measurements for each tire at each mileage interval was calculated and we used the inverses of these variances as a weighting factor in the specified regression analysis to determine the treadwear of that tire. The results of these corrected regression analyses could be compared to the previously reported using ANOVA techniques.

Other statistical procedures were used, when appropriate, to further analyze the results reported herein.

TABLE 1. BASIC ELEMENTS OF SAS DATA SETS

SWRI DATA* AND NHTSA COMPLIANCE DATA**

Phase # (I, II, or III)*

Convoy # (1 to 4)*

Tire Man. (1 to 5)*

Tire # (1 to 4)*

Tire Man. and Model**

Tire I.D.**

Circuit # (1 to 10)

Groove Depth Measurements (usually 24 measurements at each circuit)

4.0 RESULTS

4.1 GROOVE WEAR ANALYSIS - SWRI DATA

The SWRI test results analyzed here (Phase I and III) consisted of four convoys for each phase -- two day and two night convoys. Identical tire types were used in each convoy. Table 2 lists the convoys and the tire types and their tread wear and weight loss as reported by SWRI for both phases .

Phase I was performed during relatively cool spring weather whereas Phase III was performed during hot summer months. The wear rates for each group were calculated using the standard regression techniques found in 49 CFR. Table 3 shows the overall wear rates compared to the individual wear of the grooves, and Figures 1 through 4 show the averaged overall and groove wear rates by convoy for each tire type. Figure 5 shows the wear rates averaged over all four convoys of Phase I.

Comparable results are shown in Table 4 and Figures 6 through 10 for Phase III. In general, the following conclusions can be drawn:

1. The outside grooves (SS and OSS) wear more than the inside grooves (A and B);
2. The exception to (1) is the Goodyear tire (Phase I only) in which the A groove wears more than the SS groove and B groove, but less than the OSS groove;
3. The two outside grooves wear differently as do the two inside grooves;
4. Phase III wear rates are much higher, but the tire wear pattern is more even.

TABLE 2. SWRI TEST RESULTS

PHASE I

Tire Type*	Convoy	Treadwear Mean Mils/1000 Miles	Tire Weight Loss Mean g/1000 Miles
1	1	2.04	18.23
2	1	2.60	19.13
3	1	3.29	19.30
4	1	5.38	22.08
1	2	2.17	17.93
2	2	2.58	18.83
3	2	3.23	18.68
4	2	5.48	23.18
1	3	2.26	17.48
2	3	2.71	19.37
3	3	3.57	19.03
4	3	5.25	20.55
1	4	2.28	17.23
2	4	2.75	19.93
3	4	3.37	18.60
4	4	5.15	20.30

* 1 - Uniroyal Tiger Paw
2 - Michelin XA4
3 - Goodyear Arriva
4 - Bridgestone RD401
All tires P195/75R14

TABLE 2. SWRI TEST RESULTS (Continued)

PHASE III

Tire Type	Convoy	Treadwear Mean Mils/1000 Miles	Tire Weight Loss Mean g/1000 Miles
1	1	3.81	25.1
2	1	3.85	24.0
3	1	5.64	26.3
4	1	8.40	32.3
1	2	3.73	24.3
2	2	3.76	23.9
3	2	5.13	25.1
4	2	7.84	30.6
1	3	3.38	23.2
2	3	3.27	23.5
3	3	5.19	24.4
4	3	7.47	28.8
1	4	3.38	22.1
2	4	4.36	24.2
3	4	4.90	24.1
4	4	7.49	26.7

TABLE 3. PHASE I GROOVE COMPARISONS

Tire Type	Convoy		Treadwear Mean and CV%					Ratio-Groove to Overall Mean and CV%			
			SS	A	B	OSS	All	SS	A	B	OSS
Uniroyal	1	$\bar{X}$	2.62	1.62	1.63	2.27	2.03	1.29	0.79	0.80	1.11
		CV	6.99	10.62	9.74	3.46	3.07	6.12	10.26	7.16	4.68
	2	$\bar{X}$	2.64	1.73	1.90	2.39	2.17	1.22	0.8	0.87	1.10
		CV	7.58	5.23	12.37	7.4	3.59	6.27	4.86	12.19	6.0
	3	$\bar{X}$	2.85	1.89	1.82	2.47	2.26	1.26	0.83	0.80	1.09
		CV	4.99	7.61	4.19	9.8	3.52	6.47	6.65	3.11	7.25
	4	$\bar{X}$	3.02	1.71	1.92	2.46	2.28	1.33	0.75	0.84	1.08
		CV	7.11	8.0	4.3	6.9	4.2	5.57	4.87	4.88	5.74
Overall Mean		$\bar{X}$	2.78	1.74	1.82	2.40	2.19	1.28	0.79	0.83	1.09
Michelin	1	$\bar{X}$	2.87	2.20	—	2.73	2.60	1.10	0.85	—	1.05
		CV	11.68	10.76	—	16.31	12.94	2.17	2.35	—	1.05
	2	$\bar{X}$	2.71	2.21	—	2.81	2.58	1.06	0.85	—	1.08
		CV	12.89	19.35	—	2.47	19.19	6.1	2.59	—	5.96
	3	$\bar{X}$	3.21	2.15	—	2.80	2.72	1.19	0.79	—	1.03
		CV	6.6	17.4	—	19.03	12.46	8.69	6.96	—	8.08
	4	$\bar{X}$	3.21	2.12	—	2.91	2.74	1.18	0.77	—	1.05
		CV	13.81	16.24	—	21.39	14.45	13.05	6.14	—	10.43
Overall Mean		$\bar{X}$	3.00	2.17	—	2.81	2.66	1.13	0.82	—	1.05

TABLE 3. PHASE I GROOVE COMPARISONS (Continued)

Tire Type	Convoy		Treadwear Mean and CV%					Ratio-Groove to Overall Mean and CV%			
			SS	A	B	OSS	All	SS	A	B	OSS
Goodyear	1	$\bar{X}$	2.99	3.62	2.84	3.71	3.29	0.90	1.10	0.86	1.12
		CV	6.18	5.35	7.04	7.34	5.32	5.7	3.64	2.80	2.76
	2	$\bar{X}$	2.86	3.37	2.92	3.73	3.22	0.89	1.04	0.91	1.15
		CV	5.8	4.01	5.48	3.76	1.39	4.52	4.39	4.46	4.67
	3	$\bar{X}$	3.32	3.76	3.42	3.77	3.57	0.93	1.05	0.95	1.05
		CV	7.57	9.41	11.44	16.45	9.22	4.80	6.79	2.73	11.83
	4	$\bar{X}$	3.06	3.57	3.05	3.79	3.37	0.91	1.06	0.91	1.12
		CV	13.11	9.7	1.83	8.9	3.37	9.96	9.09	4.61	9.63
Overall Mean		$\bar{X}$	3.06	3.58	3.06	3.75	3.36	0.91	1.06	0.91	1.11
Bridgestone	1	$\bar{X}$	6.08	4.86	4.73	5.84	5.38	1.13	0.90	0.88	1.09
		CV	2.41	4.75	2.78	5.44	2.27	3.28	3.50	1.97	4.15
	2	$\bar{X}$	6.21	5.08	4.77	5.88	5.49	1.13	0.93	0.87	1.07
		CV	8.05	6.59	3.70	10.26	2.56	7.59	6.22	2.23	9.66
	3	$\bar{X}$	6.1	4.92	4.53	5.43	5.25	1.16	0.93	0.86	1.03
		CV	10.47	9.34	6.70	11.76	6.49	8.8	5.08	5.36	8.30
	4	$\bar{X}$	6.07	4.98	4.50	5.03	5.14	1.18	0.97	0.87	0.98
		CV	8.54	8.65	6.05	2.47	5.94	2.98	3.61	3.50	4.81
Overall Mean		$\bar{X}$	6.12	4.96	4.53	5.54	5.31	1.15	0.93	0.87	1.04

