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ANALYSIS OF DATA FROM THE FIRST WHEEL EXPERIMENT AT THE FACILITY FOR ACCELERATED SERVICE TESTING

Unified Industries Incorporated
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March 1979

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16. Abstract

The Facility for Accelerated Service Testing (FAST), located at the Transportation Test Center near Pueblo, Colorado, is a joint government/industry program for accelerated life cycle testing of railroad track and mechanical components. The facility consists of a 4.8-mile loop around which a freight train of approximately 9,500 tons travels for 15 hours per day, 5 days per week. Measurements are made periodically on various track and train components for the purpose of studying design performance and wear characteristics. As part of this overall program, a wheel experiment was designed to compare the performance of various types of wheels now in service on U.S. railroads. This report discusses an analysis conducted by Unified Industries Incorporated (UII) of wheel wear data from the first wheel experiment, which ran from September 1976 to August 1977. Six wheel variables (heat-treated versus non-heat-treated, cast versus wrought, 1-wear versus 2-wear, AAR profile versus CN profile, 14-inch center plate versus 16-inch center plate, and type 1 truck versus type 2 truck) were studied. The analysis includes graphical analysis and the development of a regression model for studying variable interactions.

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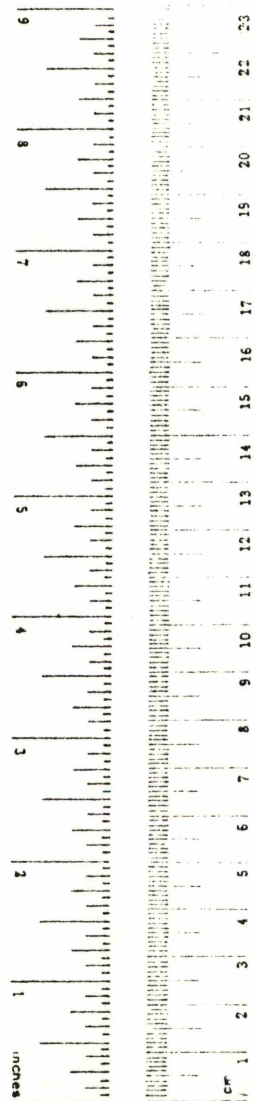
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

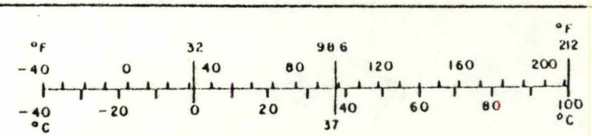
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	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 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights 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

The first wheel experiment was designed as a full factorial experiment to analyze the relative effects of six different wheel variables on wheel life. The variables were heat-treated versus non-heat-treated wheels, cast wheels versus wrought wheels, 1-wear wheels versus 2-wear wheels, 14-inch center plates versus 16-inch center plates, AAR profile versus CN profile, type 1 truck versus type 2 truck. Each of the 64 (2^6) wheel types under test was represented with 4 wheels in the original design, for a total of 256 wheels. Supply limitations caused the actual data to fall short of the design, with 240 wheels. Seven wheel types had no test wheels, three types had 2 wheels, 3 types had 6 wheels, and 3 types had 8 wheels.

Initial graphical analysis of the data led to several conclusions. First, flange wear was the most prevalent type of wheel wear evident on the FAST track. Other types of wear, such as tread wear, were relatively slight, and the amount of wear measured tended to be of the same order of magnitude as the estimated measurement error. Thus, quantitative data analysis in this study was limited to flange wear. Second, there was a wide difference in performance among wheels of the same variable type. Comparisons of estimates of average wear rates showed that the ratio of the rate of wear of the most rapidly wearing wheel to the slowest wearing wheel for a given wheel type was between 1.13 and 19.64. Third, treated wheels lasted significantly longer than untreated wheels in the FAST environment. Fourth, wear was not the only reason for removal of the test wheels. Most of the untreated wheels were removed from the test because of thin flange conditions on one of the wheels in the wheelset (83.3 percent), while most of the treated wheels were removed because of fine cracks which developed in the the tread of one of the wheels of the wheelset (78.3 percent).

Finally, an analytical model was developed based on a regression of the logarithm of the flange thickness with the logarithm of the mileage weighted by a combination of dummy variables representing the wheel variable states. This model was used to analyze the relative contributions of the test variables on flange life. The model indicated that heat treatment extended the flange life significantly, on the order of two and one-third times. In addition, the model indicated that cast wheels, CN profiles, 14-inch center plates, and type 1 trucks seemed to improve performance slightly. There was no significant difference in flange wear between 1-wear wheels and 2-wear wheels.

INTRODUCTION

The Facility for Accelerated Service Testing (FAST) track at the Transportation Test Center (TTC) in Pueblo, Colorado, is a 4.8-mile (7.7-kilometer) loop of track for testing the life cycle performance of a wide variety of track and mechanical components. The loop has 2.2 miles (3.5 kilometers) of tangent track, 1.1 miles (1.8 kilometers) of 5-degree curve, 0.3 mile (0.48 kilometer) of 4-degree curve, 0.4 mile (0.64 kilometer) of 3-degree curve, and 0.8 mile (1.29 kilometers) of spiral into and out of curve sections. The track is constructed in sections, each section being constructed using different combinations of ballast, rail, ties, and fastenings. The test consist contains mostly fully loaded 100-ton hopper cars with a total weight of about 9,500 tons (8,550 tonnes). There are also a few tank cars and trailer train cars in the consist. The consist is made up of about 75 freight cars and 4 locomotives that travel around the track 5 nights a week for 15 hours at an average speed of about 40 miles per hour (64 kilometers per hour). Started in June 1976, the FAST track has accumulated over 300 million gross ton miles to date (December 1978).

This report discusses the data from the first wheel experiment, which was run between June 1976 and August 1977 (approximate). The report includes both a general discussion of the data based on graphical analysis and a mathematical analysis based on a regression model for the flange thickness as a function of mileage and the test variables. The analysis covers the performance of the wheels up until they were removed for the first time, either for thin flange condition or other conditions such as cracks.

The data file used in this analysis was compiled by Unified Industries Incorporated (UII) using data printouts provided by the Association of American Railroads (AAR) and by the Transportation Test Center. Care has been taken to insure the accurate reproduction of the files, but neither UII nor any of the FAST program participants can warrant their total accuracy.

EXPERIMENTAL DESIGN AND MEASUREMENTS

The wheel experiment was designed to compare the performance of various types of wheels now in service on U.S. railroads, particularly their susceptibility to wear. For this experiment, six different wheel parameters were chosen for comparison. These are:

a. Heat-treated or rim-quenched wheels versus non-heat-treated wheels.

b. Wheels manufactured using the cast process versus wheels manufactured using the wrought process.

c. AAR designated 1-wear wheels versus AAR designated 2-wear wheels.

d. Wheels with the standard AAR wide flange profile versus the Canadian National (CN) "worn flange" profile.

e. Wheels mounted on trucks with a 14-inch center plate versus wheels mounted on truck with a 16-inch center plate.

f. Wheels mounted on a conventional type 1 truck (constant friction snubber) versus wheels mounted on a conventional type 2 truck (variable friction snubber).

Since each variable has two alternate states, there are 64 (2^6) different combinations of wheels possible under this test. Two hundred and fifty-six wheels on 32 cars were designated for the wheel test with the original design having 4 wheels of each type.

The train movement follows a 4-day cycle with the direction of travel alternating between clockwise and counterclockwise on each successive day. Every 2 test days the entire train is turned around. Cars were also rotated within the train on a regular basis to counterbalance location effects. Thus, wheels on an axle and both ends of the car are presumed to see the same wear environment. Also, each car is removed from the consist every 22 operating days for measurement and inspection. Any wheel which exceeded AAR condemning limits was removed from service and either reprofiled or scrapped depending on the condition. Also taken at each measurement cycle were flange thickness, flange height, rim thickness, wheel profile, and tread hardness. In addition, the wheel circumference is taken when the wheel is first installed and before and after it is turned or when it is removed from the test. Two measurements of each type are taken on each wheel 180 degrees apart. To insure that they are taken at the same point, reference marks were put on each wheel and punch marks were put on the rim faces to insure proper location of the finger gage and profilometer.

Flange thickness, flange height, and rim thickness are all measured using the standard AAR finger gage. Figure 1 is a diagram of a finger gage positioned over a wheel for measuring both the flange thickness and the rim thickness. The rim thickness is measured by reading the scale on the vertical arm at the point of contact with the lower edge of the rim face (point A). The flange thickness is measured by rotating the pivot element until point C meets the flange, removing the finger gage and measuring the distance between point C and point D with a finely graded scale. Flange height measurements are taken by rotating the movable arm until point E meets the tip of the flange and reading the height on the vernier scale (point B).

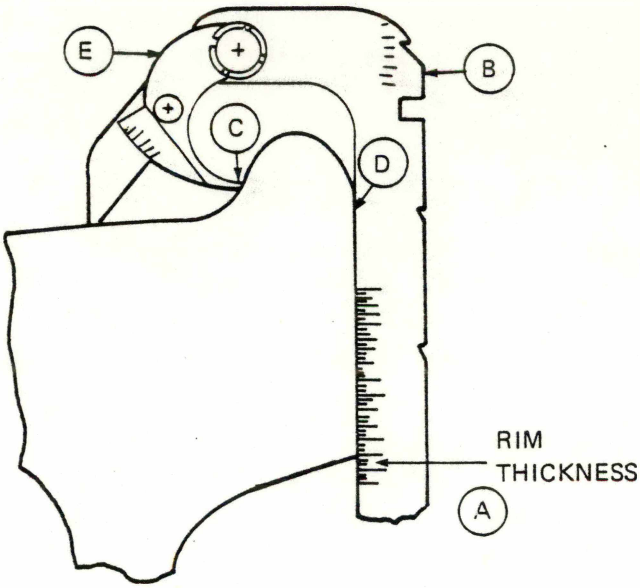

FIGURE 1. FINGER GAGE IN POSITION FOR MEASURING FLANGE THICKNESS, RIM THICKNESS, AND FLANGE HEIGHT

With this instrument, all measurements are referenced to the tread face. Since this is a wearing surface the reference point for both the flange thickness and the flange height is changing and the absolute position on the flange for the flange thickness measurement is also changing. That is, it is constantly moving downward to a wider portion of the flange. Since the tread wear was minimal during this experiment, the effect probably had little or no influence on the data. If there were significant tread wear, this effect would have to be factored into an analysis of flange thickness. Also, the point of measurement for rim thickness is not a sharp edge so there will be some error in reading the scale.

Hardness measurements were planned on both the front face of the rim and on the tread. The measurements were taken with a portable hardness tester with direct meter readout of the hardness. However, early experience with the measurements showed that the field measurements had too much variability to be useful and were discontinued.

Wheel circumference was taken with a standard circumference tape when the wheel was installed, before and after turning, and when it was removed from the test. The wheel circumference measure served mainly as a guide and as a quality control check for proper machining and installation of the wheelsets. Thus, although wheel circumferences are included in the basic AAR data file, they were not included in the special data file used in this analysis.

Wheel profiles are taken with a wheel profilometer illustrated in figure 2. The profilometer device is clamped to the wheel using three locating pins which match up with punch marks on the sides of the rim. A carbon paper sheet is placed on the board over the reference dowels and clamped in place. As the spring-loaded pin is traversed along the contour of the rim, a stylus runs over the carbon forms and traces a profile. This profile is then labeled and digitized for analytical use. Several problems were encountered in the use of this device. First, no clear reference marks are created at the ends of the pointer travel so that it becomes difficult to overlay subsequent profiles for comparison purposes. Secondly, the unit could not always be placed back in precisely the same position for each measurement. Third, metal rollover such as that which may occur at the rim face or at the top of the flange is not indicated in these profiles. The lack of accurate reference points made the analysis of the digitized data, particularly the earliest measures, extremely difficult and no computer analysis was used. The profiles for this analysis will be used mainly to illustrate the types of wear occurring.

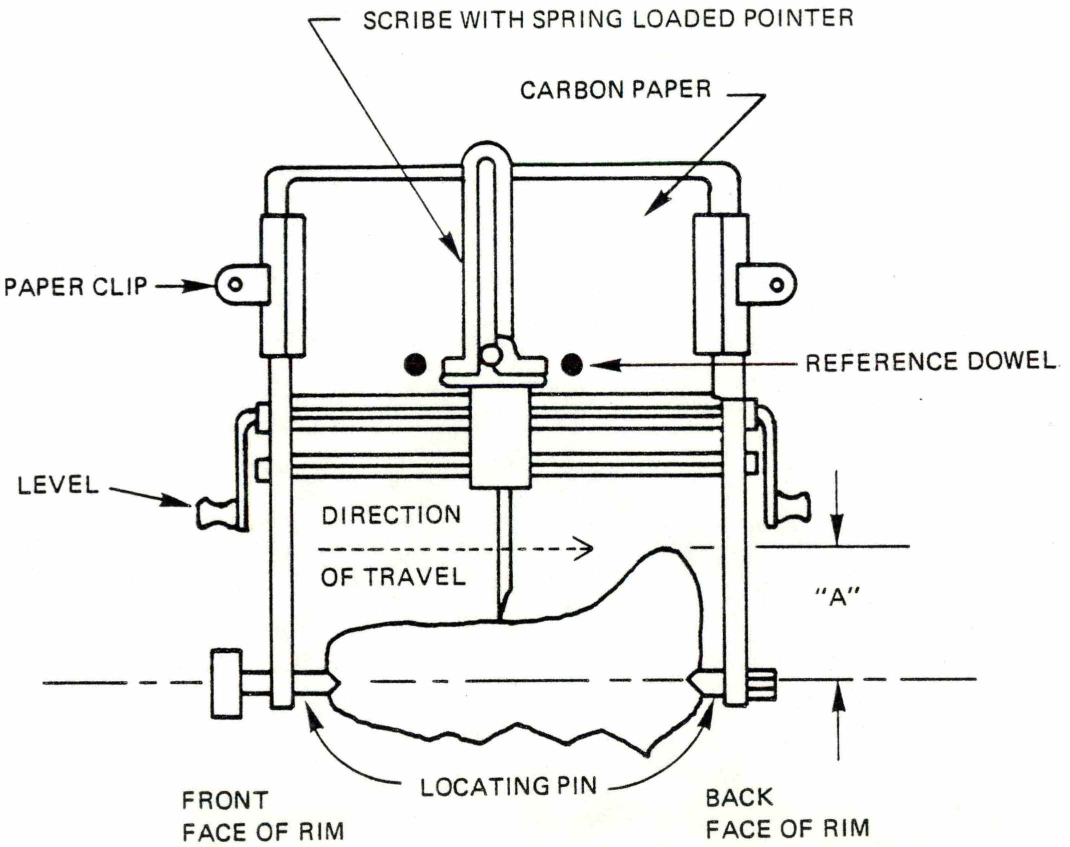

FIGURE 2. WHEEL PROFILOMETER

Source: FAST Test Specification, Volume III, Mechanical #7134.0.

Because of a shortage of wheels of all types at the start of the test and because two of the test cars did not see full test mileage, the actual distribution of wheels was not as planned. The actual test involved 240 wheels on 30 cars distributed unevenly among the planned test cells. Figure 3 shows the number of wheels which were in each test group. It can be seen that there were actually seven cells which did not have any wheels in them, three cells with two wheels, three cells with six wheels, and three cells with eight wheels.

There was another important departure from the basic experiment design which resulted from lubrication problems on the track. Although track lubrication on curves was always part of the FAST design, wheel flange wear and rail head wear were extremely rapid after startup indicating that the lubricant was not effective. Some experimenting was then carried out with different types of lubricants and with numbers of lubricators until more reasonable wear performance was observed. These trials were completed by between 20,000 and 30,000 train miles. From this mileage on the lubrication varied but it was generally agreed that overall the track was heavily lubricated. Since treated wheels lasted longer before being remachined, they spent a greater portion of their useful life in a heavily lubricated environment. This difference in environment could cause some distortion in the comparisons of the two types of wheels.