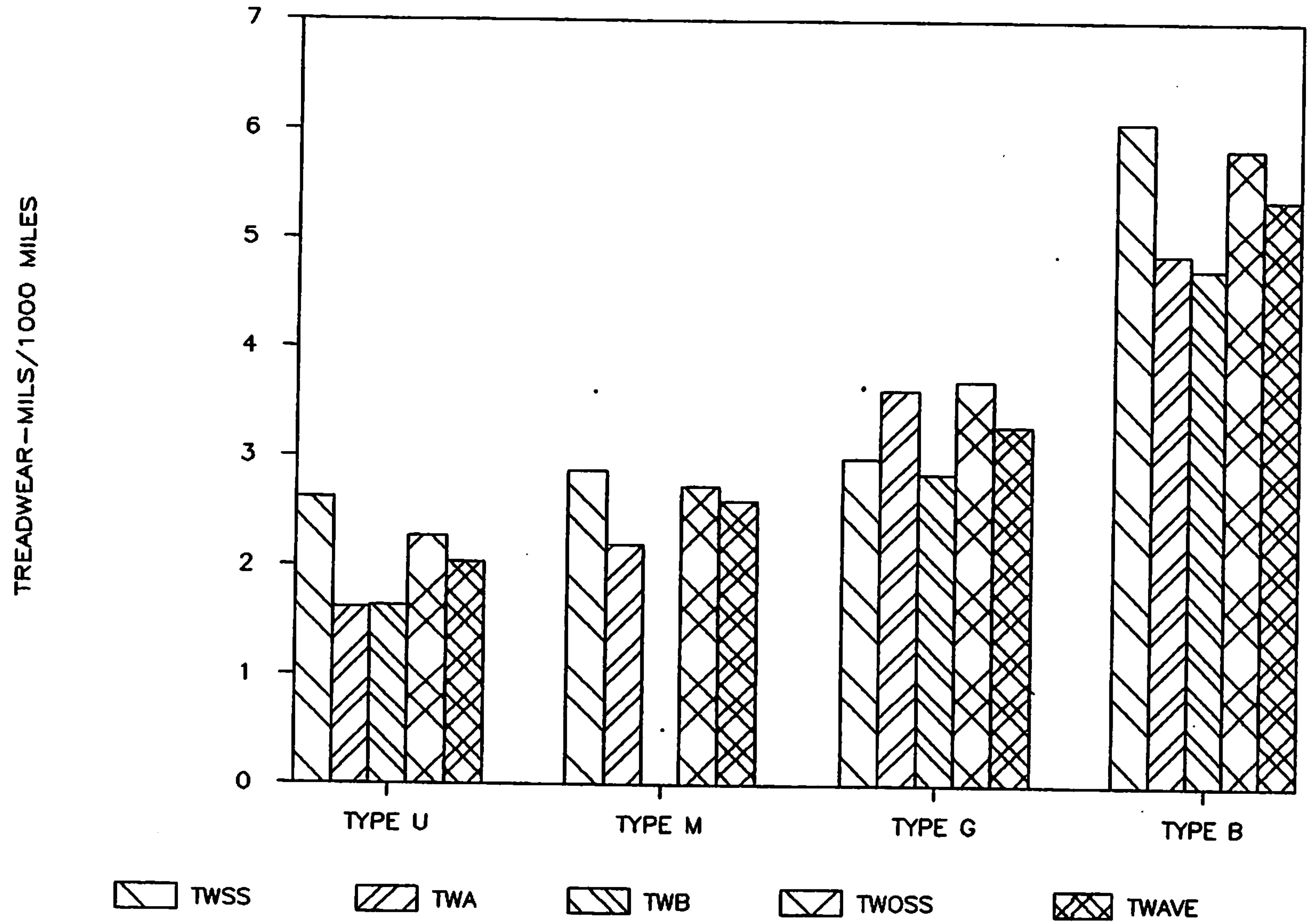

FIGURE 1. GROOVE WEAR RATES FOR SWRI TESTS - CONVOY 1, PHASE I

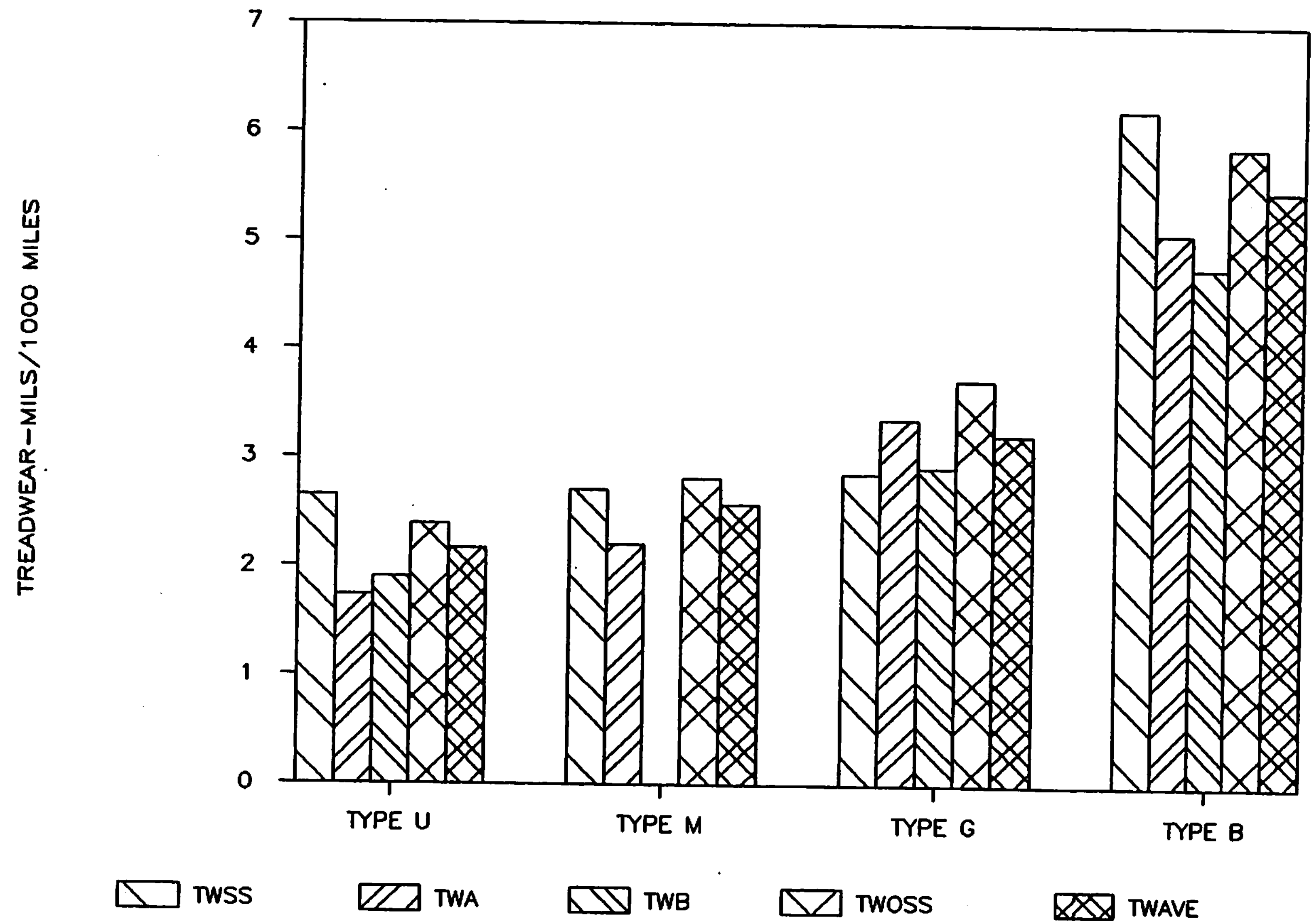

FIGURE 2. GROOVE WEAR RATES FOR SWRI TESTS - CONVOY 2, PHASE I

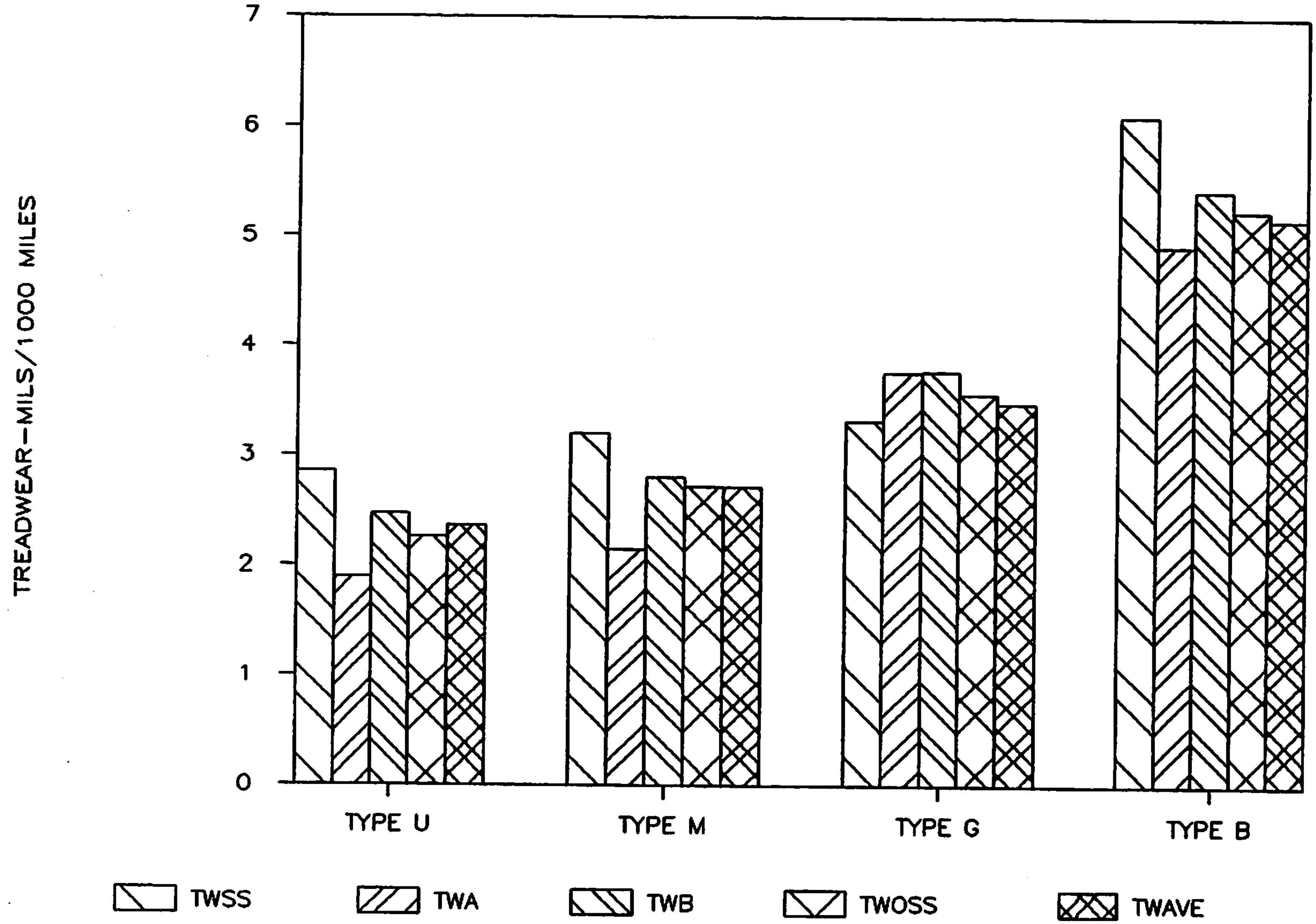

FIGURE 3. GROOVE WEAR RATES FOR SWRI TESTS - CONVOY 3, PHASE I

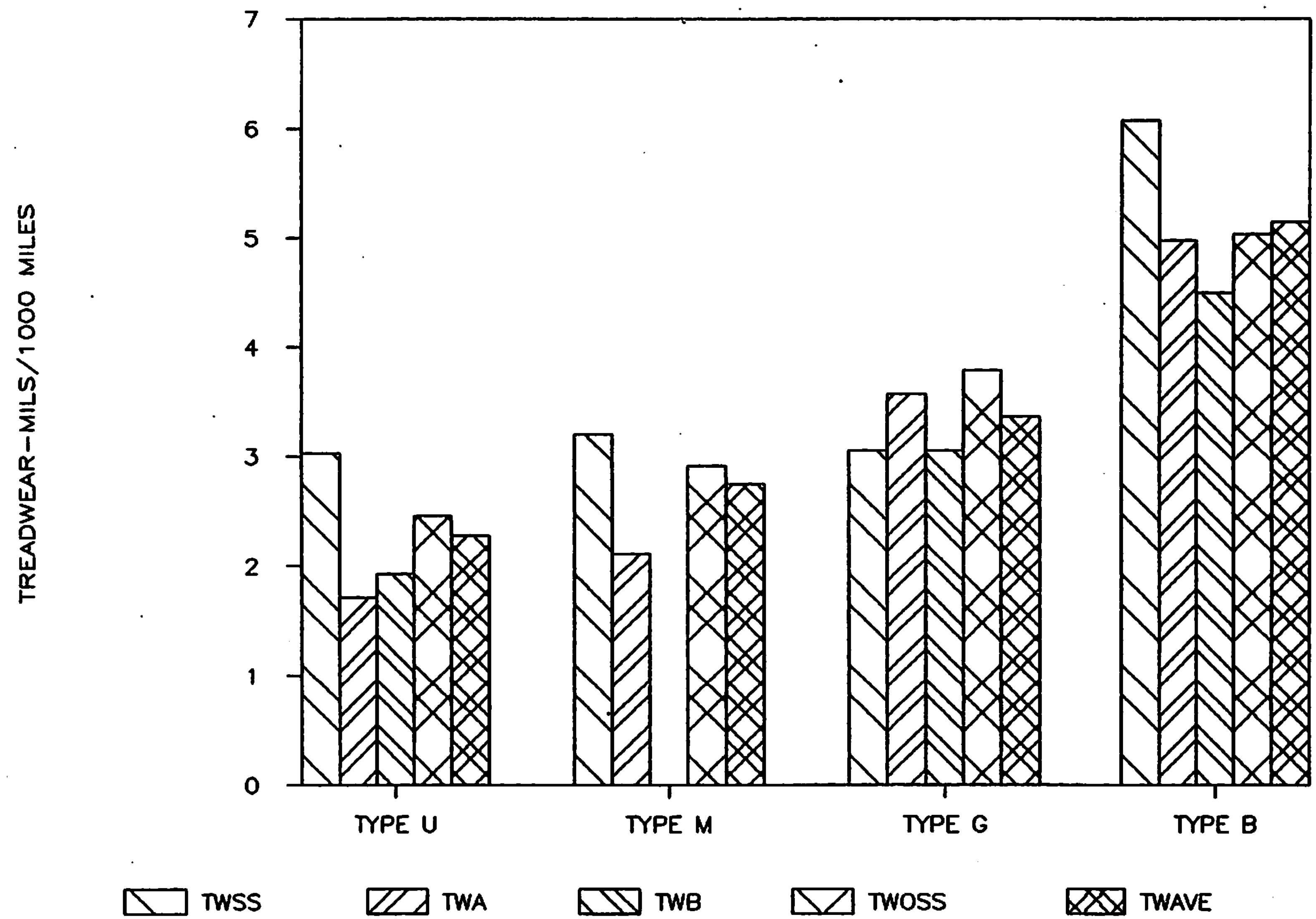

FIGURE 4. GROOVE WEAR RATES FOR SWRI TESTS - CONVOY 4, PHASE I

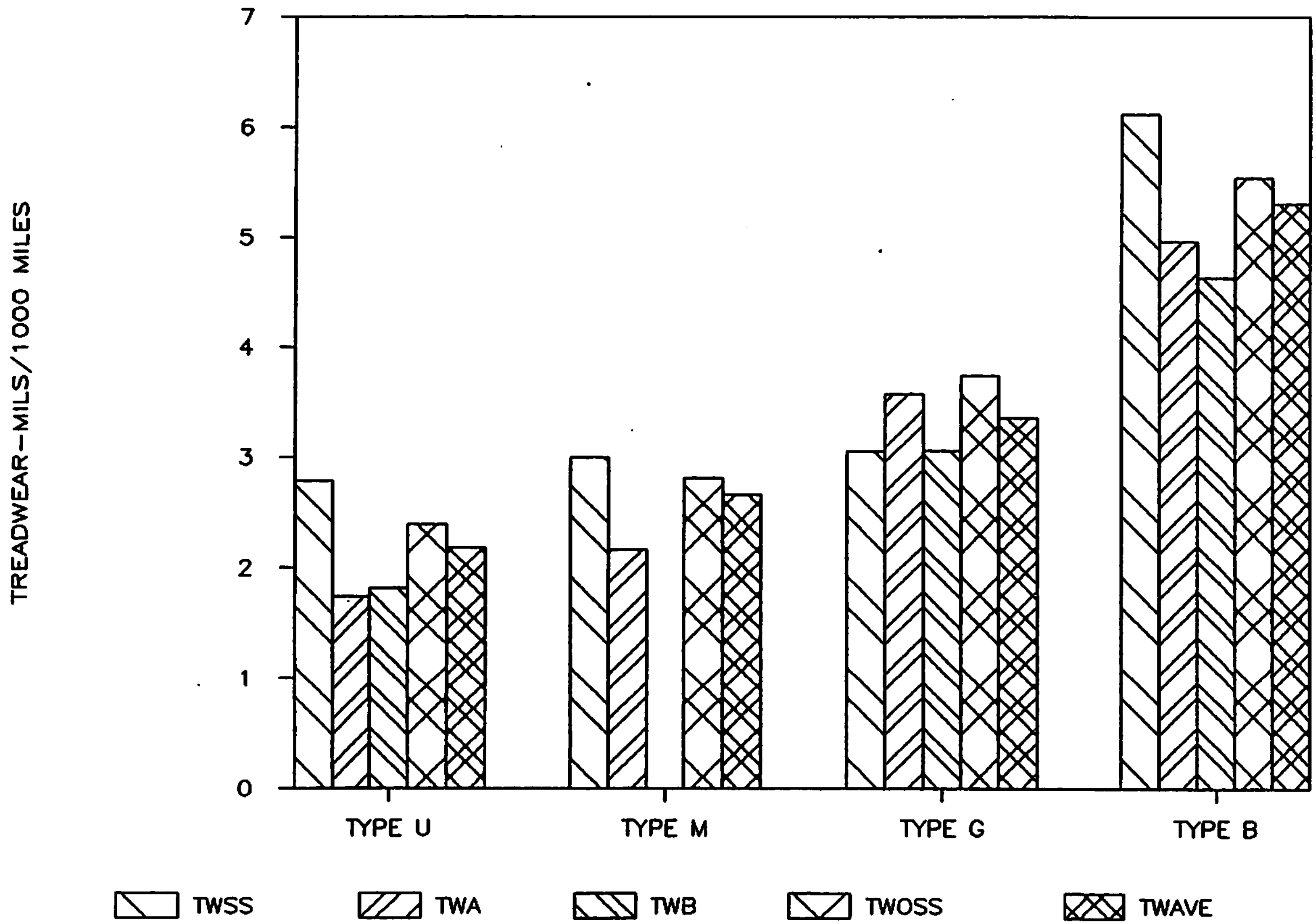

FIGURE 5. GROOVE WEAR RATES FOR SWRI TESTS - AVERAGE (CONVOYS 1-4), PHASE I

TABLE 4. PHASE III GROOVE COMPARISONS

Tire Type	Convoy		Treadwear Mean and CV%					Ratio-Groove to Overall Mean and CV%			
			SS	A	B	OSS	All	SS	A	B	OSS
Uniroyal	1	$\bar{X}$	4.25	3.39	3.46	4.14	3.81	1.12	0.89	0.91	1.09
		CV	4.99	8.41	6.84	5.77	2.63	3.88	5.96	5.19	8.04
	2	$\bar{X}$	4.05	3.27	3.47	4.11	3.72	1.09	0.87	0.93	1.10
		CV	3.84	6.59	4.05	4.76	3.53	3.19	4.12	3.80	2.19
	3	$\bar{X}$	3.79	3.08	3.00	3.65	3.38	1.12	0.91	0.88	1.08
		CV	4.54	7.25	2.19	2.93	3.62	1.67	4.87	1.98	2.05
	4	$\bar{X}$	3.62	3.11	2.97	3.79	3.37	1.07	0.92	0.88	1.12
		CV	2.79	5.75	9.20	7.93	1.61	4.28	4.21	9.54	6.93
Overall Mean		$\bar{X}$	3.92	3.21	3.22	3.92	3.57	1.10	0.90	0.90	1.10
Michelin	1	$\bar{X}$	4.25	3.36	—	3.93	3.85	1.10	0.88	—	1.92
		CV	19.82	16.48	—	20.79	19.04	2.68	2.85	—	3.55
	2	$\bar{X}$	3.89	3.32	—	4.08	3.77	1.04	0.88	—	1.07
		CV	16.63	24.13	—	29.98	22.90	8.65	5.30	—	7.81
	3	$\bar{X}$	4.18	3.64	—	4.22	4.01	1.04	0.91	—	1.05
		CV	19.94	14.98	—	17.17	17.25	3.40	4.03	—	2.76
	4	$\bar{X}$	4.84	3.82	—	4.41	4.36	1.11	0.88	—	1.01
		CV	6.5	6.77	—	9.77	6.24	4.84	5.24	—	3.83
Overall Mean		$\bar{X}$	4.29	3.53	—	4.16	4.00	1.07	0.89	—	1.04

TABLE 4. PHASE III GROOVE COMPARISONS (Continued)

Tire Type	Convoy		TW Treadwear Mean and CV% SS	A	B	OSS	All	Ratio-Groove to Overall Mean and CV% SS	A	B	OSS
Goodyear	1	$\bar{X}$	5.51	5.11	5.21	6.72	5.64	0.97	0.91	0.92	1.19
		CV	3.77	10.68	6.65	5.21	1.92	1.87	9.64	5.76	6.77
	2	$\bar{X}$	5.42	5.00	4.71	5.40	5.13	1.05	0.97	0.92	1.05
		CV	5.15	5.91	4.51	5.77	3.12	4.53	3.52	4.60	4.90
	3	$\bar{X}$	5.03	4.94	5.00	5.79	5.19	0.97	0.95	0.96	1.11
		CV	2.34	1.29	6.06	5.65	1.97	1.89	3.16	5.51	4.29
	4	$\bar{X}$	4.93	4.78	4.73	5.16	4.90	1.00	0.97	0.96	1.05
		CV	6.60	4.37	7.59	5.90	1.94	4.77	3.34	6.65	7.81
Overall Mean		$\bar{X}$	5.22	4.96	4.91	5.76	5.21	1.00	0.95	0.94	1.10
Bridgestone	1	$\bar{X}$	8.89	7.97	7.83	8.85	8.39	1.06	0.95	0.93	1.05
		CV	4.50	5.06	3.75	8.47	4.39	7.52	4.34	1.54	5.70
	2	$\bar{X}$	8.28	7.59	7.35	8.05	7.81	1.06	0.97	0.94	1.03
		CV	5.73	1.50	2.50	10.08	4.66	2.63	3.89	2.55	5.38
	3	$\bar{X}$	8.05	7.24	6.90	7.66	7.46	1.07	0.97	0.92	1.02
		CV	5.73	1.50	2.50	10.08	4.66	2.63	3.89	2.55	5.38
	4	$\bar{X}$	7.88	7.06	6.99	8.02	7.49	1.05	0.94	0.93	1.07
		CV	1.90	2.25	2.11	7.49	1.89	3.45	2.31	2.56	5.64
Overall Mean		$\bar{X}$	8.27	7.46	7.26	7.79	7.79	1.06	0.95	0.93	1.04