The method of statistical analyses which was used for this data was that of multiple regression with dummy variables included to indicate the relative effects of the test variables. This analysis which is discussed in the section on model development showed that wheel treatment was the variable which exhibited the major effect on wheel wear with the other variables showing only small effects. The section which follows provides a general overview of the data to give the reader an understanding of the type of wear patterns occurring and an estimate of the effects of measurement error. Separate example plots are given for heat-treated and non-heat-treated wheels because of the large differences in wear characteristics. The following section also discusses three of the model formulations which were explored and a discussion of the conclusions which were drawn from the model selected as the most appropriate.

				14" CENTER PLATE		16" CENTER PLATE	
				TRUCK TYPE 1	TRUCK TYPE 2	TRUCK TYPE 1	TRUCK TYPE 2
TREATED	1W	CAST	CN PROFILE	4	2	4	4
			AAR PROFILE	4	0	4	6
		WROUGHT	CN PROFILE	4	4	6	4
			AAR PROFILE	4	0	4	4
	2W	CAST	CN PROFILE	4	4	2	0
			AAR PROFILE	4	8	4	4
		WROUGHT	CN PROFILE	4	4	4	4
			AAR PROFILE	4	4	4	4
UNTREATED	1W	CAST	CN PROFILE	0	6	4	4
			AAR PROFILE	4	4	4	2
		WROUGHT	CN PROFILE	4	4	4	4
			AAR PROFILE	4	4	4	4
	2W	CAST	CN PROFILE	8	4	4	8
			AAR PROFILE	4	0	0	4
		WROUGHT	CN PROFILE	4	4	4	4
			AAR PROFILE	4	4	0	4

FIGURE 3. ACTUAL NUMBER OF WHEELS IN EACH CELL OF EXPERIMENT DESIGN FOR EXPERIMENT 1

DISCUSSION OF DATA

The FAST track, being a loop, has a large percentage of curved track ((1.8 miles (2.9 kilometers) curve, 0.8 mile (1.3 kilometers) spiral, 2.2 miles (3.5 kilometers) tangent). Thus, the wear that was seen in experiment 1 was predominantly flange wear. Also, since the same wheels tend to move over the same track repeatedly, both the track and the wheel flange tend to wear towards conforming shapes in areas of contact. Figure 4 shows an overlay of two wheel profiles taken on one of the test wheels -- one taken after 3,834 miles (6,134 kilometers) and the other taken after 51,107 test miles (81,771 kilometers). The shape and area of wear show up clearly.

It can be seen that there was practically no tread wear and extensive flange wear. There is also growth on the flange tip and possibly on the tread near the front face. These are due to metal flow. The shape as shown is not entirely accurate due to the fact that the profilometer does not indicate overlaps. Also, the magnitude of the changes are only approximate because the profiles lack consistent reference points and are thus difficult to overlay. The profiles therefore have been overlaid so that the wear shown matches that measured with the finger gage readings. The profiles shown are for a treated wheel. However, wear on the untreated wheels produced a similar shape. The main difference was that untreated wheels exhibited a greater rate of wear.

Also superimposed on the diagram are the finger gage measurement locations. It should be noted that they give a somewhat incomplete picture of the wear on the wheel. The flange thickness is measured at only one point and provides no information on the changing shape of the front face of the flange. The flange height is heavily influenced by the metal flow on the tip of the flange, a thin strip of metal not directly related to overall wear although it has been implicated in the development of flange cracks (see discussion on reasons for removal given below). Finally, there seems to be very little tread wear. The limitations of these measures should be kept in mind in evaluating results of further analysis.

In order to explore general treads in the data, scatter plots (figures 5-10) were made of the finger gage measurements for some sample treated and untreated wheels. In each case, the average of the two finger gage measurements was plotted against mileage. A line was drawn through the points to illustrate the trend of the points. The line is a freehand approximation and does not correspond to a mathematical fit. Superimposed on the plots are two horizontal lines representing the estimated measurement error range for each measurement.

Figure 5 is a plot of the average of the two flange thickness measurements against mileage for a typical treated wheel (treated, 2 wear, wrought, CN profile, 14-inch center plate, type 1 truck), and figure 6 is a similar plot for a typical untreated wheel (untreated, 1 wear, cast, AAR profile, 14-inch center plate, type 1 truck). Several things can be observed from these. First, the difference in wear rates between treated and untreated wheels is apparent. Many untreated wheels are near condemning limits after 19,000 miles (30,400 kilometers), while many treated wheels still have flange life after 50,000 miles (80,000 kilometers). The mileage and wear differentials vary considerably among the wheels. Some untreated wheels, in fact, lasted longer than some treated wheels, but in general the difference in performance is clearly seen.

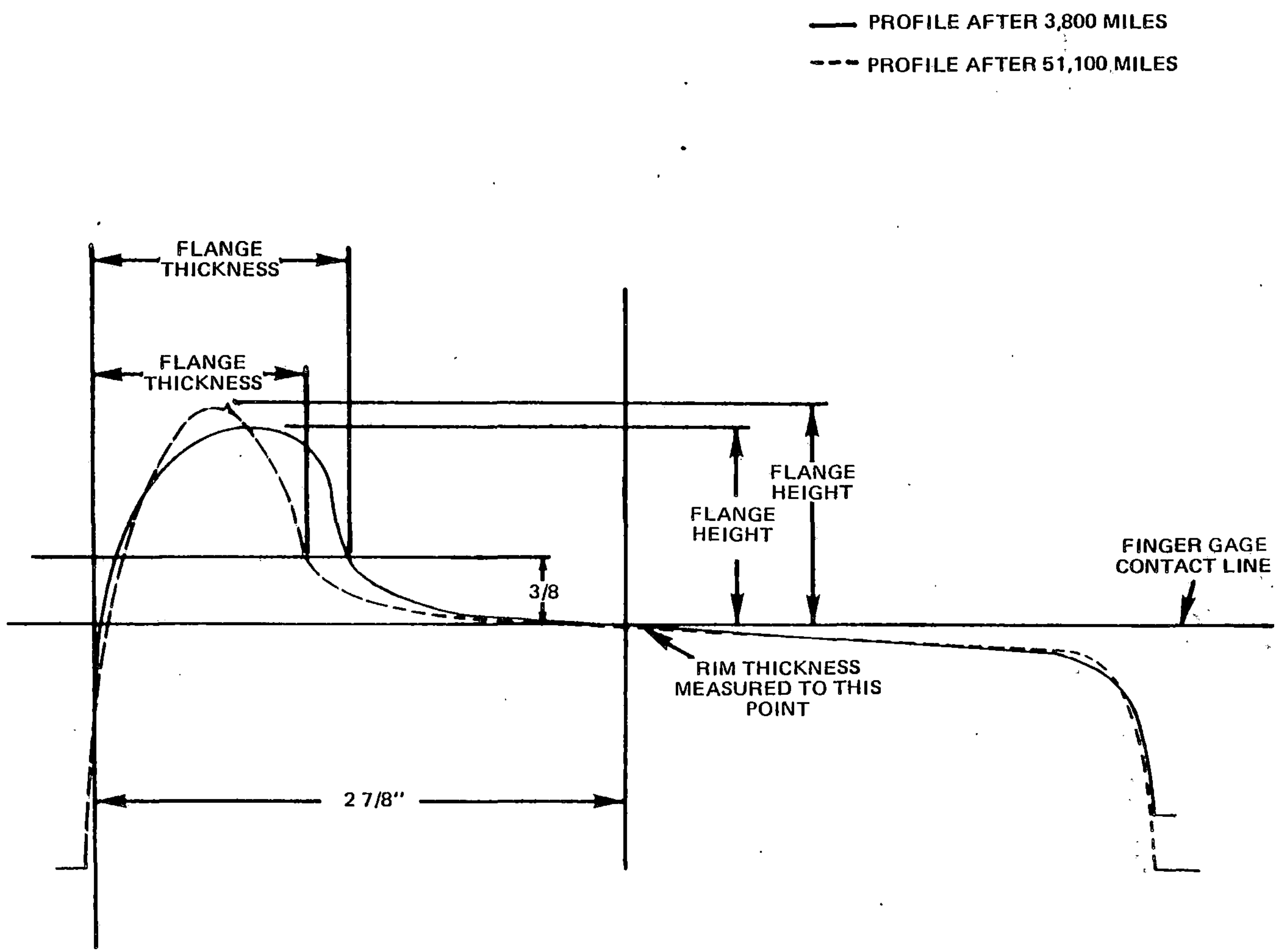

FIGURE 4. WHEEL PROFILE COMPARISON SHOWING NATURE OF WHEEL WEAR

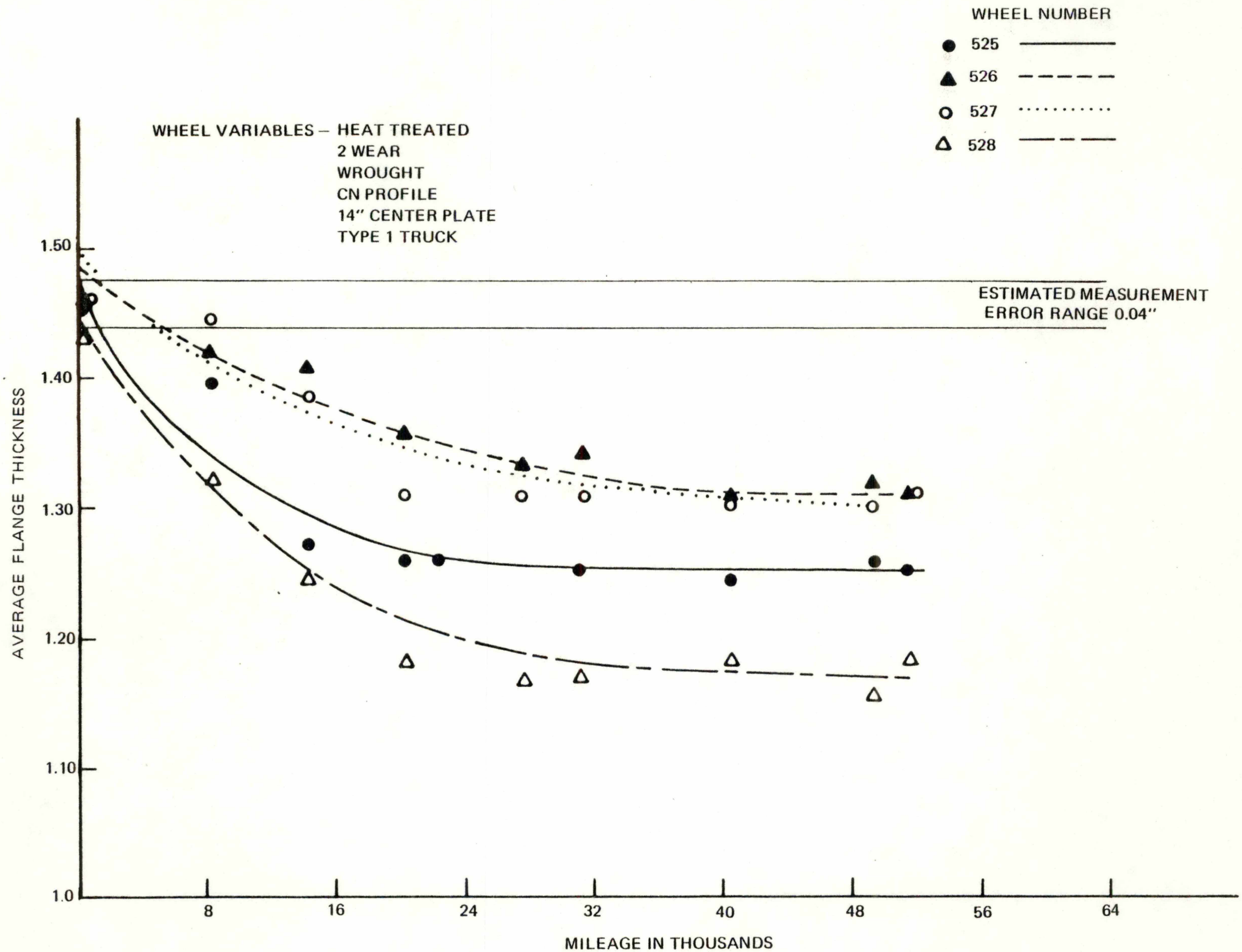

FIGURE 5. FLANGE THICKNESS VERSUS MILEAGE SCATTER PLOT FOR EXAMPLE TREATED WHEELS FROM FAST EXPERIMENT 1

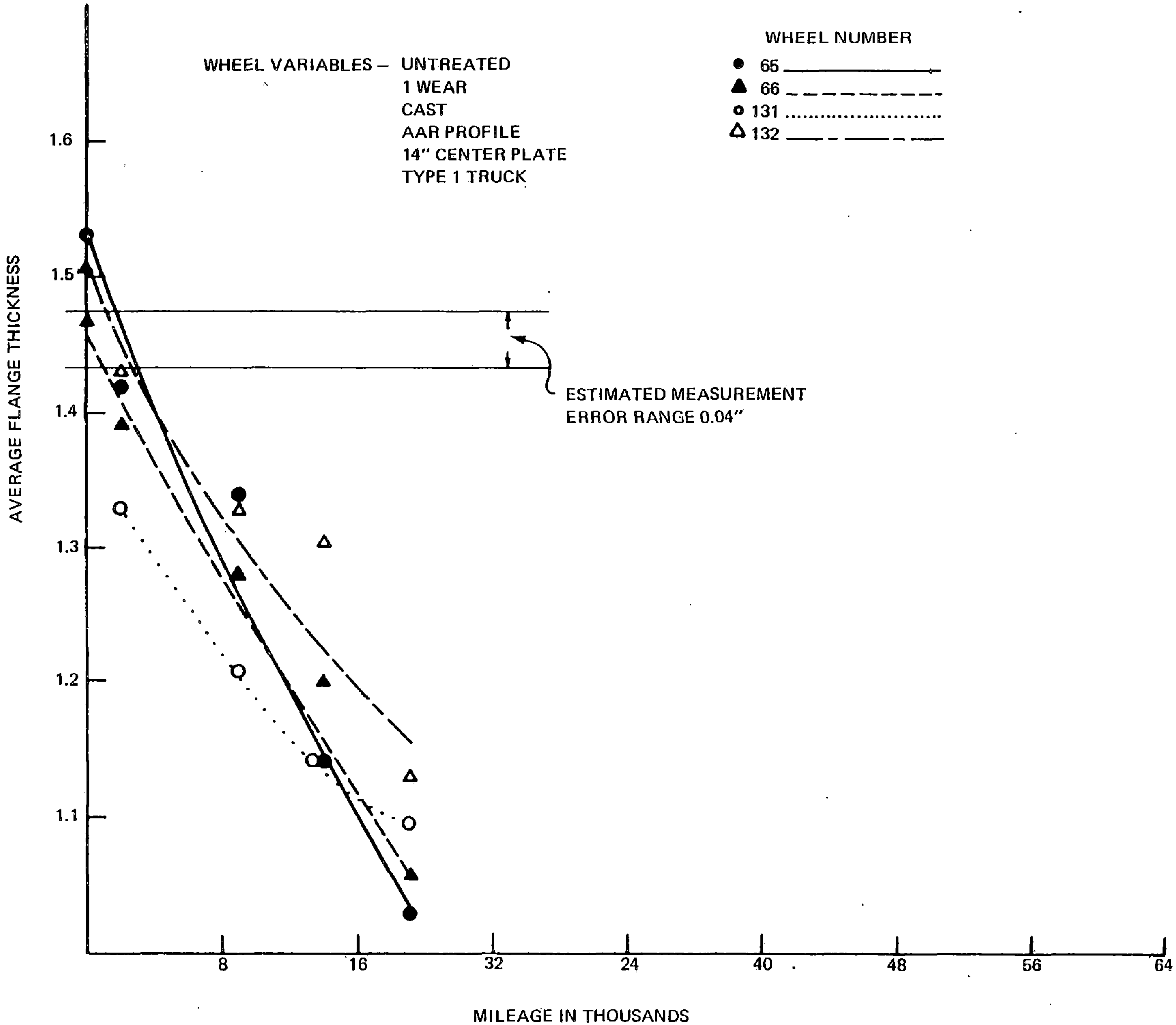

FIGURE 6. FLANGE THICKNESS VERSUS MILEAGE FOR EXAMPLE UNTREATED WHEELS FROM FAST EXPERIMENT 1

A second observation is that there is a clear difference in performance between the wheels within a group. As an indication of this, the slope of the average flange thickness versus mileage was calculated for each wheel. Although this is not the most accurate way of portraying the wear curve, it is conceptually easy for some purposes and does provide a general indication of the overall rate of wear of the flange. These slopes were then grouped by wheel type and the ratio of the largest slope to the smallest slope was calculated for each wheel group. The ratios ranged from 1.13 to 19.64. The mean ratio was 3.21. Of the 56 wheel types for which this was tabulated, 24 had ratios between 1 and 2, 12 had ratios between 2 and 3, 9 had ratios between 3 and 4, 2 had ratios between 4 and 5, and 9 had ratios greater than 5.