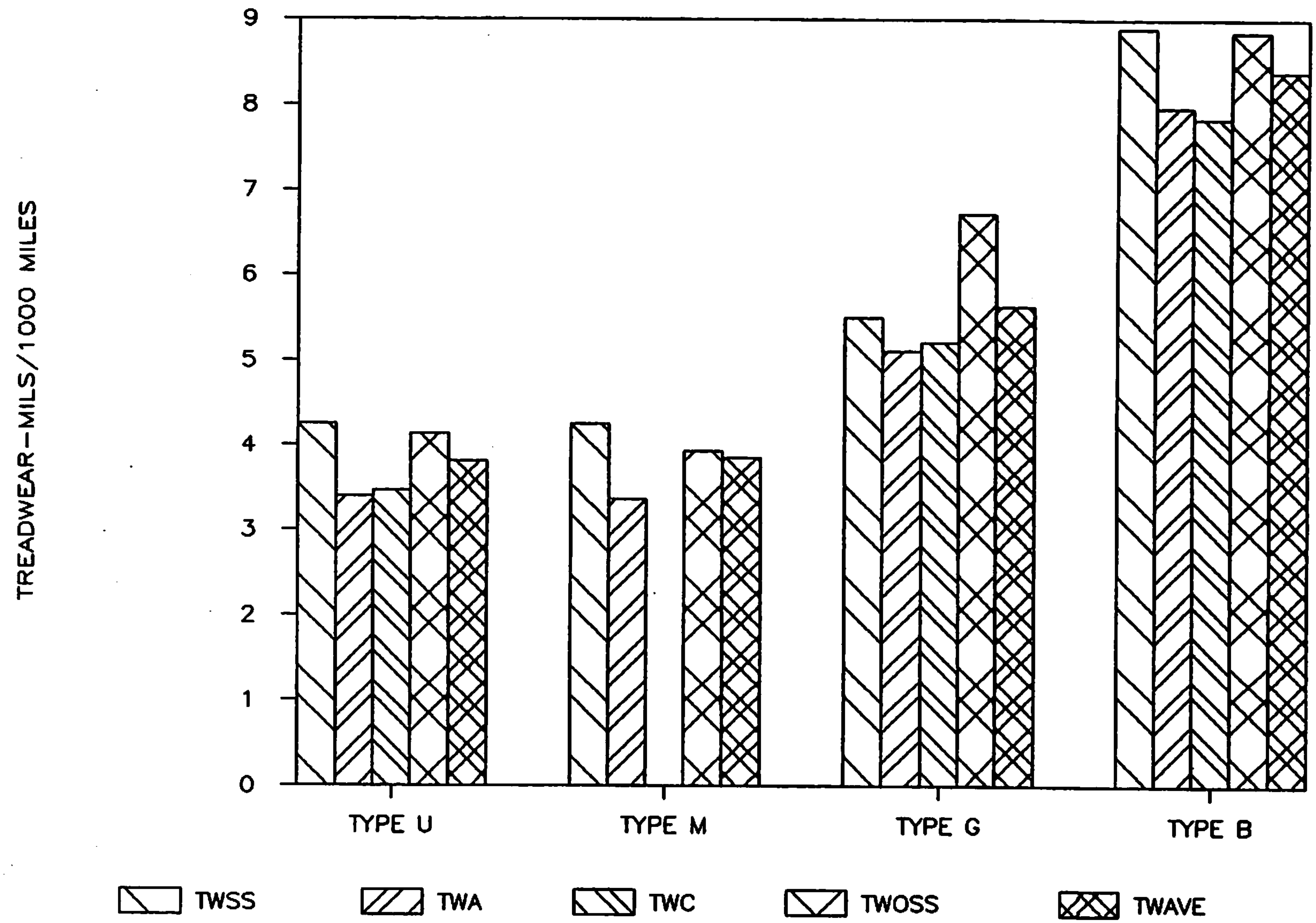

FIGURE 6. GROOVE WEAR RATES FOR SWRI TESTS - CONVOY 1, PHASE III

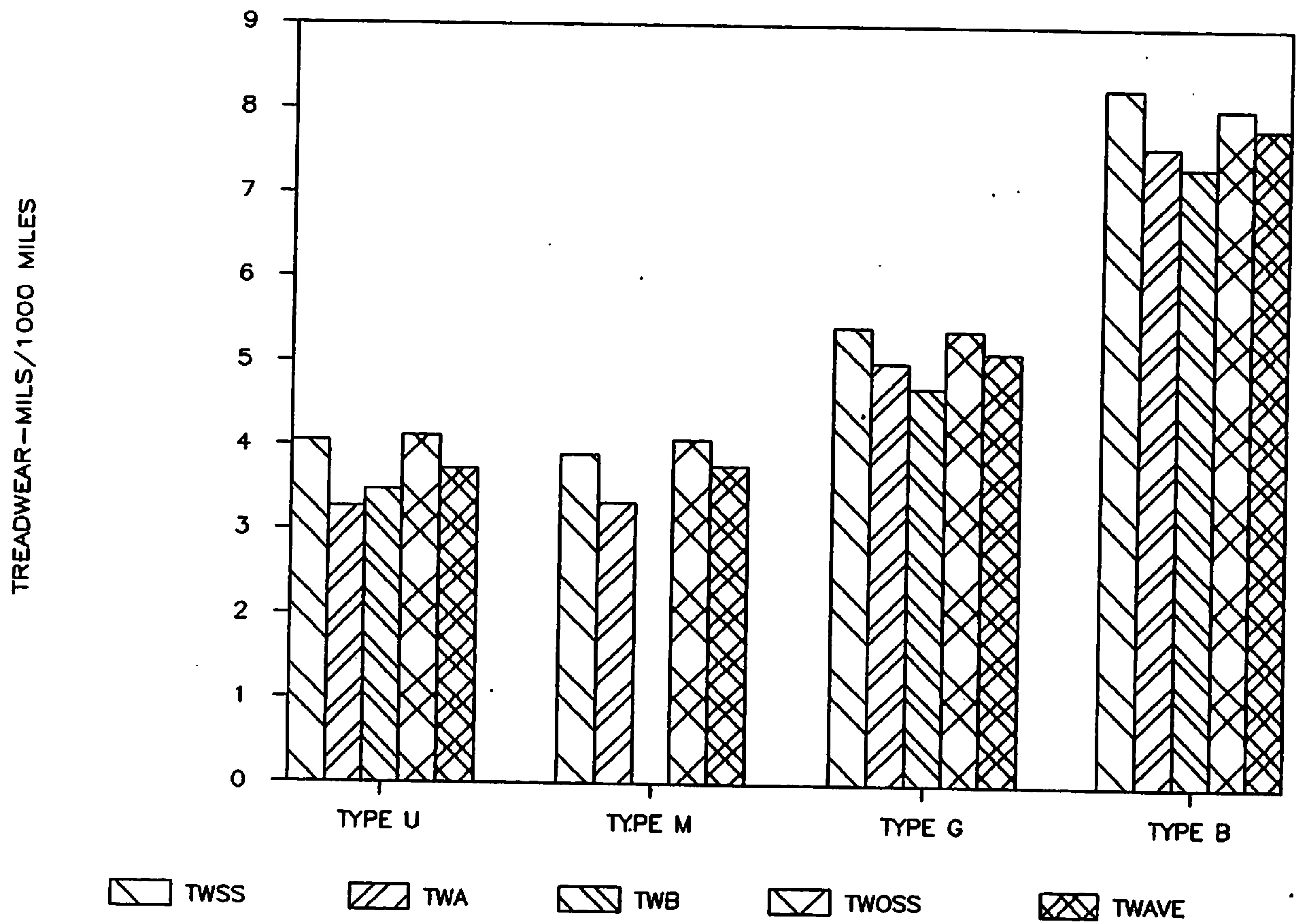

FIGURE 7. GROOVE WEAR RATES FOR SWRI TESTS - CONVOY 2, PHASE III

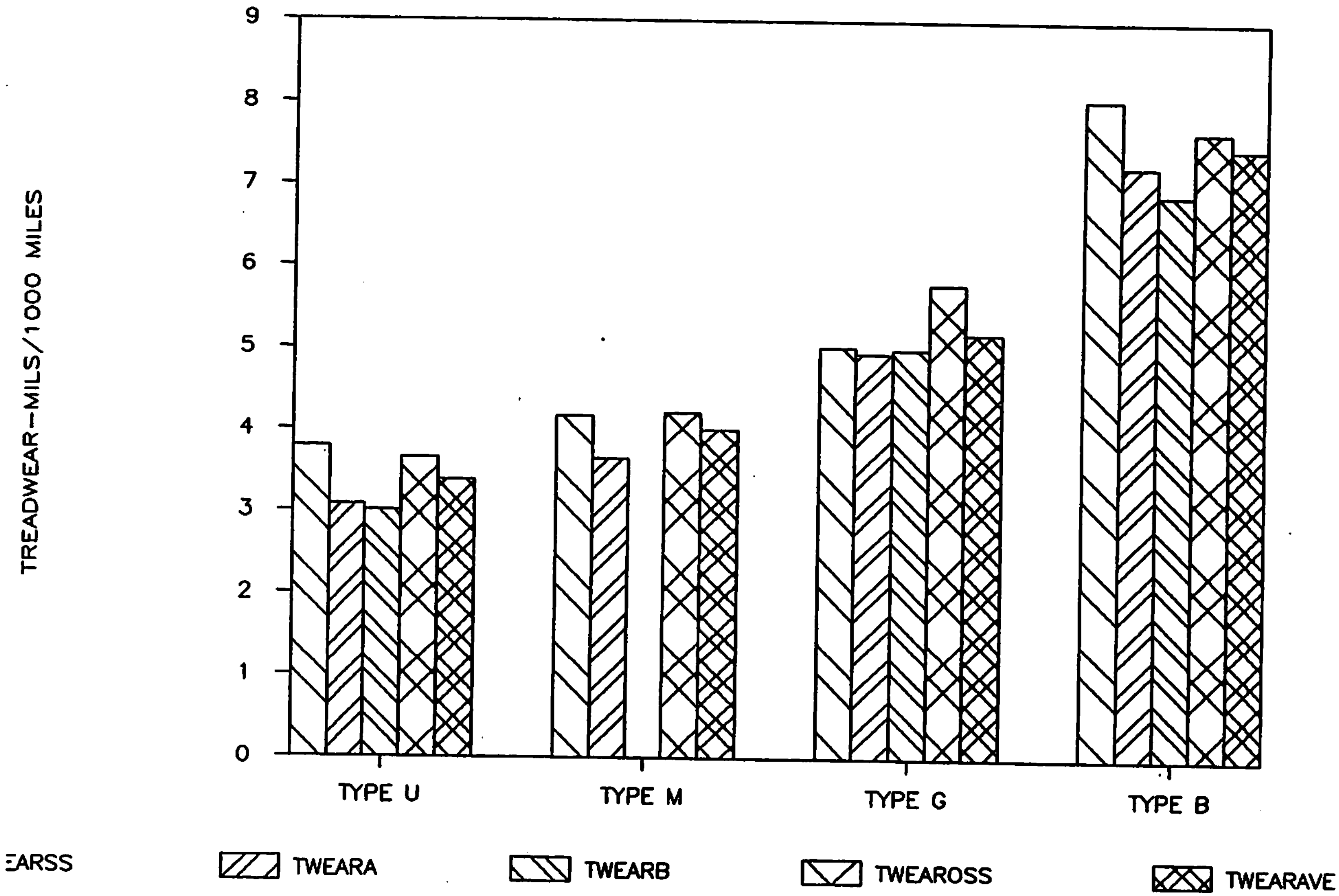

FIGURE 8. GROOVE WEAR RATES FOR SWRI TESTS - CONVOY 3, PHASE III

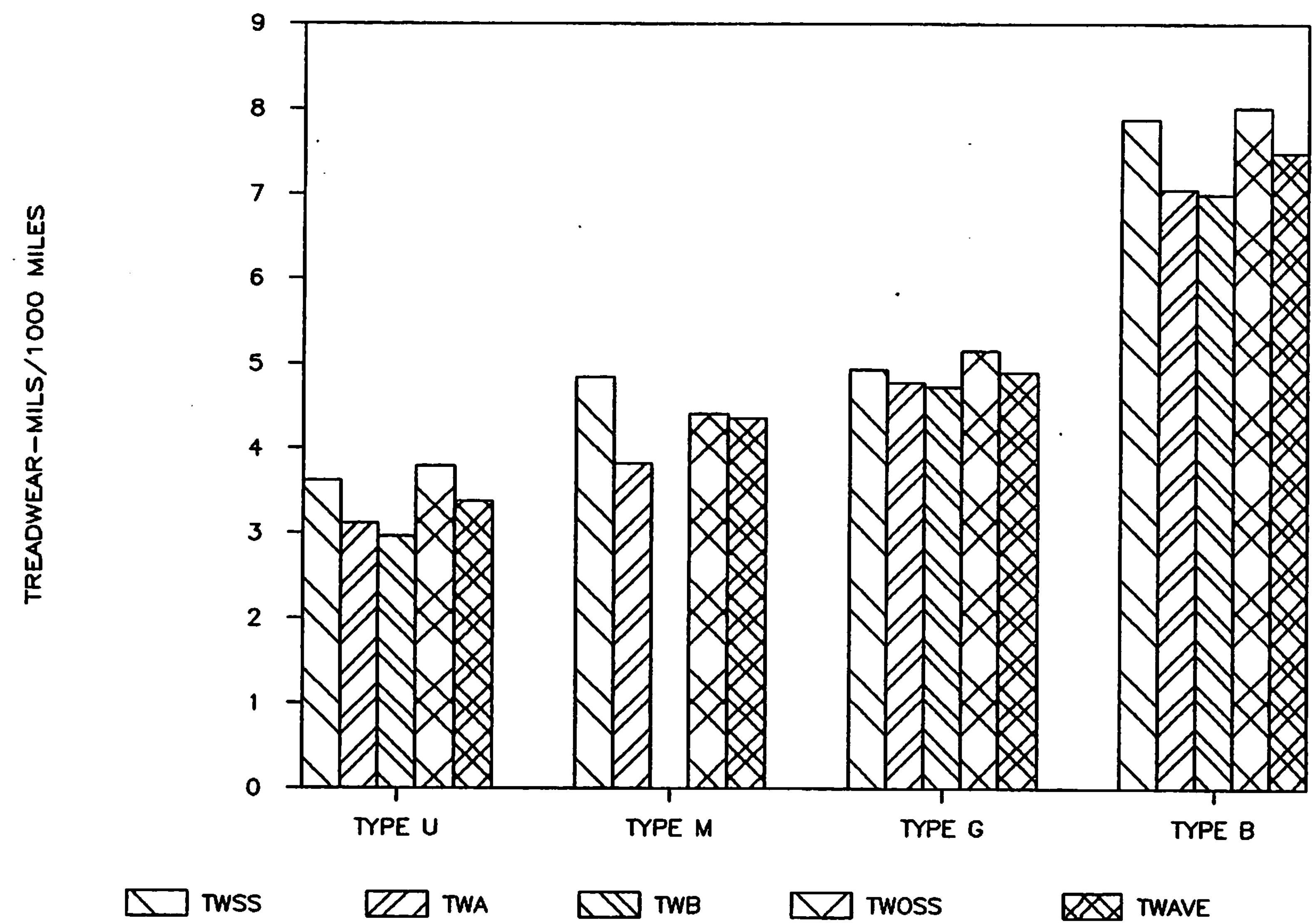

FIGURE 9. GROOVE WEAR RATES FOR SWRI TESTS - CONVOY 4, PHASE III

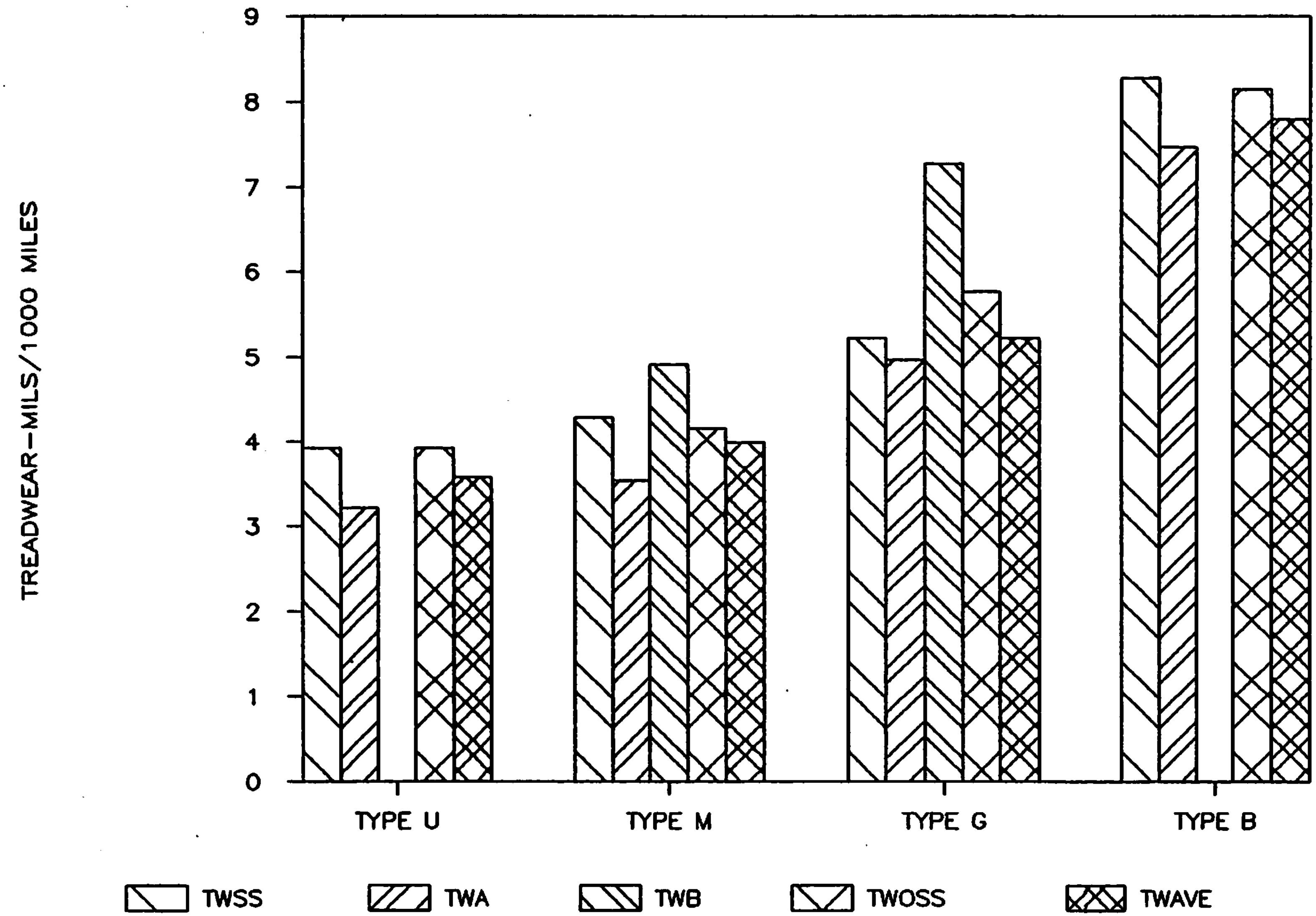

FIGURE 10. GROOVE WEAR RATES FOR SWRI TESTS - AVERAGE (CONVOYS 1-4), PHASE III

5. The tread wear patterns are consistent from tire to tire within tire type-within phase, but change from phase to phase, indicating that these patterns are a complex function of tire construction and test conditions.

Tables 3 and 4 also indicate that the coefficient of variation (COV) shows little uniformity both within and between grooves of a tire type, perhaps indicating that the variation in the groove depth measurements is more a function of the measurements procedure than the tire wear pattern. Tables 3 and 4 and Figures 11 and 12 also show the ratios of the grooves to the overall tire wear. The figures are the average over the four convoys of each Phase. Tables 3 and 4 also show the coefficients of variation of these ratios. During Phase I, the Uniroyal tire had the highest groove variation with the outside grooves being 9 and 28 percent higher than the overall and the inside grooves 21 and 17 percent less than the overall tire average. The Goodyear tire showed the least groove-to-groove variation. The effect of these groove variations on the tire attained grade is shown in Figures 13 through 22 for Phases I and III. For the attained grade calculation of various groove combinations, we used the Uniroyal tire as a Course Monitoring Tire (CMT). The base wear rate (BWR) was the overall average of the Uniroyal tire over all of Phase I or Phase III, respectively. The ratio of the BWR to the average overall wear of the Uniroyal tire within the particular convoy under analysis was the course severity adjustement factor (CSAF) used in calculating the attained grade for the remaining three tires in that convoy. The attained grade for the various groove combinations varied, in most cases, by less than 10 percent from the overall tire attained grade. The Michelin tire had the largest spread in attained grade whereas the Goodyear tire had the least. (The Uniroyal would have the largest if it was considered in this calculation.)

The Phase III results show that the tread wear increased significantly with a like drecrease in attained grade during the hot weather tests. This increase is shown in

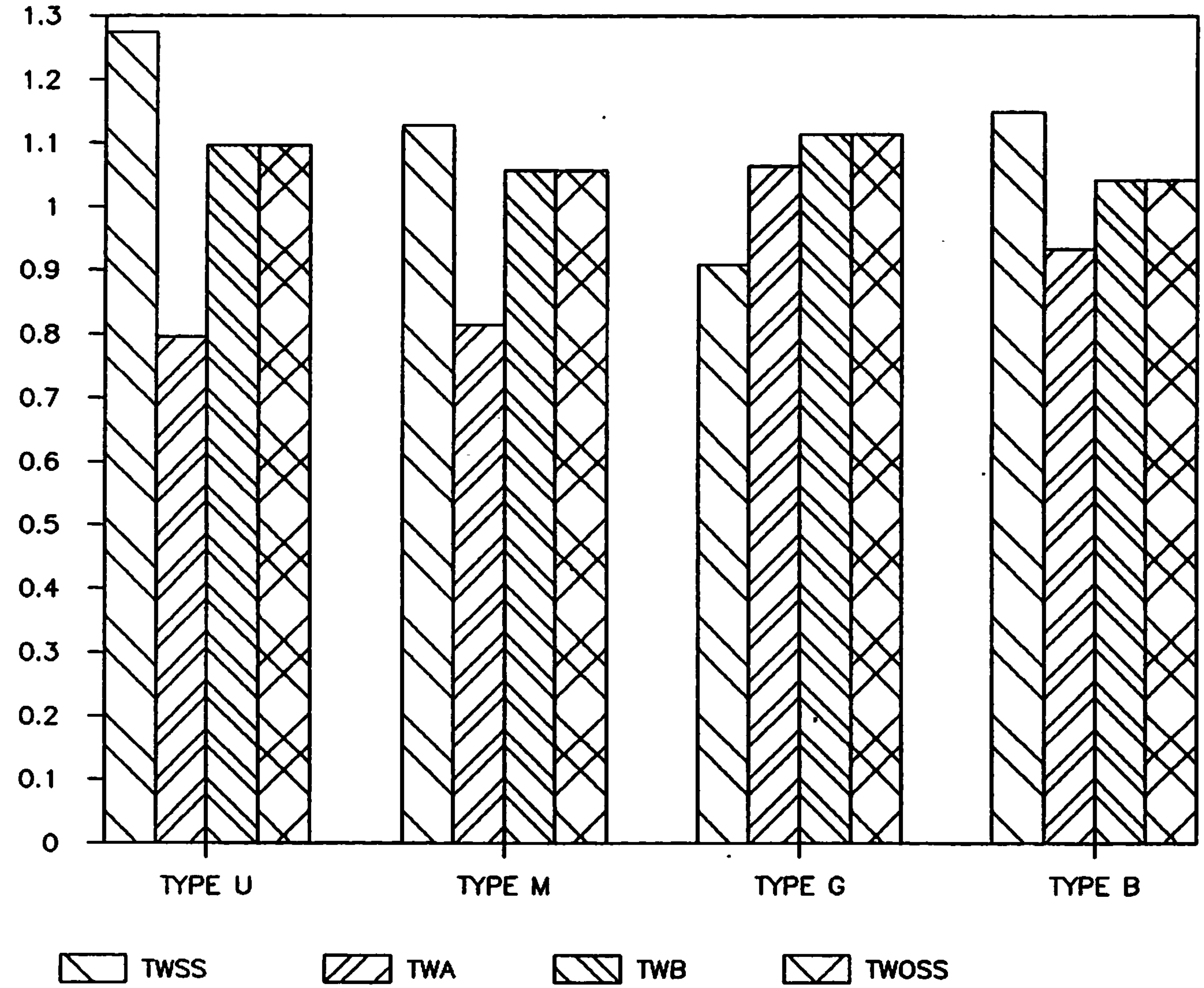

FIGURE 11. RATIOS OF GROOVE WEAR RATES TO TIRE OVERALL WEAR RATES FOR SWRI TESTS - PHASE I, ALL CONVOYS

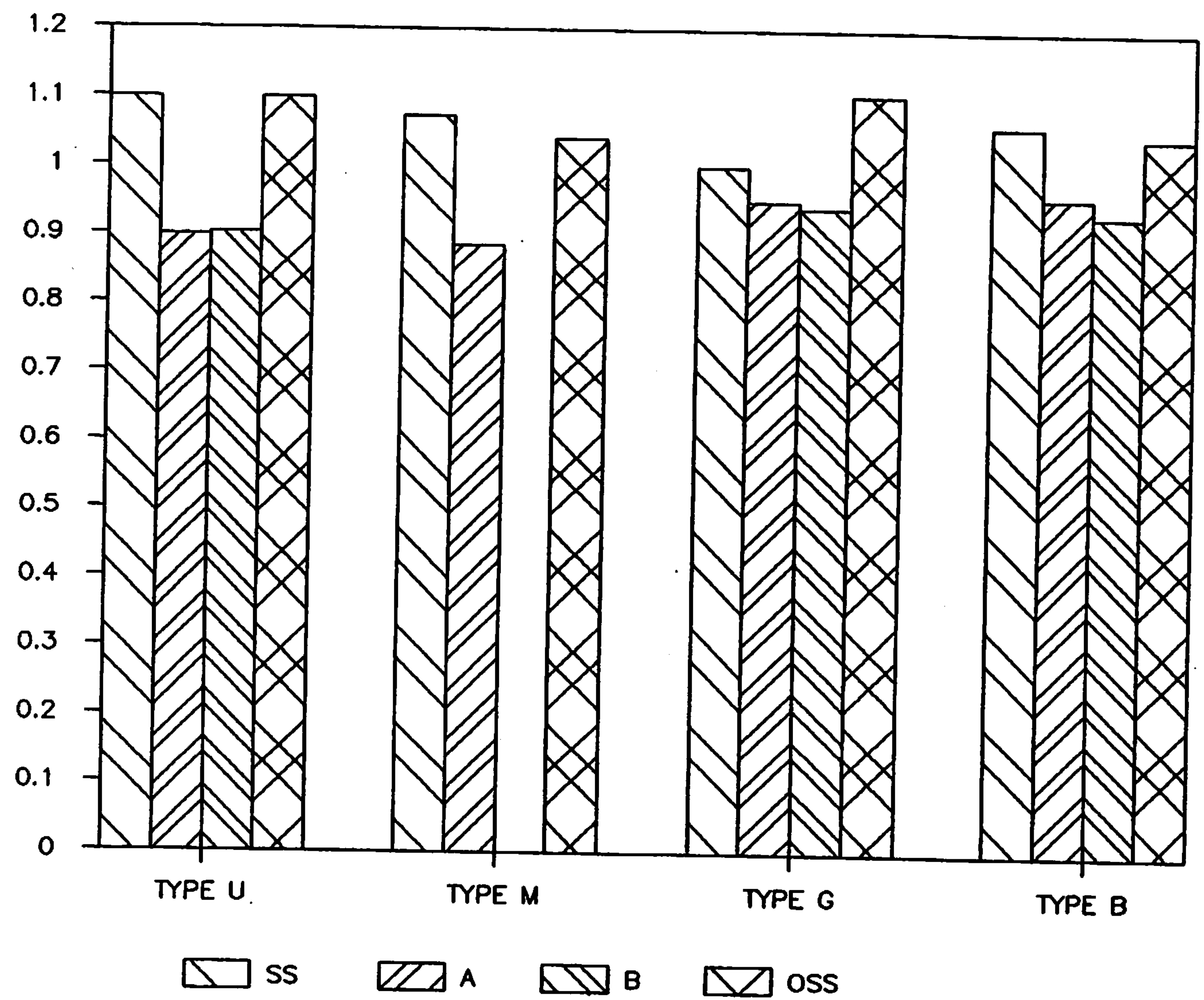

FIGURE 12. RATIOS OF GROOVE WEAR RATES TO TIRE OVERALL WEAR RATES FOR SWRI TESTS - PHASE III, ALL CONVOYS

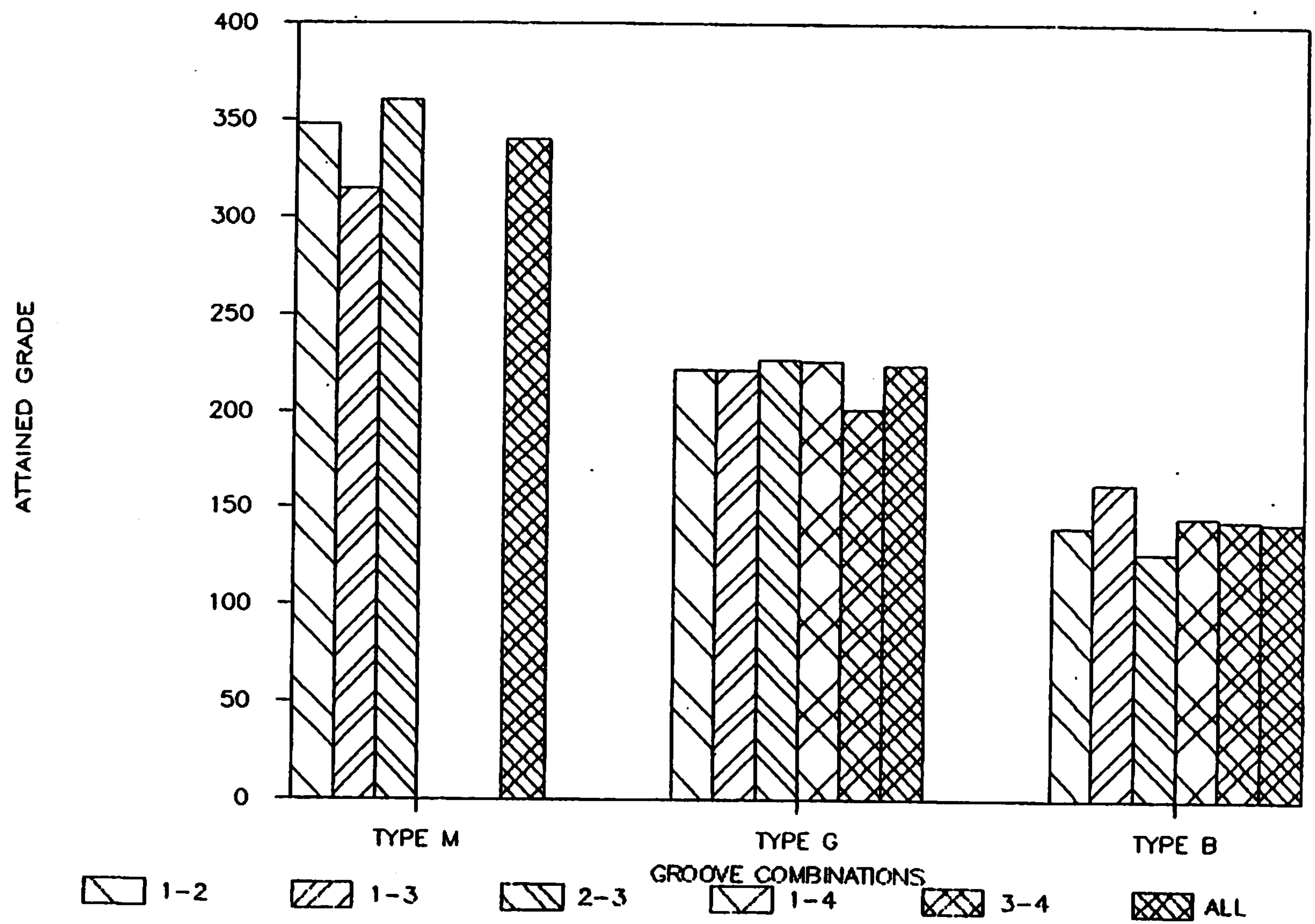

FIGURE 13. ATTAINED GRADES FOR VARIOUS GROOVE COMBINATIONS - SWRI DATA, CONVOY 1, PHASE I

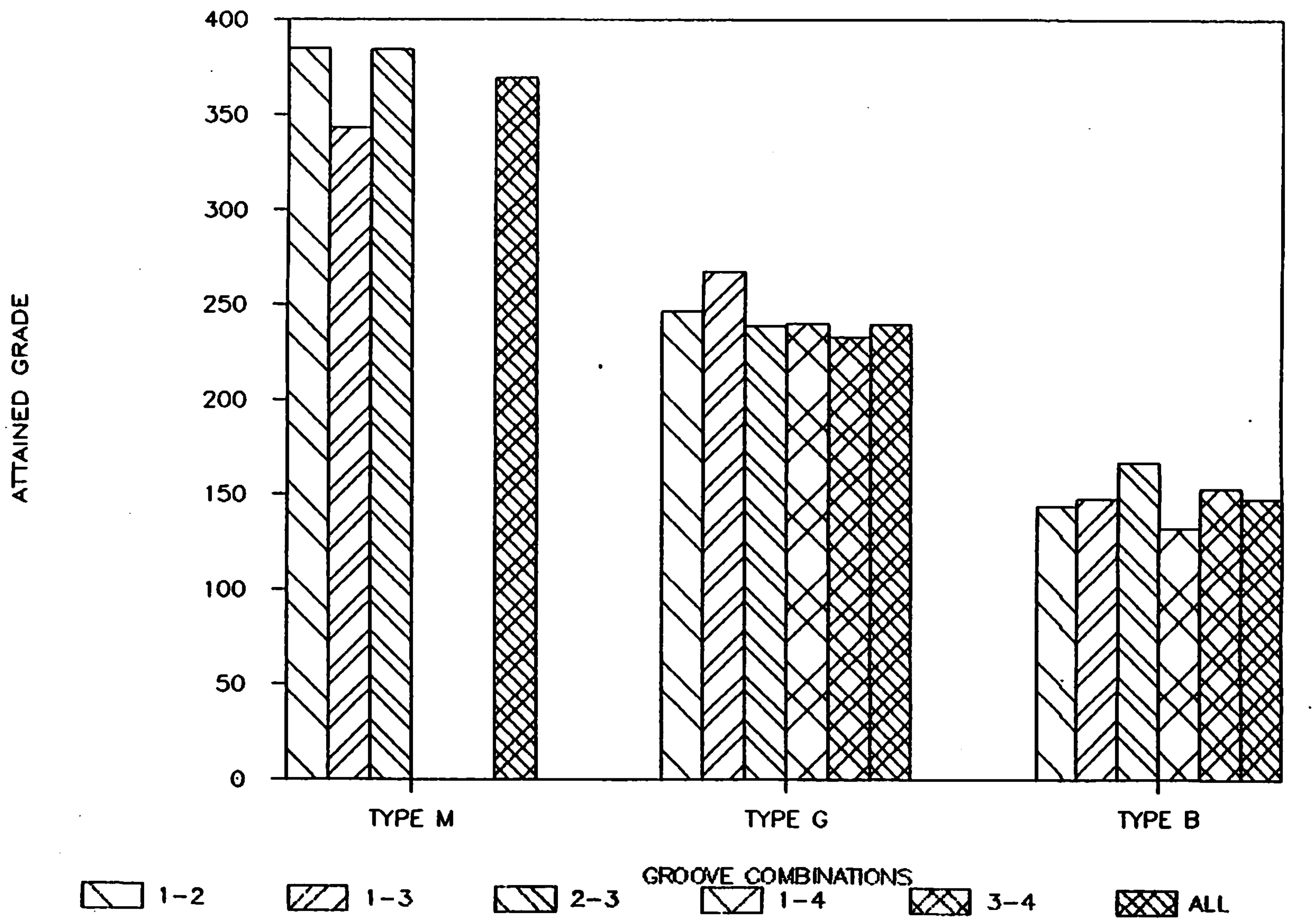

FIGURE 14. ATTAINED GRADES FOR VARIOUS GROOVE COMBINATIONS - SWRI DATA, CONVOY 2, PHASE I

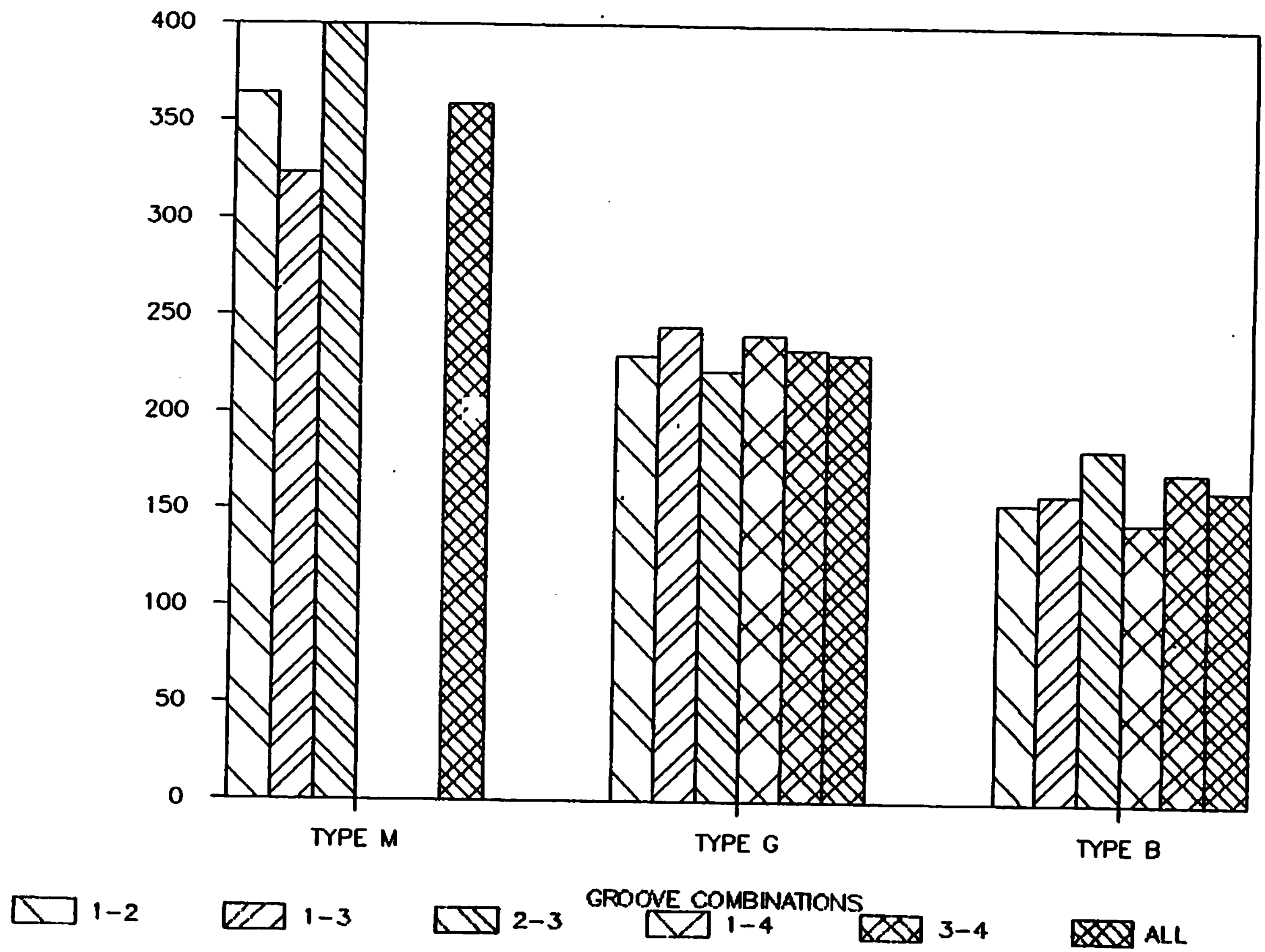

FIGURE 15. ATTAINED GRADES FOR VARIOUS GROOVE COMBINATIONS - SWRI DATA, CONVOY 3, PHASE I

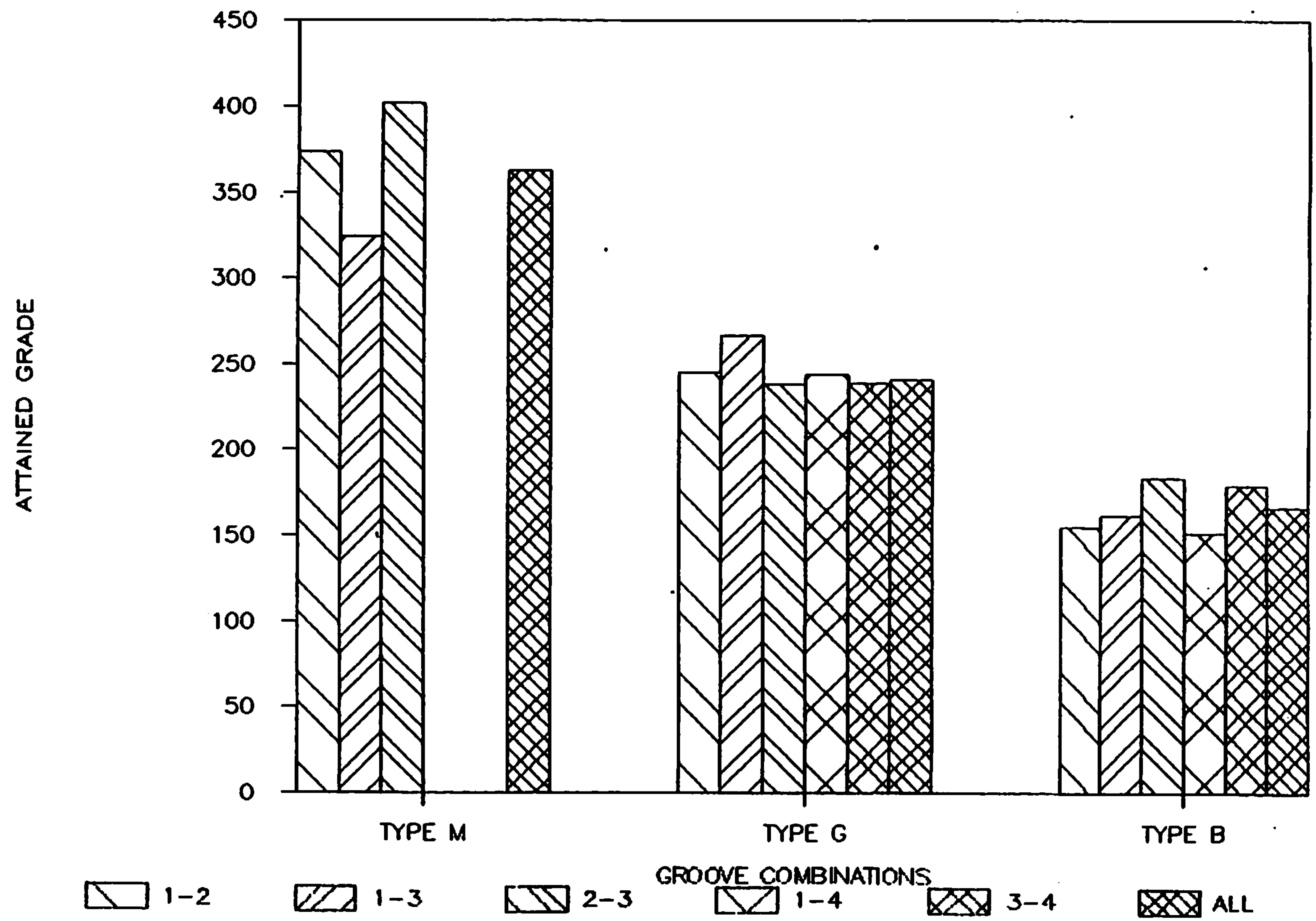

FIGURE 16. ATTAINED GRADES FOR VARIOUS GROOVE COMBINATIONS - SWRI DATA, CONVOY 4, PHASE I

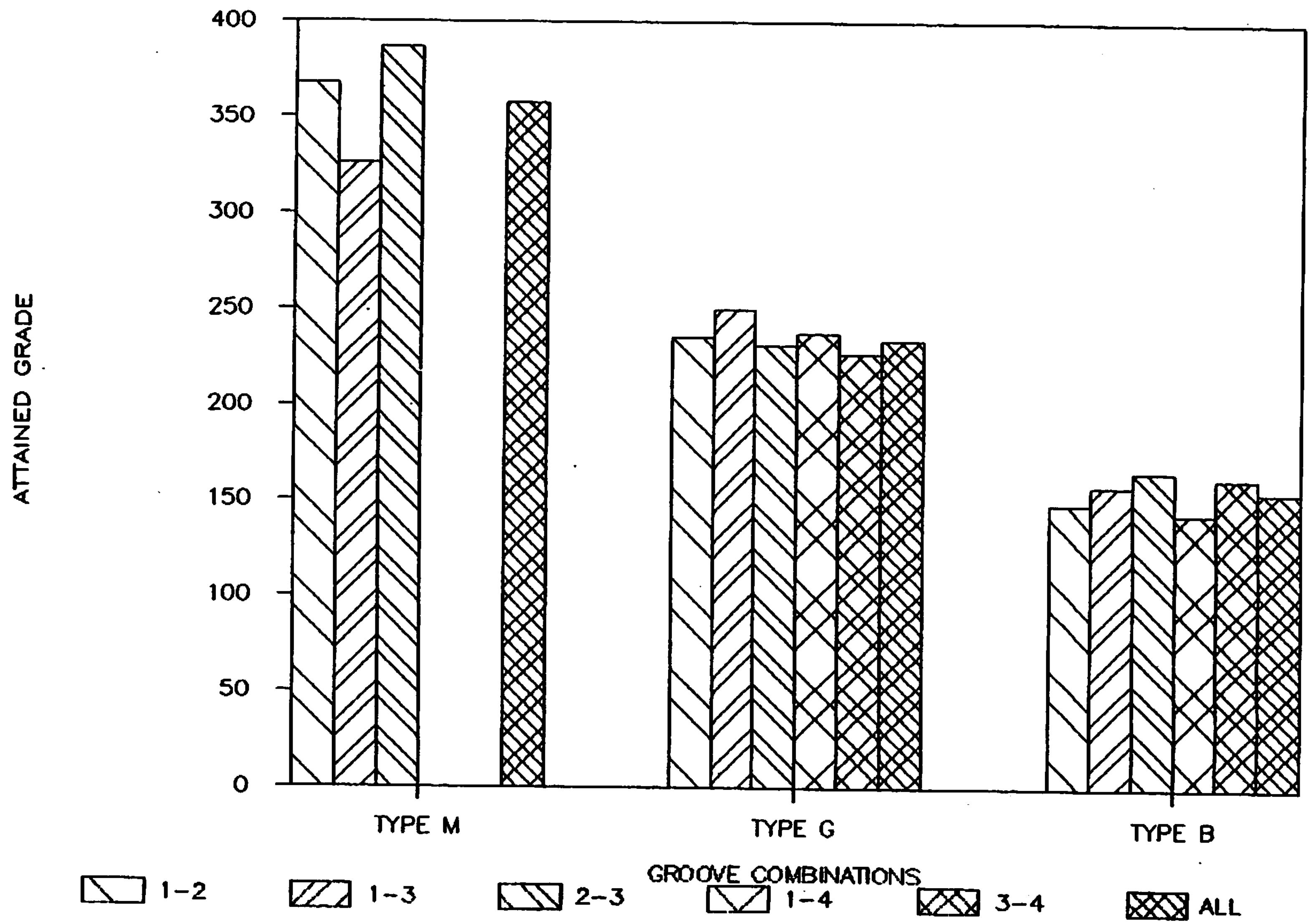

FIGURE 17. ATTAINED GRADES FOR VARIOUS GROOVE COMBINATIONS - SWRI DATA, AVERAGE (CONVOYS 1-4), PHASE I

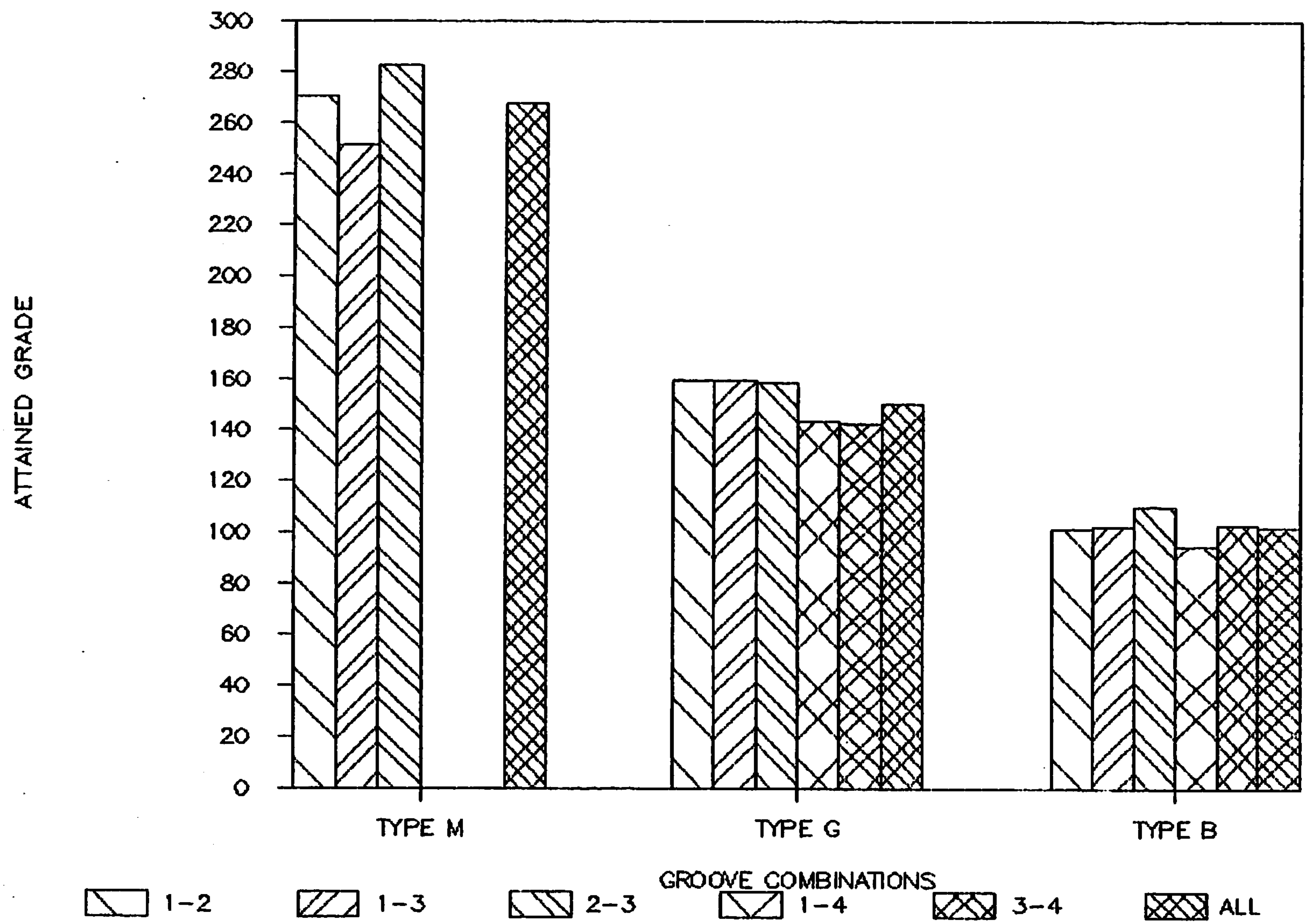

FIGURE 18. ATTAINED GRADES FOR VARIOUS GROOVE COMBINATIONS - SWRI DATA, CONVOY 1, PHASE III

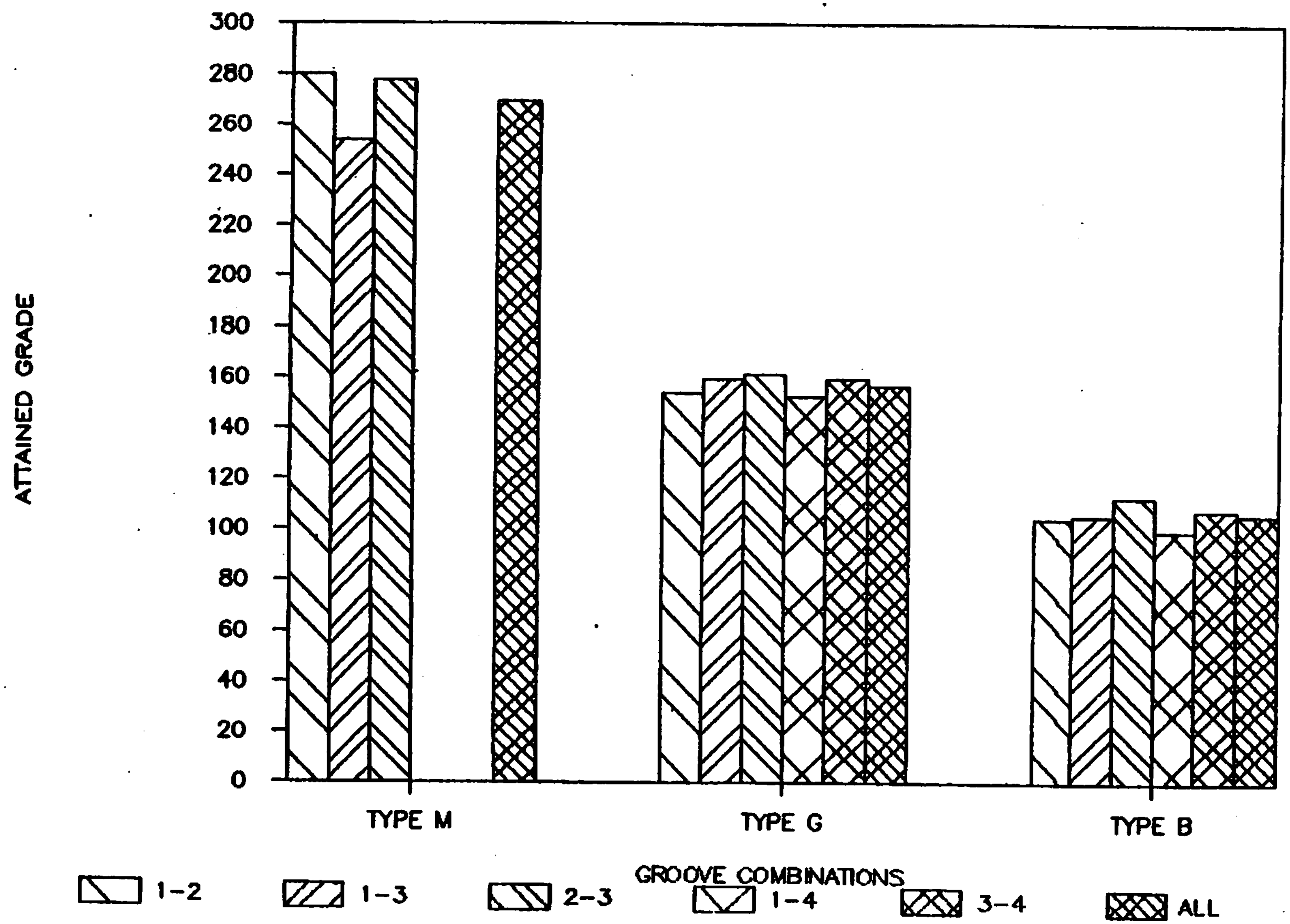

FIGURE 19. ATTAINED GRADES FOR VARIOUS GROOVE COMBINATIONS - SWRI DATA, CONVOY 2, PHASE III

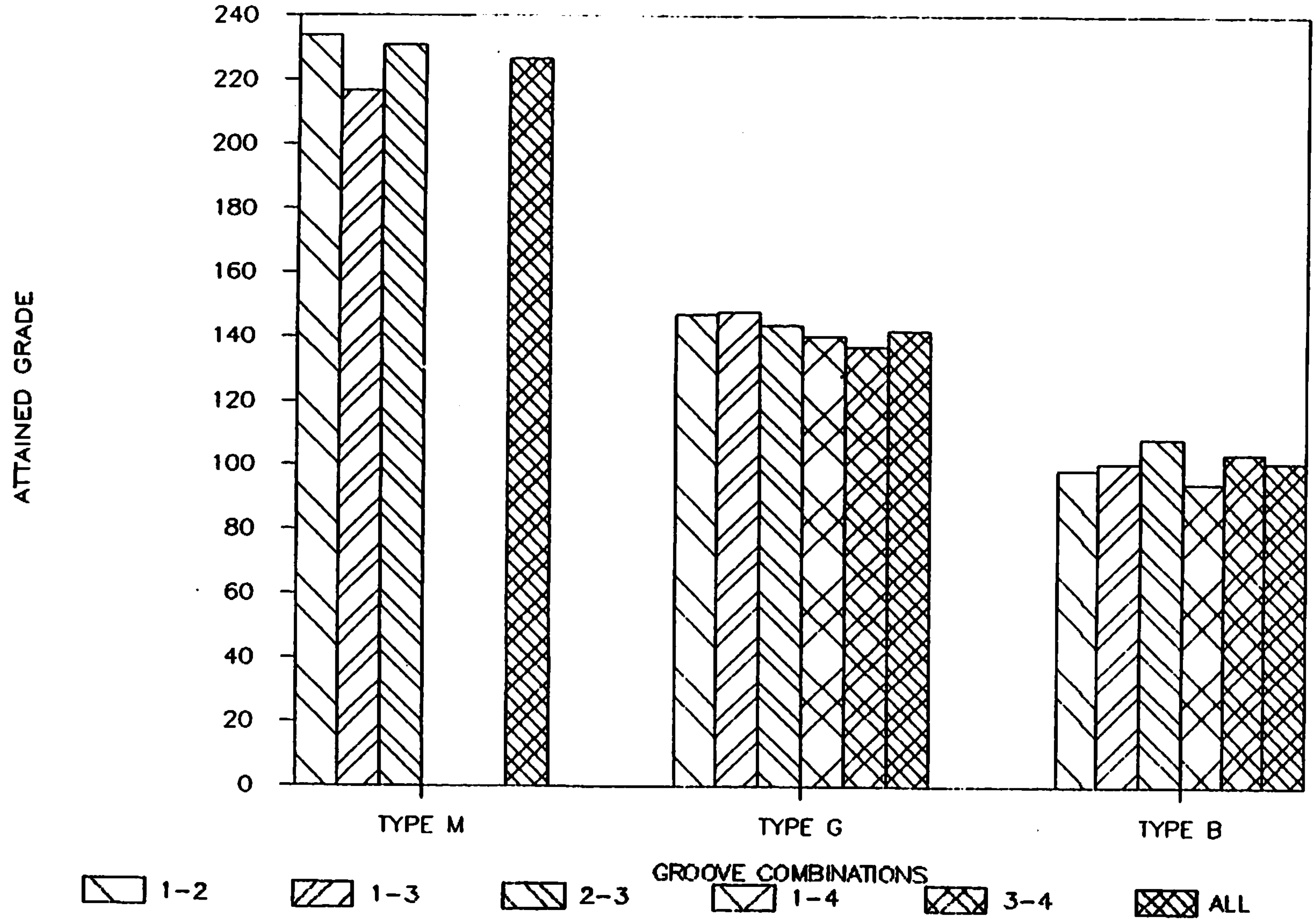

FIGURE 20. ATTAINED GRADES FOR VARIOUS GROOVE COMBINATIONS - SWRI DATA, CONVOY 3, PHASE III

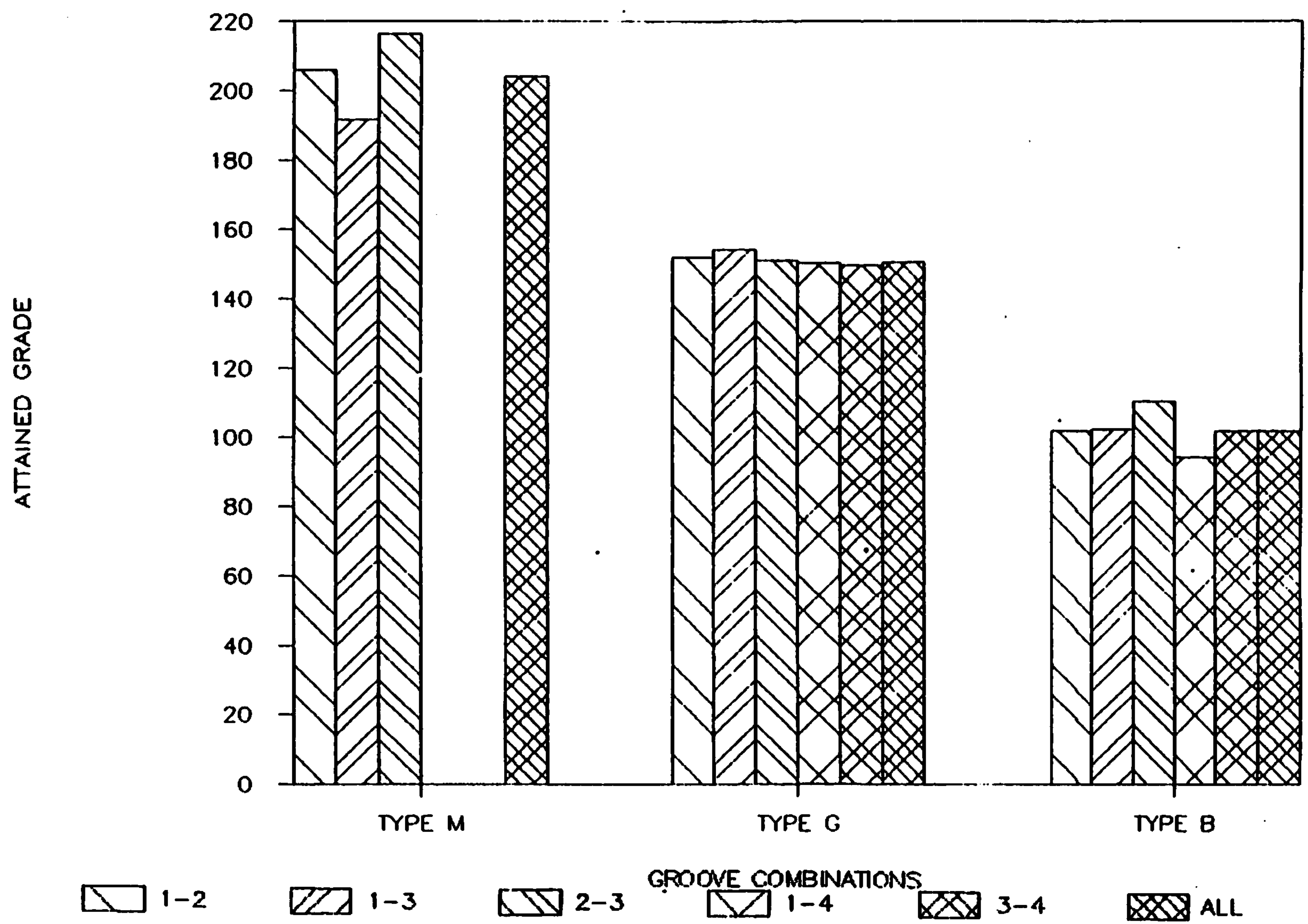

FIGURE 21. ATTAINED GRADES FOR VARIOUS GROOVE COMBINATIONS - SWRI DATA, CONVOY 4, PHASE III

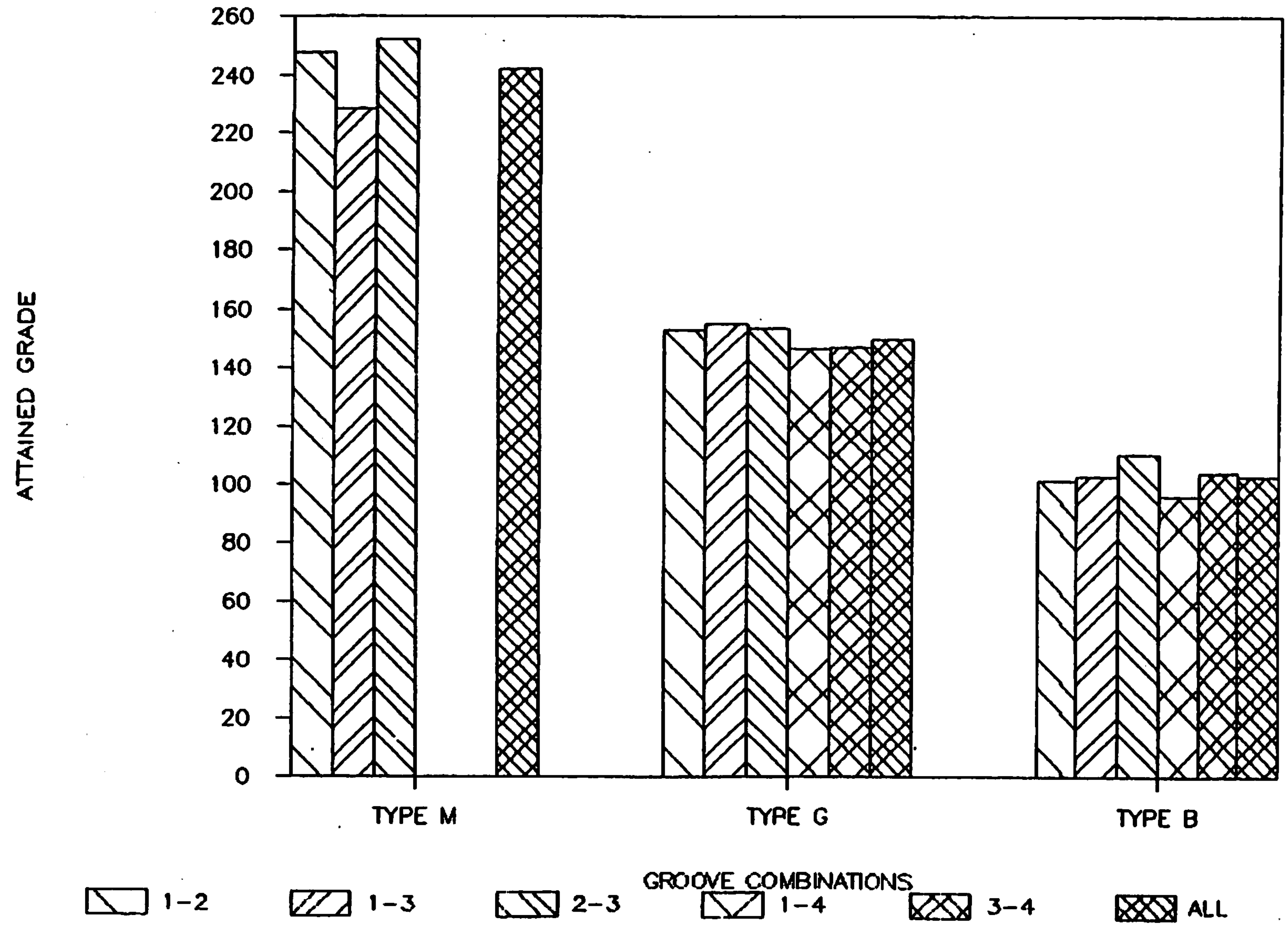

FIGURE 22. ATTAINED GRADES FOR VARIOUS GROOVE COMBINATIONS - SWRI DATA, AVERAGE (CONVOYS 1-4), PHASE III

TABLE 5. COMPARISION OF PHASE I AND III TREAD WEAR RESULTS

Tire Type	Phase I Mean & (CV%)*	Phase III Mean & (CV%)*	Ratio Phase I/Phase III
Uniroyal	2.19 (3.59)	3.57 (2.84)	.613
Michelin	2.66 (14.76)	4.00 (16.36)	.665
Goodyear	3.36 (4.82)	5.21 (2.23)	.645
Bridgestone	5.31 (4.31)	7.79 (4.33)	.682

*Mean and CV of 16 tires in 4 convoys.

TABLE 6. COMPARISON OF PHASE I AND III GROOVE WEAR

Tire Type	Phase	Ratio of Groove Wear to Overall Wear*			
		Groove SS	Groove A	Groove B	Groove OSS
Uniroyal	I	1.28	0.79	0.83	1.09
	III	1.10	0.90	0.90	1.10
Michelin	I	1.13	0.82	—	1.05
	III	1.07	0.89	—	1.04
Goodyear	I	0.91	1.06	0.91	1.11
	III	1.00	0.95	0.94	1.10
Bridgestone	I	1.15	0.93	0.87	1.04
	III	1.06	0.95	0.93	1.04

*Mean of 16 tires in 4 convoys.

Table 5. (SWRI's report analyzed the factors that may effect tread wear variability.) A comparison of the individual groove wear during Phases I and III is given in Table 6.