Since it can be assumed that the wheels saw approximately the same wear environment, it seems likely that the variation is due to differences in the wear characteristics of the wheel. Thus, it can be inferred that the variables chosen for study do not fully characterize the wear performance of the wheels. Also, it can be seen that any mathematical attempt at curve fitting based on these variable groups will be approximate at best.

The third observation concerns the shape of the curves. The curves seem to have a definite tendency towards non-linearity with the greatest wear occurring at the early mileages. The non-linear nature was confirmed mathematically, and this investigation is discussed below. There can be several causes postulated for this non-linear nature, although at this point estimates of relative contribution cannot be made. These explanations include:

- During the early miles, both the wheels and the rail had new profiles. Thus, during curving the contact area between flange and rail would be smaller than the contact area later in the test when the wheels and rail had worn to matching profiles.

- During the early miles, the track was ineffectively lubricated, then was partially lubricated as new lubricants were tried. It was finally heavily lubricated after 20,000 to 30,000 miles (32,000 to 48,000 kilometers).

- Some work hardening of the wheels may have occurred.

The error range for the flange thickness measurement has been estimated to be 0.04 inch (0.10 centimeter). This estimate is a judgment based on observations of the data and of the measurements. The measurement technicians read the scale to the nearest 1/64 of an inch (0.04 centimeter). However, there are several other major sources of error. First, the finger gage must be held precisely against the face of the wheel each time. This is a hand-held operation with no clamps or other aids, and some error is expected. Second, the inside edge of the flange has been observed to be rough and pitted at different times during the test. The rough surface could easily affect the measurement since the placement of the gage for each measurement is approximate, being based on simply alining the gage with reference marks. Finally, the finger gage is removed from the wheel and the distance between the contact point and gage edge are measured with a ruler. No matter how carefully the gage is handled, some movement of the contact point could occur. For these reasons, the error range was estimated at 0.04 inch (0.10 centimeter) or about two and one-half the specified scale reading accuracy. The overall wear range, however, is between 4 and 13 times the expected error range so the data should be usable for studying the wear phenomena.

Figure 7 is a plot of the average of the two flange height measurements against mileage for a typical treated wheel (treated, 2-wear, wrought, CN profile, 14-inch center plate, type 1 truck) and figure 8 is a similar plot for a typical untreated wheel (untreated, 1-wear, cast, AAR profile, 14-inch center plate, type 1 truck).

Again, several observations can be made on the flange height measurements. First, it should be noted that the flange is growing. Because of the nature of the measurement techniques, some of this growth can be attributed to tread wear but not all of it, since in this experiment the tread wear was slight. There was also the growth of a small metal ridge at the tip of the flange. This tip was brittle metal which would, on occasion, break off the flange. In this case, also the differences in performance between wheels of the same type can be observed.

For these plottings, the measurement error was again estimated at 0.04 inch (0.10 centimeter). The vernier scale was readable to 1/64 of an inch (0.04 centimeter), but the problems with alinement, rough surfaces at both the tread face and the flange tip, and the tendency for the flange tip to break cause deterioration in this basic reading accuracy. The change in flange height ranged from a decrease of 0.15 inch (0.38 centimeter) to an increase of 0.29 inch (0.73 centimeter) with the mean change being an increase in height of 0.11 inch (0.28 centimeter) for treated wheels and 0.12 inch (0.3 centimeter) for untreated wheels. It is difficult to make a reasonable quantitative estimate of how much of this change is due to flange growth and how much of it is due to tread wear. Thus, it was decided that quantitative analysis of this data to determine relations would not be productive.

Similar plots were made of rim thickness versus mileage for the first turning for each of the two types of example wheels. Figure 9 is for the treated wheel and figure 10 is for the untreated wheel. The measurement error was estimated at 0.09 inch (0.23 centimeter). The scale on the finger gage was read only to the nearest 1/16 of an inch (0.16 centimeter) and problems with gage alinement coupled with the fact that the edge of the face of the rim where the measurement was taken is rounded would reduce this accuracy. In this case, the reading accuracy was reduced by a factor of 1.5. Two data points occur in figure 10 at about 20,000 miles which vary greatly from the remaining measures. Presumably errors occurred in either the recording or transfer of the data.

The change in rim thickness was calculated for each wheel by subtracting the final measurement from the initial measurement. These differences ranged from a decrease in rim thickness (wear) of 0.57 inch (1.43 centimeters) to an increase in rim thickness (growth) of 0.17 inch (0.43 centimeter). The average change for all wheels was a decrease (wear) of 0.8 inch (0.20 centimeter). It can be seen from the overall averages and from examining graphs of the flange thickness versus the mileage such as figures 9 and 10 that some wear is occurring; however, it is also clear that the large measurement error relative to the total changes greatly reduces the ability to draw quantitative conclusions from the data. Further analysis of the rim wear data was not done as part of this study.