As we observed in Phase I, the outside groove wear rate is higher than the inside groove wear rate. However, it is interesting to note that ratios in Phase III are closer to 1.00 (the tire overall wear rate) indicating the tires are running with a "flatter" footprint on the road. In fact, the Goodyear tire, which was the exception to the observation in Phase I that the outside grooves wear faster than the inside grooves, is now wearing similar to the other tire types.

The Uniroyal tire still had the highest groove variation, but the Bridgestone had the lowest in Phase III. However, these variations are less than those found in Phase I.

Table 7 shows the ratio of the inner to the outer grooves for each convoy in Phases I and III as well as the ambient mean temperature during the convoy as reported by SWRI. This table indicates that: (1) the within tire type, within phase groove wear is fairly consistent even with large, within phase, ambient temperature changes; (2) the Phase III tire profile indicates more even groove wear than Phase I; (3) ambient temperature effects are not evident in differential groove wear data.

These results show that the tire deflection and subsequent wear patterns changed substantially between Phases I and III. The sources of variability in the UTQG test are complex and difficult to analyze. Sufficient data is not available at this time to apply statistical analysis to determine these variables. However, environmental effects are only one part of the complex analysis. For instance, it is known that tire tread compounds and their wear rate are affected by temperature. The wear rates between tire types are significantly different within both Phases I and III, indicating the tires

TABLE 7. TEMPERATURE COMPARISON GROOVE WEAR AND TEMPERATURE AVERAGE OF FOUR TIRES PER CONVOY

Tire Type	Convoy	Ratio Inner/Outer		Ambient Temperature F	
		Phase I	Phase III	Phase I	Phase III
Uniroyal	1	.66	.81	65.9	88.2
	2	.72	.82	70.4	90.0
	3	.69	.81	53.4	78.6
	4	.66	.82	53.6	77.0
Michelin	1	.79	.82	65.9	88.2
	2	.79	.83	70.4	90.0
	3	.71	.87	53.4	78.6
	4	.69	.83	53.6	77.0
Goodyear	1	.97 (.79*)	.84	65.9	88.2
	2	.96 (.82*)	.90	70.4	90.0
	3	1.01 (.90*)	.92	53.4	78.6
	4	.97 (.83*)	.94	53.6	77.0
Bridgestone	1	.80	.89	65.9	88.2
	2	.82	.91	70.4	90.0
	3	.82	.90	53.4	78.6
	4	.85	.88	53.6	77.0

*Ratio of 2 lowest grooves/2 highest grooves.

were compounded and constructed differently. However, the change in wear rates between Phase I and Phase III is approximately the same for all tire types (approximately .65, Table 5) indicating that other factors predominate in these changes. It is outside the scope of this present effort to evaluate the causes of this variability.

The attained grades of the Phase III tires for various groove combinations (Figure 22) are not as different from the overall tire attained grade as were the Phase I results. This is because of the more even tire wear observed in Phase III. The attained grade was again calculated using the Uniroyal tire as a CMT. The CSAF was calculated using only the within phase Uniroyal wear rates as the BWR. If the BWR was the average of all Uniroyal tires (Phase I and Phase III), the CSAF would greatly lower the between phase test variability. (See Appendix A for this analysis.)