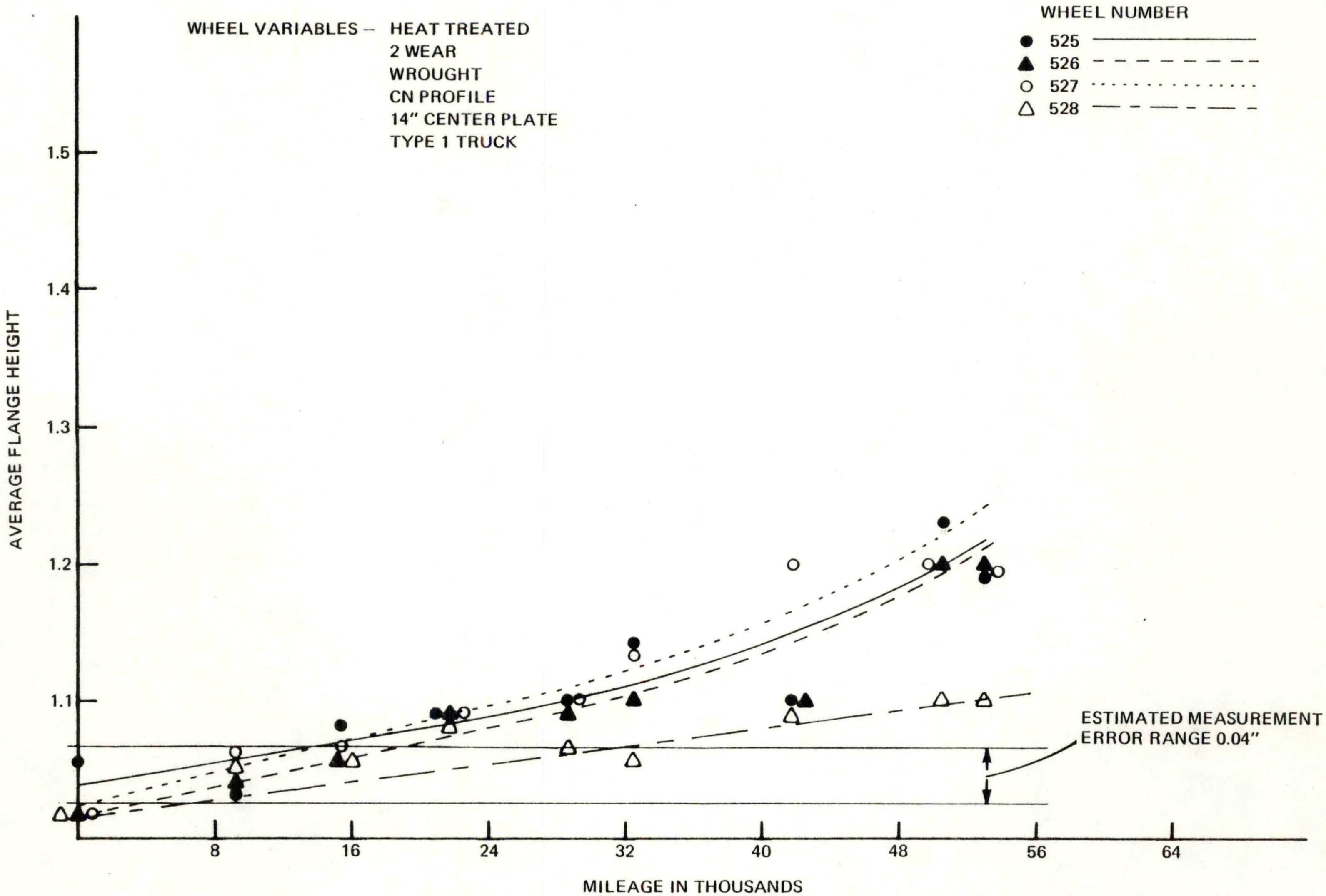

FIGURE 7. FLANGE HEIGHT VERSUS MILEAGE FOR EXAMPLE TREATED WHEELS FROM FAST EXPERIMENT 1

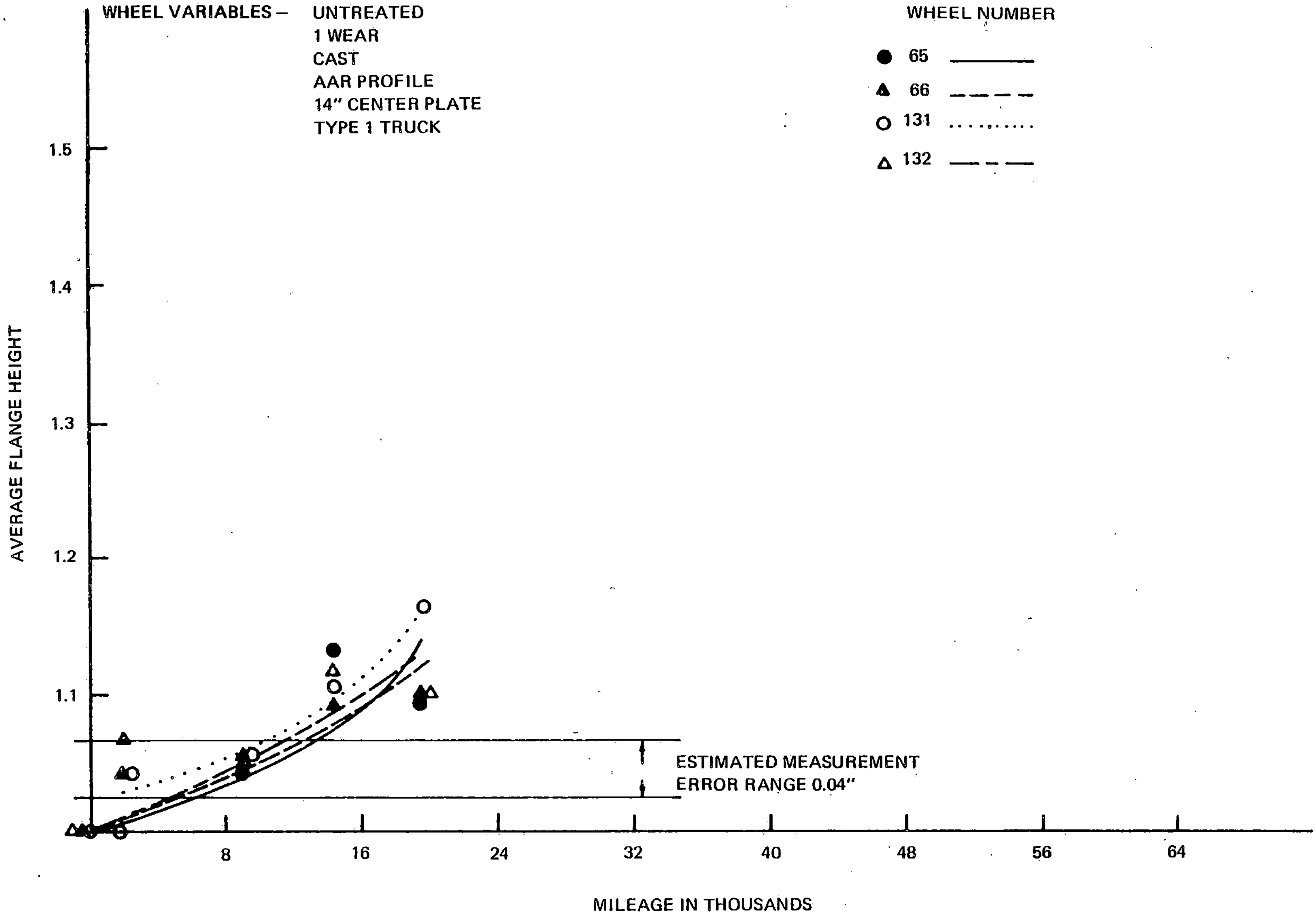

FIGURE 8. FLANGE HEIGHT VERSUS MILEAGE FOR EXAMPLE UNTREATED WHEELS FROM FAST EXPERIMENT 1

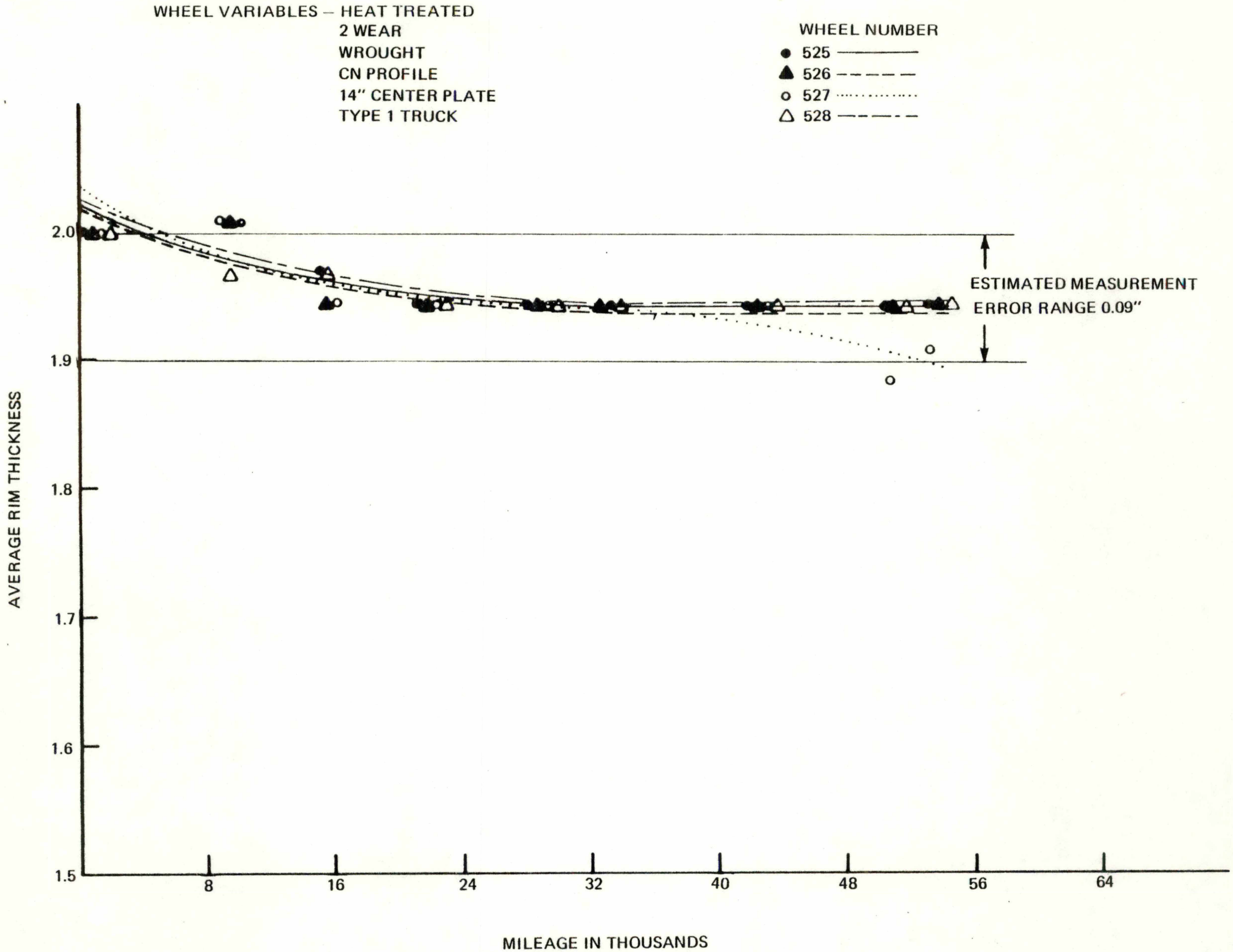

FIGURE 9. RIM THICKNESS VERSUS MILEAGE FOR EXAMPLE TREATED WHEELS FROM FAST EXPERIMENT 1

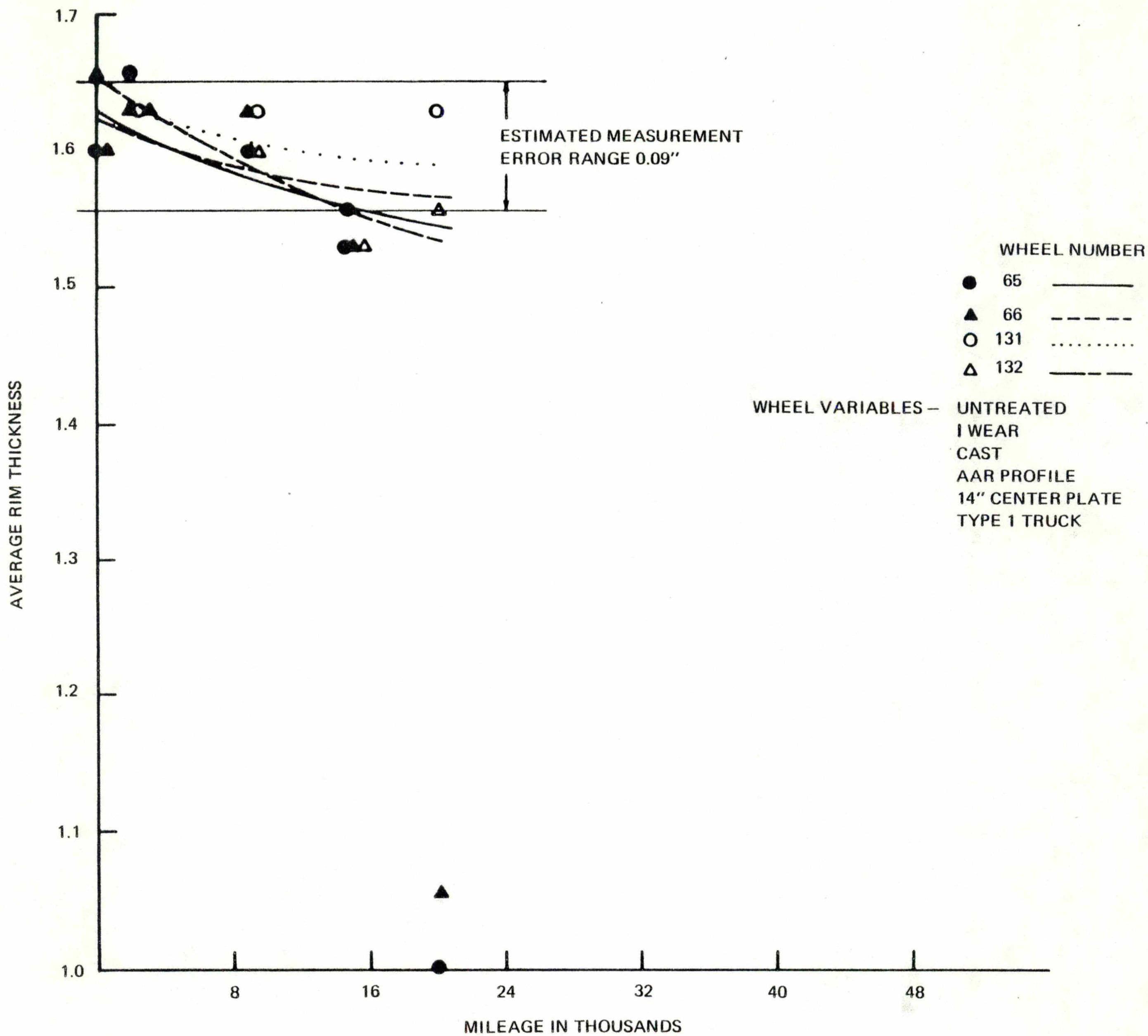

FIGURE 10. RIM THICKNESS VERSUS MILEAGE FOR EXAMPLE UNTREATED WHEELS FROM FAST EXPERIMENT 1

Analysts for the Association of American Railroads, taking a different approach, studied the effects of the experiment variables on the rate of rim wear over the first 20,000 test miles when the wheels were experiencing their most rapid wear. They found that treated wheels wore at a slower rate than untreated wheels at the 99.95 percent level of significance. Their analysis showed that the rim wear rate for treated wheels was less than half of the rate for untreated wheels. (Source: "Facility for Accelerated Service Testing (FAST), Progress Report No. 2," Association of American Railroads, Report Number R-288, September 1977.)

Finally, the reasons for removal need to be discussed. The reasons for removal in experiment 1 can be grouped into four categories. These are:

Thin flange - The AAR condemning limit of 15/16 of an inch (2.34 centimeters) was chosen as the removal criteria for this test. The axle set was removed or turned whenever one or more of the wheels reached 15/16 of an inch (2.34 centimeters), or when it was estimated by the test operation staff that it would reach 15/16 of an inch (2.34 centimeters) before the next 22-day measurement cycle. Where possible, the wheels were turned to a narrow flange profile and returned to service.