4.2 GROOVE WEAR ANALYSIS - NHTSA COMPLIANCE DATA

An analysis similar to that performed on the SWRI test results was completed on tires from NHTSA's compliance tests. In this case, 96 four-groove tires (8 copies of twelve-tire types) were randomly selected from approximately 600 test tires. Again, the wear rates of the individual grooves were calculated using standard regression techniques.

As with the SWRI data, the groove wear demonstrated a consistent pattern. In general, the wear rate of the outside grooves was higher than that of the inside grooves and the wear patterns were consistent from tire to tire within tire type. These results are shown in Table 8 and Figures 23 through 26. In the figures, the results are means of all identical tires within a group. (It should be noted that the identical tires were tested in two separate convoys of four tires each.) As with the SWRI results, with a few exceptions, the tires in the compliance data exhibited the same tire wear pattern, i.e.,

TABLE 8. NHTSA COMPLIANCE DATA GROOVE COMPARISONS MEANS OF EIGHT TIRES

Tire Type*		Treadwear Groove Means and CV%					Ratio-Groove to Overall and CV%			
		1	2	3	4	All	1	2	3	4
1	$\bar{X}$	5.77	4.63	5.07	7.08	5.64	1.03	0.82	0.90	1.26
	CV	8.62	7.21	6.66	7.37	6.31	4.17	2.16	5.77	3.31
2	$\bar{X}$	5.07	3.34	3.24	6.19	4.46	1.14	0.75	0.73	1.39
	CV	5.81	8.05	10.55	7.82	6.52	3.00	5.80	5.16	4.45
3	$\bar{X}$	7.29	3.21	3.47	6.60	5.14	1.41	0.63	0.67	1.28
	CV	16.91	7.61	16.9	15.5	12.68	10.50	11.14	8.51	6.03
4	$\bar{X}$	7.60	4.39	4.40	8.31	6.18	1.22	0.71	0.71	1.35
	CV	7.90	7.61	6.96	5.19	5.95	3.31	4.46	3.97	2.19
5	$\bar{X}$	5.53	3.86	3.59	4.49	4.37	1.26	0.88	0.82	1.03
	CV	23.99	23.35	19.17	21.34	21.31	6.74	5.37	5.72	7.21
6	$\bar{X}$	5.99	4.66	4.67	8.17	5.88	1.01	0.79	0.79	1.38
	CV	16.72	8.18	10.39	13.45	8.59	14.81	3.86	4.81	8.91
7	$\bar{X}$	5.23	4.88	5.01	5.83	5.24	1.01	0.92	0.94	1.12
	CV	5.20	19.92	25.78	7.37	10.05	10.4	11.0	16.44	14.47
8	$\bar{X}$	8.25	12.67	12.87	6.70	10.13	0.81	1.25	1.27	0.66
	CV	19.32	9.10	8.26	8.98	8.99	13.75	1.37	5.13	6.73
9	$\bar{X}$	6.10	6.97	6.60	3.99	5.91	1.03	1.17	1.12	0.68
	CV	20.27	17.63	13.69	15.99	16.09	6.41	4.19	5.29	8.89
10	$\bar{X}$	5.87	4.24	4.25	4.57	4.73	1.24	0.89	0.89	0.96
	CV	6.84	4.30	11.62	7.70	7.24	6.37	5.86	6.42	4.85
11	$\bar{X}$	5.26	2.99	2.88	5.15	4.07	1.29	0.73	0.71	1.27
	CV	19.47	14.19	14.90	14.62	10.72	13.22	9.28	10.26	12.13
12	$\bar{X}$	6.56	3.68	3.59	5.83	4.92	1.33	0.74	0.73	1.20
	CV	17.68	19.79	18.05	9.43	14.75	4.70	6.25	4.70	9.96

*Tire Types:

1 - Exxon Steel Belted Radial P19575/R13
2 - Goodyear Arriva P19575/R14
3 - General Steel Belted Radial P19575/R14
4 - Javalin P18575/R13
5 - Lemans FR 70-14
6 - General VSR P19575/R14
7 - Michelin XZX 185SR14
8 - Pirelli Cinturato 195-70 HR14
9 - Semperit VTT 155SR13
10 - Sonic Super Ride P18575/R14
11 - Stratton Supreme 70 P19570/R14
12 - Firestone Trax 12 P19570/R14

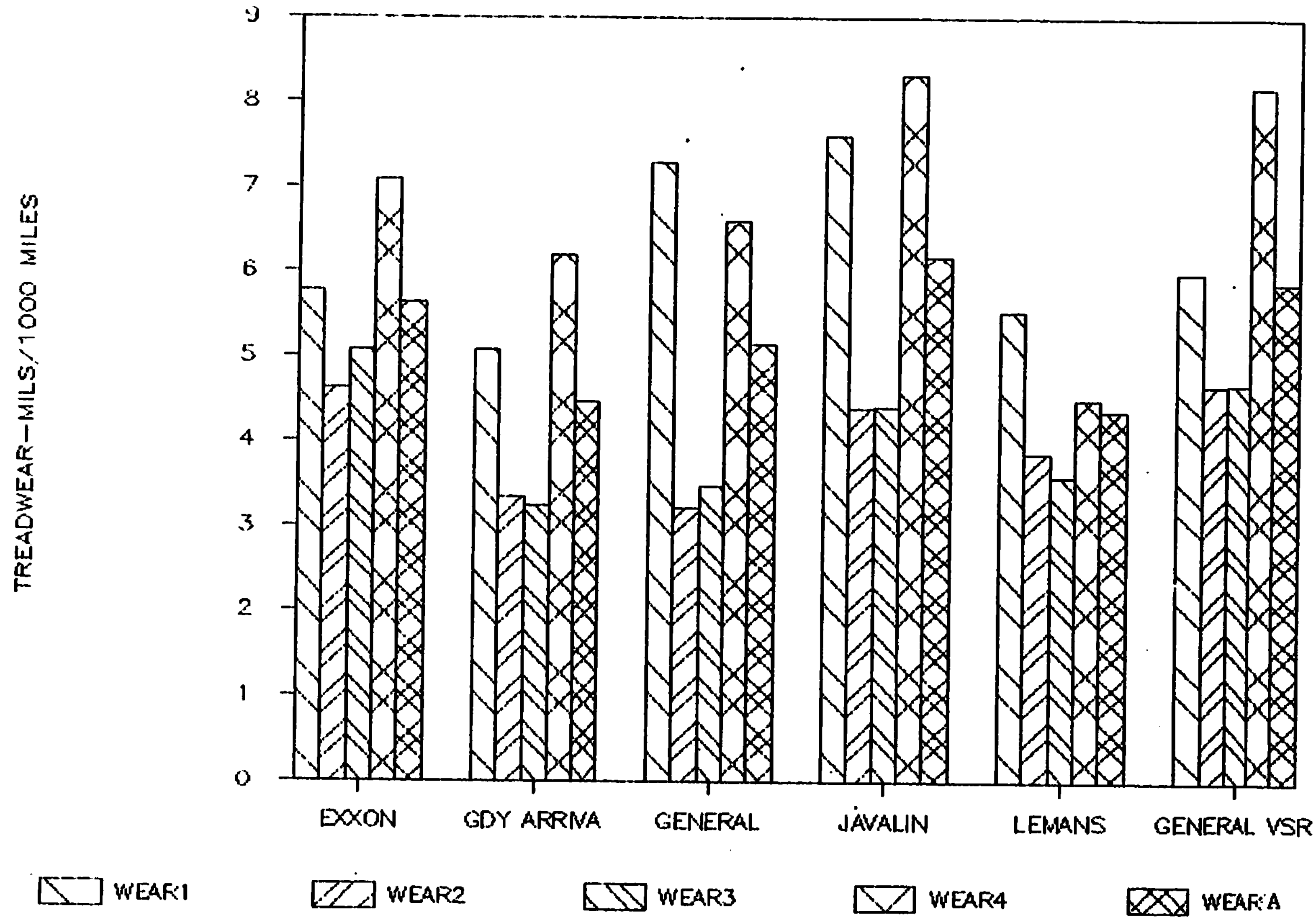

FIGURE 23. GROOVE WEAR RATES FOR NHTSA COMPLIANCE DATA

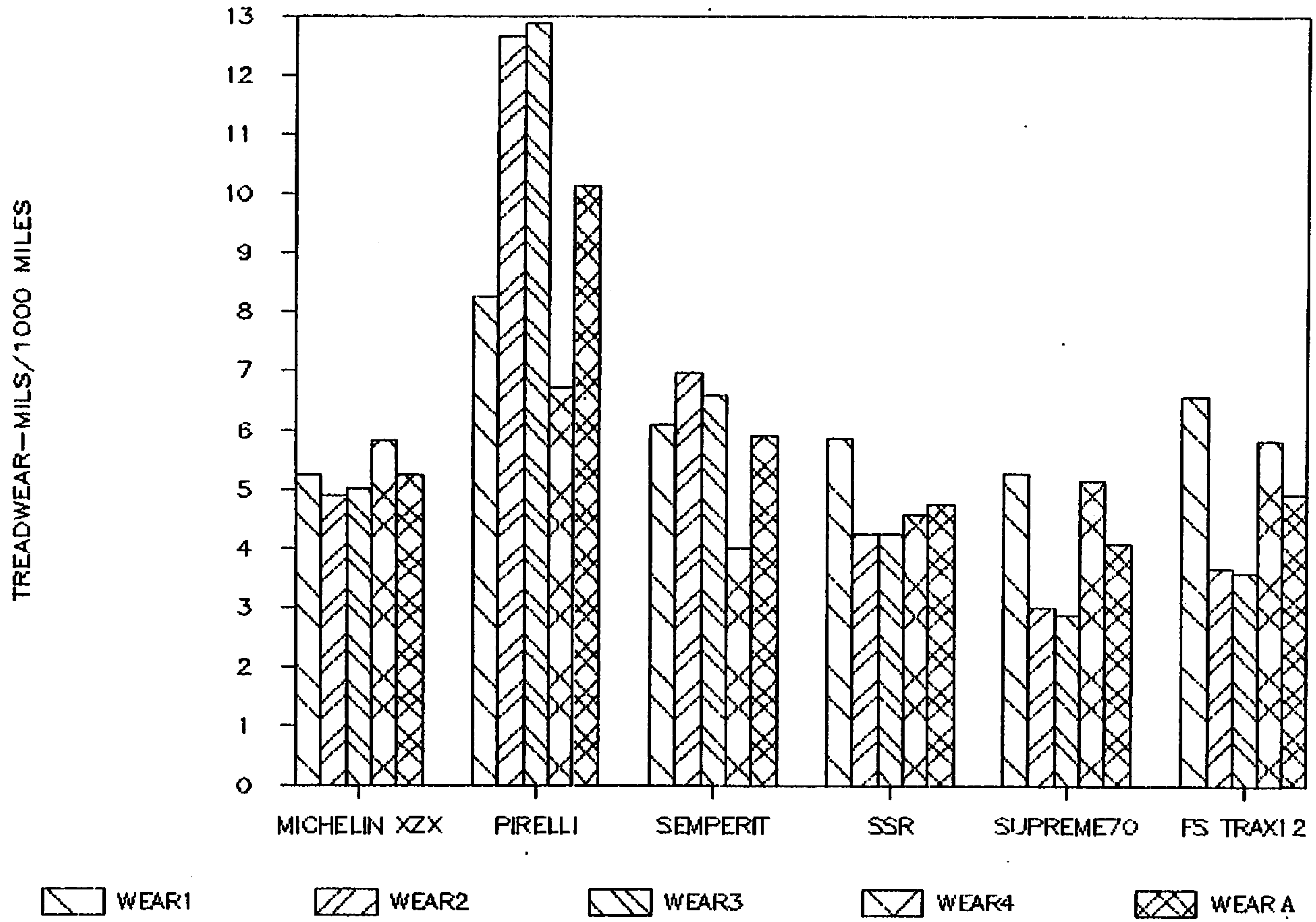

FIGURE 24. GROOVE WEAR RATES FOR NHTSA COMPLIANCE DATA

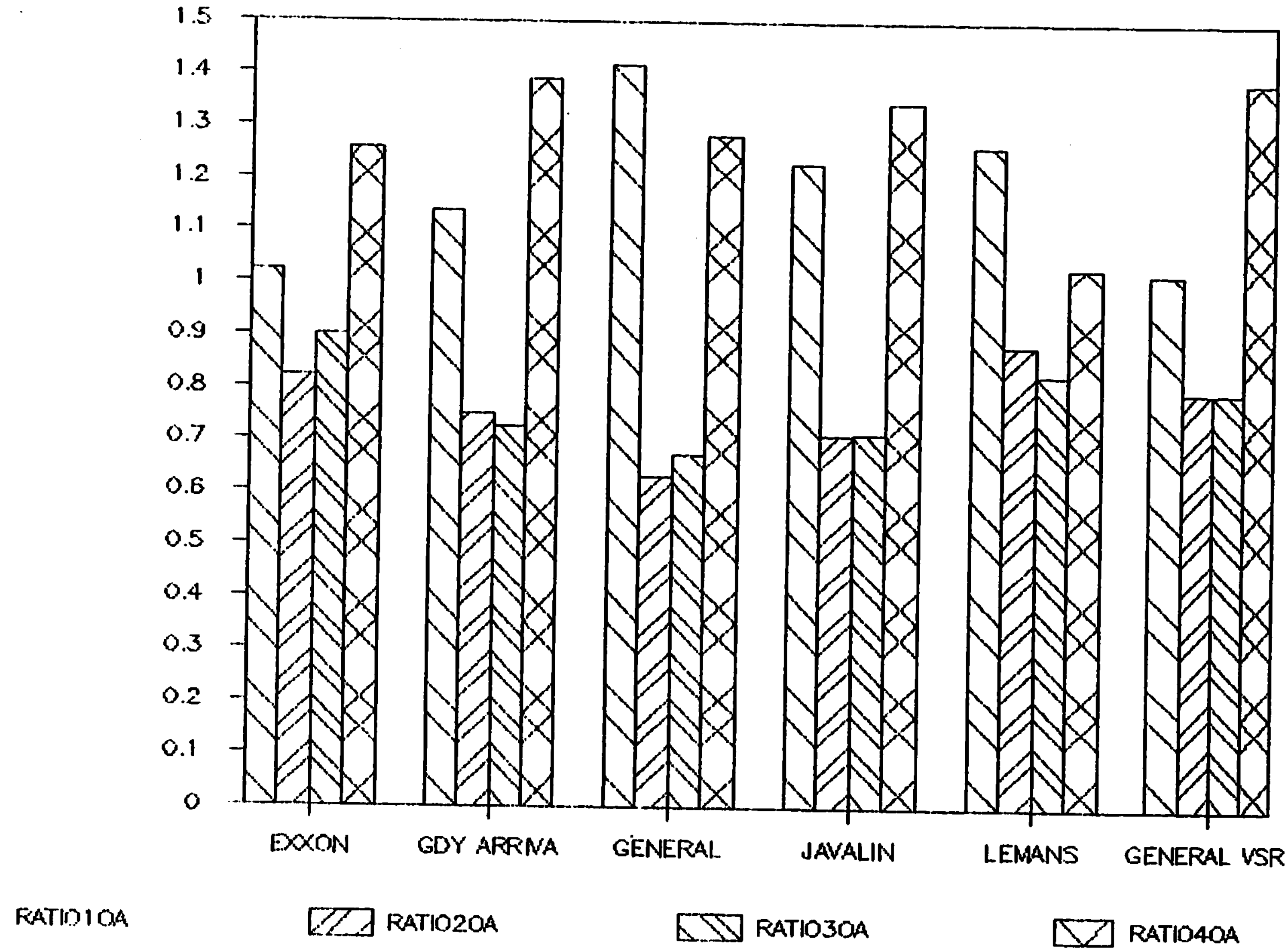

FIGURE 25. RATIOS OF GROOVE WEAR RATES TO OVERALL WEAR RATES FOR NHTSA COMPLIANCE DATA

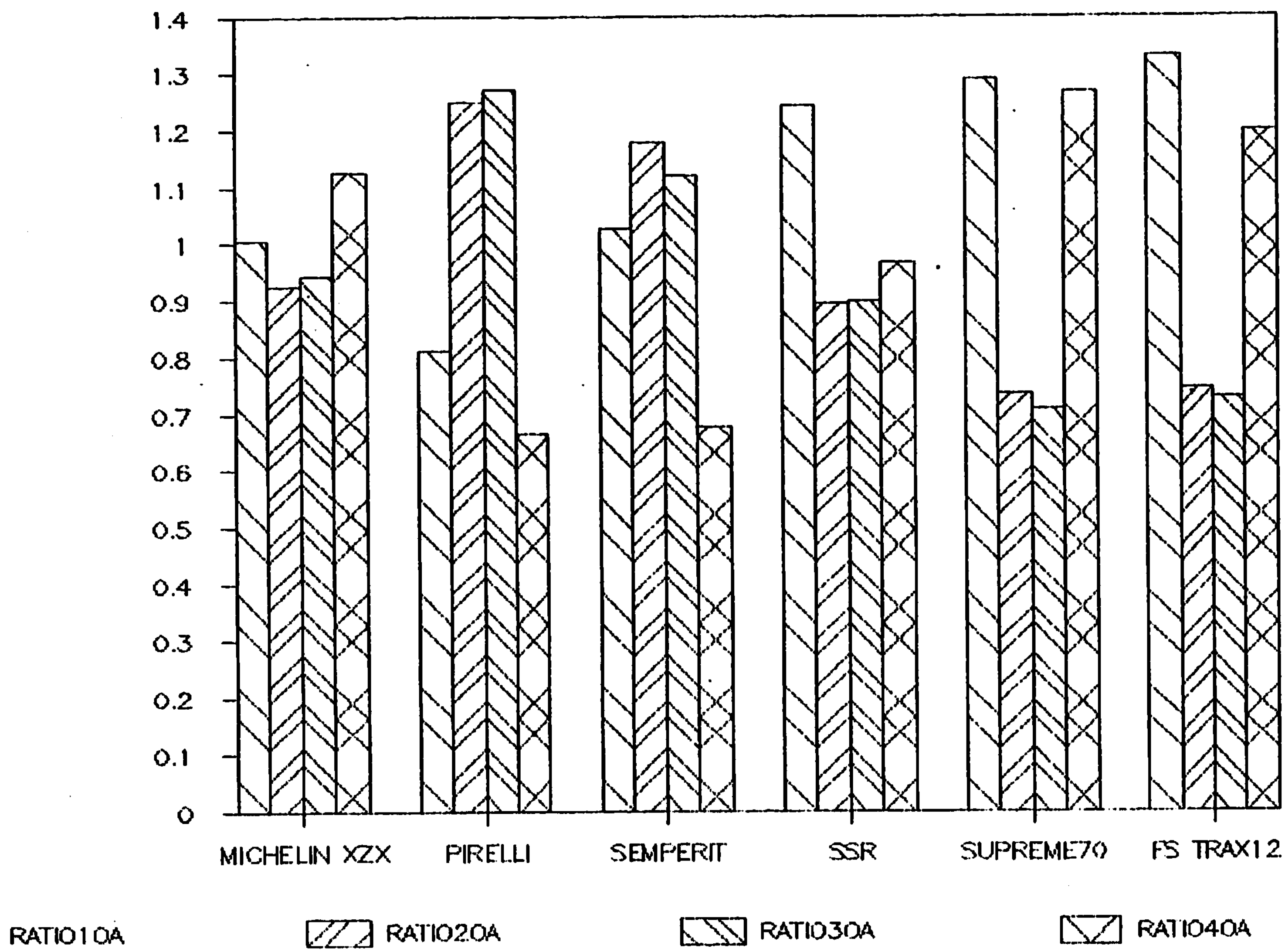

FIGURE 26. RATIOS OF GROOVE WEAR RATES TO OVERALL WEAR RATES FOR NHTSA COMPLIANCE DATA

outside grooves wear more than inside grooves. The exceptions are the Pirelli tire (Tire Type 8) and the Semperit (Tire Type 9). In the case of the Pirelli tire, the wear rates of the two inner grooves were much higher (approximately 50 percent) than the outer grooves. For the Semperit, the wear rate of one of the outer grooves was less (approximately 35 percent) than the other three grooves. The other three grooves had approximately the same wear rate. For the compliance tires, the groove variations are, in most instances, more pronounced that those variations found in the SWRI data. For instance, in the SWRI data, the largest difference of the grooves from the overall mean is approximately 30 percent whereas some of the compliance test tires are as high as 50 to 60 percent.

With respect to the effects of groove wear variability on attained grade, 24 tires (3 groups of 8 identical tires) were selected from the 96 tires previously analyzed. Attained grade was calculated for various groove combinations using the mean tread wear of the combined grooves. For all of these tests, the CMT tire was the Goodyear Polysteel radial with the BWR of 3.74. The results of this analysis is shown in Figure 27. These results are the average of the eight tires within each identical tire type. Both the Pirelli and Semperit tire were included here. For the Pirelli, the average attained grade of the combined inner grooves was 90, whereas the averaged attained grade for the outer grooves was 140 (both rounded down to the nearest tenth). The ratio of these two attained grades is 0.64. For the Semperit, the highest grade was obtained with a combination of grooves 1 and 4. In this case, the average grade was 180 compared to the lowest attained grade of 120 for grooves 2 and 3. The ratio of these grooves is 0.66. The third tire in this analysis was the Le Mans radial. For this tire, the combined outer grooves average attained grade was 220; the combined inner grooves average attained grade was 270; a ratio of 0.81.

A mechanism has been suggested whereby the coefficient of variation in tread wear by groove gauging would be larger than that by weighing and this woud be associated with uneven tread wear patterns. (See Reference 2.) Specifically, these calculations show that if there is a large (tire-to-tire) variation in the (groove-to-groove) pattern of wear, then the variation of tread wear from tire-to-tire (within a tire type) should be larger by groove depth gauging than by weighing. In this study, the variation of tread wear patterns is measured by the coefficient of variation for each groove of the ratio of wear rate to the overall wear rate. This is shown in Tables 3, 4, and 8 in the columns headed "Ratio-Grove to Overall." When this coefficient of variation is high for a given tire type and convoy or phase, one may expect the coefficient of variation of the tread wear by gauging to be higher than that of tread wear by weighing for that tire type and convoy, or phase. However, the precise quantitative relationship to expect among the coefficients of variation involved, although possible in principle to calculate based on the model, appears to be very difficult and outside the scope of this effort.

Consequently, no further attempt is made here to explore the relationship among the:

1. Coefficients of variation of the ratio of individual groove wear to overall tread wear;
2. Coefficients of variation of tread wear by gauging; and
3. Coefficients of variation of tread wear by weighing.

However, these quantities are available in the tables. Since theoretical analysis is not evident, it would be difficult or impossible to draw conclusions regarding the applicability of the model.