Flange cracked or broken - In some instances, small cracks were observed in the flange originating in the area of the metal flow at the tip. Whenever there was indication that these cracks were propagating into the flange, the wheels were condemned. This phenomena was studied in detail by metallurgists from the AAR. (Source: "Facility for Accelerated Service Testing (FAST), Progress Report No. 2," Association of American Railroads, Report No. R-288, September 1977.)

Tread cracks - Fine cracks were observed forming in the tread of many of the wheels after 30,000 miles (48,000 kilometers) of testing. They occurred mostly in treated wheels, but it should be noted that most of the untreated wheels were removed or returned before 30,000 miles (48,000 kilometers). The cracks on the treated wheels had not reached AAR condemning limits when most of these wheels were removed because of concern for safety on the part of the test operations staff.

Other reasons - A few wheelsets of each type were removed for reasons unrelated to wheel performance such as bad bearings or general repairs.

Table 1 shows the percentage of wheelsets removed for the first turning for various reasons for treated and untreated wheels. This information is presented graphically in figure 11. In this case, wheelsets were treated as one unit, since if one wheel failed both wheels had to be removed. It should be noted that the treated and untreated wheels had not seen the same mileage since untreated wheels reached thin flange condemning limits much sooner than treated wheels.

TABLE 1. REASONS FOR FIRST REMOVAL
BY WHEELSET IN EXPERIMENT 1

Reason	Treated Wheels	Untreated wheels
Thin flange	6.7%	83.3%
Flange cracked or broken	5.0%	5.0%
Tread cracks	78.3%	1.7%
Other reasons	10.0%	10.0%

Based on observations and graphical analysis several conclusions can be drawn:

- Flange wear is the most prevalent type of wear experienced on FAST.
- The measurement most likely to produce useful quantitative data is the flange thickness data.
- There is a wide difference in performance among wheels of the same variable combinations.
- Treated wheels last longer than untreated wheels, on the average.
- Wear is not the only determinant of wheel life on FAST.