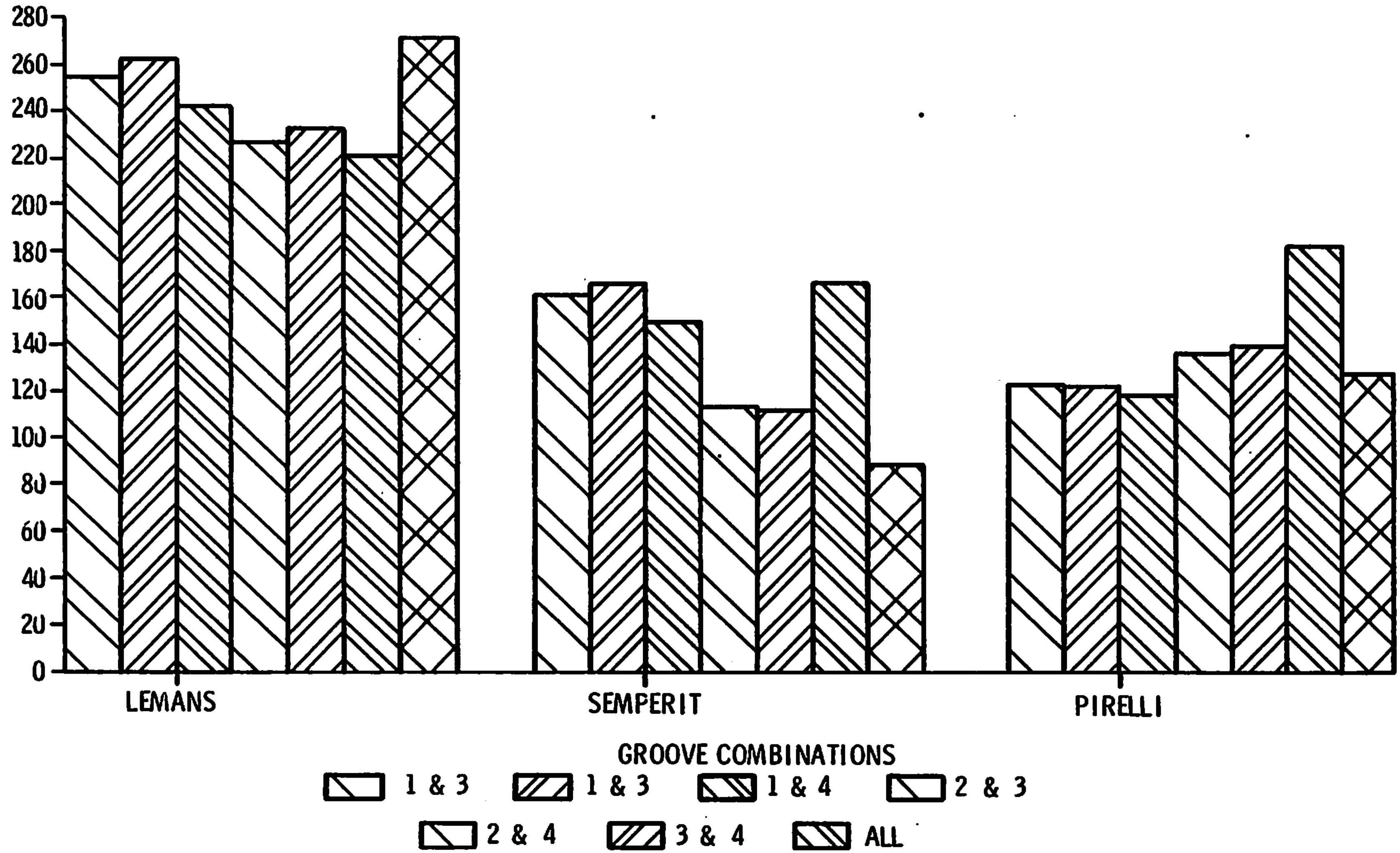

FIGURE 27. ATTAINED GRADES FOR VARIOUS GROOVE COMBINATIONS - NHTSA COMPLIANCE DATA

4.3 ANALYSIS OF VARIANCE FOR TIRE WEIGHING

Analyses of variance were performed on both the SWRI test results and the NHTSA compliance test results. These ANOVA's had two primary goals:

1. To determine which method of tread wear loss (groove depth or weight) more consistently distinguishes between tire types, and
2. To examine the effects of variable variance (heteroscedasticity) on the ability of the UTQG test to distinguish between tire types.

In addition to these two primary goals, other issues of interest were addressed using ANOVAs and standard statistical techniques as they became evident during this analysis.

Table 9 shows ANOVAs that compare tread wear results obtained from SWRI by groove depth measurement and by tire weight (Phase I and III). In these ANOVAs, the factor was tire type and the dependent variable was the log of the tread wear or log of the tire weight respectively. These results indicate that, for Phase I, the within tire type variance (of the log tread wear) of the tires measured by weighing is much lower (.0026 vs. .0069) than the variance of the same tires that were measured by groove depth. However, the between tire type variance of the weighed tires in Phase I is much less (0.1196 vs. 2.354). The F ratio is higher for the case of the groove depth data than for the weight method, indicating that, for the tests completed here, the groove method would distinguish more consistently between tire types (on the basis of tread wear). It should be pointed out that in both cases, the F values are high, indicating that both tread wear measurement procedures could do an adequate job of distinguishing consistently between tires.

TABLE 9. COMPARISON OF GAUGING AND WEIGHT METHOD OF TREAD WEAR LOSS (PHASE I AND III)

ANOVA Gauging

Dependent Variable	Degrees of Freedom	Mean Squares	Std Dev.	F Value	Waller-Duncan Grouping	Mean	Tukey Significant at .05 Level
Log tread wear	3	2.354		338.4	A	1.6691	All
(Phase I)	60	0.0069	.083		B	1.2101	
					C	0.9687	
					D	0.7816	
Log tread wear	3	1.939		198.6	A	2.0520	All
(Phase III)	60	0.0097	.098		B	1.6500	
					C	1.2721	
					D	1.2749	

ANOVA Weight

Dependent Variable	Degrees of Freedom	Mean Squares	Std Dev.	F Value	Waller-Duncan Grouping	Mean	Tukey Significant at .05 Level
Log Weight	3	0.1196		45.6	A	3.0804	10 out of 12
(Phase I)	60	0.0026	.051		B	2.9638	
					B	2.9386	
					C	2.8732	
Log Weight	3	0.1728		40.1	A	3.3852	
(Phase III)	60	0.0043	.065		B	3.2082	6 out of 12
					B	3.1719	
					C	3.1629	

Factor: Tire Type

This result was further analyzed using the Waller-Duncan K-ratio T-test and the Tukey Studentized Range Test (Reference 4). These results are also shown in Table 9, and substantiate the previous conclusions, that is, that groove depth measurements potentially distinguish more consistently between tire types than weight measurments. The Waller-Duncan test indicated that all tire types are signficantly different by groove measurements whereas two of the types are not significantly different with weight measurement. The Tukey test indicated that all pairs of tire types (12 total) are significantly different at the 0.05 level with groove measurement whereas only 10 of the 12 pairs of tire types are significantly different for the weight measurement. Similar results were obtained for Phase III, except the within tire type variance is higher for both gauged and weighed tires and the Tukey Test results indicated that only 6 of 12 pairs were distinguishable by weighing.

The ANOVA results can be also be compared with those previously reported for the NHTSA compliance data (Table 10).

TABLE 10. COMPARISON OF NHTSA AND SWRI PHASE I AND III RESULTS

Dependent Variable		Degrees of Freedom	Mean Squares	Standard Deviation	Factor
(NHTSA)	Log Tread Wear	696	.01152	.107	Tire Type
(SWRI)	Log Tread Wear (Phase I)	60	.00695	.083	Tire Type
(SWRI)	Log Tread Wear (Phase III)	60	.0097	.098	Tire Type

These results indicate the reduced variability in the SWRI Phase I data when compared to the NTHSA compliance data. The differences in these two results are significant at the 95 percent level. The Phase III SWRI results were comparable to the NHTSA results. However, it should be pointed out that in the NHTSA complaince tests, identical tires (8 copies of each type) were tested in two back-to-back convoys of four tires each whereas in the SWRI tests, the tires (16 copies of each type) were run in four convoys of four tires each, 2 day and 2 night convoys and the phases were separated by approximately four months. Analysis of variability between phases of the SWRI data is given in Appendix A.

4.4 THE EFFECTS OF HETEROSCEDASTICITY

The effect of correcting for heteroscedasticity in the tire tread wear testing was evaluated using both SWRI Phase I and III data and selected results from the NHTSA compliance data. In each case, the reciprocal of the variance of the tread wear groove measurements (24 points for a four-groove tire) was used as a weighting factor in the regression analysis to calculate tread wear. In general, the following observations were made regarding the variance of the groove measurements and the effects of the heteroscedasticity:

1. The groove measurement variances for the SWRI Phase I and NHTSA data were comparable and less than that observed for the SWRI Phase III data;
2. The magnitudes and mileage trends of the within-tire variances were consistent from tire to tire within-tire type for both the NHTSA and SWRI data;
3. The variance, especially in some instances of the NHTSA compliance data, increased dramatically with mileage; in other instances, the variance was nearly constant with mileage especially in the case of the SWRI Phase I data which, in general, showed little change of variance with mileage;
4. The corrections for variable variance, had a small effect on the magnitude of the tread wear estimate in the SWRI Phase I data and the NHTSA data, generally being on the order of 1-2 percent, and, in a few cases, six to eight

percent; however, the SWRI Phase III data had larger corrections, on the average of four percent;

5. These relatively minor corrections did not change the conclusions of the ANOVA analyses as presented in the original TSC report. However, it should be pointed out that on a tire type basis, a change of eight percent could impact the attained grade of that tire and cause it to invert with other tires.

4.4.1 SWRI Data

The effects on tread wear by correcting the regression analysis for heteroscedasticity for Phase I and III can be seen in Table 11.

The last column of this table is the ratio of the uncorrected tread wear to the corrected tread wear. The corrections in the Phase I data are generally less than one to two percent ($\bar{x}$ = 1.2 percent) with one correction as high as eight percent. The Phase III corrections were somewhat higher ($\bar{x}$ = 4 percent). The effect of these heteroscedastic corrections on ANOVAs (uncorrected and corrected for heteroscedasticity) with the factors being tire type and the dependent variable the log of the tread wear, is given in Table 12.

The corrections for heteroscedasticity are minor. In fact, for the SWRI Phase I and III results, the corrected within tire type standard deviation on the average is only changed by 1.2 and 4.2 percent, respectively.

TABLE 11. SWRI TREAD WEAR - UNCORRECTED AND CORRECTED FOR HETEROSCEDASTICITY

PHASE I

Tire Type	Convoy	Tread Wear Mean		
		Uncorrected	Corrected	Ratio U/C
1	1	2.04	2.21	0.92
2	1	2.60	2.65	0.98
3	1	3.29	3.36	0.98
4	1	5.38	5.48	0.98
1	2	2.17	2.26	0.96
2	2	2.58	2.57	1.00
3	2	3.23	3.17	1.02
4	2	5.48	5.51	0.99
1	3	2.26	2.39	0.95
2	3	2.71	2.71	1.00
3	3	3.57	3.49	1.01
4	3	5.25	5.22	1.01
1	4	2.28	2.37	0.96
2	4	2.75	2.74	1.00
3	4	3.37	3.36	1.00
4	4	5.15	5.17	1.00

1 - Uniroyal
2 - Michelin
3 - Goodyear
4 - Bridgestone

TABLE 11. SWRI TREAD WEAR - UNCORRECTED AND CORRECTED FOR HETEROSCEDASTICITY (Continued)

PHASE III

Tire Type	Convoy	Tread Wear Mean		
		Uncorrected	Corrected	Ratio U/C
1	1	3.81	3.58	1.06
2	1	3.85	3.61	1.07
3	1	5.64	5.29	1.07
4	1	8.40	7.87	1.07
1	2	3.73	3.57	1.04
2	2	3.76	3.61	1.04
3	2	5.13	9.42	1.04
4	2	7.84	7.49	1.05
1	3	3.38	3.58	0.94
2	3	4.21	4.25	0.99
3	3	5.19	5.49	0.95
4	3	7.47	7.90	0.95
1	4	3.38	3.57	0.95
2	4	4.36	4.61	0.95
3	4	4.90	5.18	0.95
4	4	7.49	7.92	0.95

1 - Uniroyal
2 - Michelin
3 - Goodyear
4 - Bridgestone

TABLE 12. ANOVA COMPARISON OF HETEROSCEDASTICITY - SWRI RESULTS

Phase I

Dependent Variable	Degrees of Freedom	Mean Squares	Standard Deviation	F Value	Factor
Log tread wear	3 (between)	2.354		338.4	tire type
(uncorrected)	60 (within)	0.00695	0.083		
Log tread wear	3 (between)	2.175		322.8	tire type
(corrected)	60 (within)	0.00674	0.082		

Phase III

Dependent Variable	Degrees of Freedom	Mean Squares	Standard Deviation	F Value	Factor
Log tread wear	3 (between)	1.939		195.6	tire type
(uncorrected)	60 (within)	0.00976	0.0988		
Log tread wear	3 (between)	1.944		183.9	tire type
(corrected)	60 (within)	0.0105	0.103		

4.4.2 NHTSA COMPLIANCE DATA

Similar analyses for heteroscedasticity were performed on selected NHTSA compliance data (24 tires, 8 copies of 3 different tire types). As with the SWRI data, tread wear was calculated using the variance of the groove depth measurements as a weighting factor in the regression equation. The corrected and uncorrected tread wears are shown in Table 13 ($\overline{X}$ = 1.9 percent). An ANOVA was also performed using both the corrected and uncorrected tread wear (Table 14).

In the case of the compliance tires, the corrections for heteroscedasticity made a minor improvement in the ability of the test to distinguish between tire types and the F value reflects this small change (approximately 5 percent). However, the within tire type variance of .167 was unchanged by the correction. (It should be noted that these results should not be compared with the NHTSA results shown in Table 10. Those results were for all 800 tires in the data set and, in that case, the standard deviation was much less.)

The examples given in this report indicate that any corrections for heteroscedasticity in tire tread wear statistical analysis would be minor. We, therefore, conclude that the original analyses reported by TSC were valid and require no corrections for variable variance. However, on an individual tire type basis, when the corrections are relatively large, the tires attained grade could be affected.

TABLE 13. NHTSA COMPLIANCE DATA - UNCORRECTED AND CORRECTED

Tire Type	Convoy	Tread Wear Mean*		
		Uncorrected	Corrected	Ratio U/C
PIR	1	10.58	10.40	1.017
PIR	2	9.68	10.38	0.932
SEM	1	5.21	5.22	0.998
SEM	2	3.52	3.49	1.008
LEM	1	6.78	7.07	0.959
LEM	2	5.06	5.21	0.971

*Mean of 4 tires in one convoy.

TABLE 14. ANOVA COMPARISON FOR HETEROSCEDASTICITY

Dependent Variable	Degrees of Freedom	Mean Squares	Standard Deviation	F Value	Factor
Log tread wear	2 (between)	1.509		53.5	tire type
(uncorrected)	21 (within)	0.0282	.167		
Log tread wear	2 (between)	1.596		56.4	tire type
(corrected)	21 (within)	0.0282	.167		

APPENDIX A

FURTHER COMPARISONS OF SWRI DATA AND NHTSA COMPLIANCE DATA

A further analysis was performed on the SWRI Phase I and III data. For this analysis, the Phase I and III data were combined at the tire test (convoy) level. The Uniroyal tire was used as a CMT with the BWR being the average of the Uniroyal tire during both Phase I and III. The CSAF was then calculated by dividing the BWR by the average of the four within convoy Uniroyal tires. The corrected rates were calculated for both tire gauging and tire weight. Attained grade was also calculated for the gauging method. ANOVA's were used to compare the results as shown in Table A-1. In addition, these results were compared to those for the original NHTSA compliance tests (Table A-2).

For the gauging, the within tire type test variability* of the logarithm of treadwear for the SWRI data across both phases is twice that obtained in the original NHTSA data (0.231 vs. 0.122). However, whereas in the original NHTSA data, the CSAF reduced the test variability by approximately a factor of 1.5, the CSAF here reduced the test variability by approximately a factor of 2.7. Although the SWRI tests were to reduce test variability, little change has been made in the variability of the attained grade, the most important result in the UTQG procedure. In fact, the TSC's original conclusion that within a 95 percent confidence level, the average test grade of four identical tires should not shift by more than 23 percent is still valid here (the percent would be reduced to 22 percent for SWRI tests. The reader is referred to the original report for the method of calculating this percent).

*By the variability here we mean the pooled standard error (over all tire types) of the means of the four-tire sets (one set for each convoy) for each tire type.

TABLE A-1. SWRI PHASE I AND III TIRE ANOVA'S - TEST LEVEL

Dependent Variable	Degrees of Freedom	Mean Square	Standard Deviation	F
Log Treadwear				
(between)	2	1.0857		20.28
(within)	21	0.0535	.2310	
Log Adjusted Treadwear				
(between)	2	1.0162		137.89
(within)	21	0.0073	.0858	
Log Attained Grade				
(between)	2	1.5824		245.36
(within)	21	0.0064	.0803	
Log Weight				
(between)	2	0.0704		3.23
(within)	21	0.0218	.1470	
Log Adjusted Weight				
(between)	2	0.0704		35.23
(within)	21	0.0020	.0447	

Factor: Tire Type

TABLE A-2. NHTSA COMPLIANCE ANOVA'S - TEST LEVEL

Dependent Variable	Degrees of Freedom	Mean Square	Standard Deviation
Log Treadwear			
(within)	99	0.01503	.122
Log Adjusted Treadwear			
(within)	99	0.00649	.081
Log Attained Grade			
(within)	99	0.00683	.083

Factor: Tire Type

With respect to tire weighing, the within tire type standard deviation for the logarithm of the uncorrected treadwear is lower by about 50 percent than that obtained by gauging (.147 vs. .231). By adjusting the treadwear with the CMT correction, the variability is further reduced a factor of 3.2 (.147 vs. .0447). However, as was pointed out in the report, the low F factors of the weight method indicate that the ability to distinguish between tire types (by treadwear) is diminished when tires are weighed as opposed to when they are gauged. If we assume that any method found for establishing wear out by weight does not significantly increase the variability, then we could conjecture that the variance of the attained grade by weight would be of the same order as the adjusted treadwear by weight. When the tires are weighed, the original TSC conclusion of 23 percent quoted above would be reduced to approximately 13 percent.

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