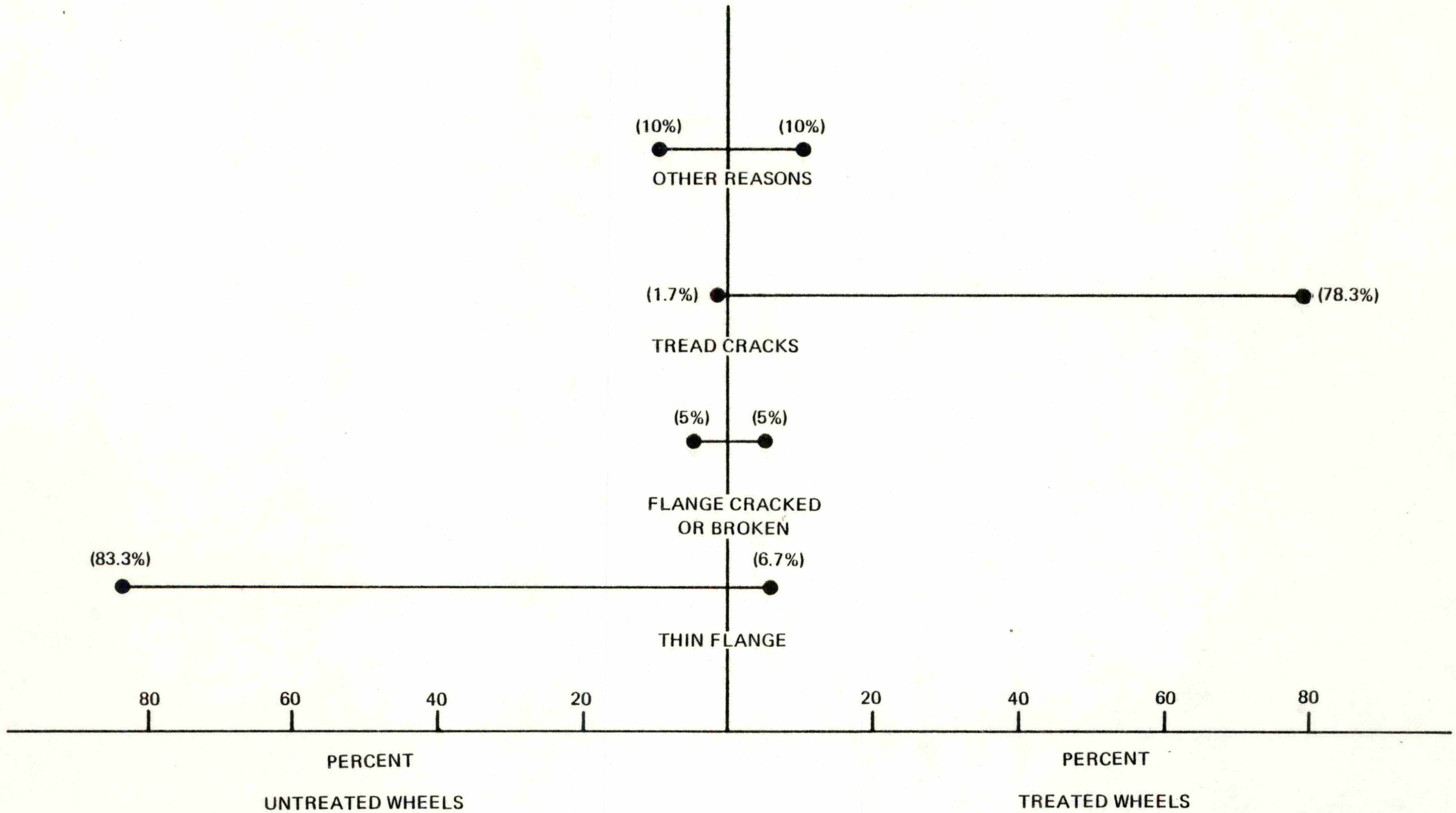

FIGURE 11. REASONS FOR FIRST REMOVAL BY WHEELSET IN EXPERIMENT 1
COMPARISON OF TREATED AND UNTREATED WHEELS

MODEL DEVELOPMENT

In order to investigate the relations between the variables, several mathematical models were investigated for appropriateness. The first step in evaluating the possible models involved a more detailed investigation of the observed non-linearity of the data. For this investigation, two regressions were run on the flange thickness measurements versus mileage for the first turning on each wheel. The first formulation regressed the average flange thickness at each mileage against mileage, the second regressed the logarithm of the average flange thickness at each mileage against the logarithm of the mileage plus 10,000. Ten thousand was added to the mileage in order to avoid taking the logarithm of 0. These regressions yielded least squares best fits for each wheel. In the case of the linear formulation, this yielded a least square average wear rate and in the non-linear case it yielded the least square slope of the ln-ln plot or what might be considered a non-linear wear rate.

The fits of these regressions were then compared. In each case there was a range of fits with the square of the correlation coefficient (R^2) (percentage of variation explained by model) ranging from near zero to near 1. However, the non-linear formulation had a mean R^2 of 0.853, while the linear had a mean R^2 of 0.798. In addition, out of the 233 wheels which had 3 or more observations in the first turning, 150 had an R^2 for the non-linear formulation which was greater than that for the linear formulation.

Based on this analysis, it was concluded that the flange thickness versus mileage plot for the first turning of the experiment 1 wheels, can be considered non-linear. This conclusion applies only to experiment 1 data. Other wheel data should be examined independently for the most appropriate model.

The next investigation involved using the results of the above regressions as an index of the wear rates of the flange thickness. That is, since the coefficient on the non-linear regression represents a slope of the ln-ln plot it could be considered as characterizing the wear of the wheel. The following model was therefore formulated for analysis:

$$\text{Wear index} = A_0 + A_1 X_1 + A_2 X_2 + A_3 X_3 + A_4 X_4 + A_5 X_5 + A_6 X_6$$

where:

X_1 = 1 if wheel is heat treated
0 if wheel is untreated

X_2 = 1 if wheel is 1 wear
0 if wheel is 2 wear

X_3 = 1 if wheel is cast
0 if wheel is wrought

X_4 = 1 if wheel has CN profile
0 if wheel has AAR profile

X_5 = 1 if truck has 14-inch center plate
0 if truck has 16-inch center plate

X_6 = 1 if truck is type 1
0 if truck is type 2

Physically, this is analogous to postualting that the basic wear index for all wheels is changed depending on the state of the test variables. The size of the coefficients $A_1 \ldots A_6$ determine the effect of the variable on wear, the sign of the coefficients determine whether the variable increases or decreases wear and the statistical significance of the variable provides an indication of the uncertainty of the estimate. The results of this regression are given in table 2.

TABLE 2. RESULTS OF REGRESSION ON MODEL

$$\text{Wear index} = A_0 + A_1 X_1 + A_2 X_2 + A_3 X_3 + A_4 X_4 + A_5 X_5 + A_6 X_6$$

Correlation coefficient R = 0.6745

Variable	Coefficient Value	"F"	Statistical Significance
Intercept (A_0)	0.3268		
X_1 (A_1)	-0.1984	181.15	0.9999
X_2 (A_2)	0.0107	0.52	0.5294
X_3 (A_3)	0.0028	0.04	0.1510
X_4 (A_4)	0.0079	0.29	0.4084
X_5 (A_5)	-0.0140	0.89	0.6540
X_6 (A_6)	-0.0181	1.51	0.7795

In this first model the wheel treatment had a very high significance as would be expected while none of the other variables showed much effect. The variable with the next significance was the truck type and its significance was only 78 percent; i.e., there was a 22-percent probability of obtaining a number this significant due purely to chance.

The low statistical significance of the variables other than the wheel treatment can be attributed to two main factors. First, the use of a single index to describe an entire set of observations for one wheel reduces the number of available observations and thereby reduces the statistical sensitivity of the procedure. Second, the use of a wear rate index to describe the wear phenomena may result in an inadvertant filtering of secondary effects before the regression.

Consequently, a new model was tried which incorporated the idea that the general rate of wear is related to the test variables but deals with the data observation by observation. This model is:

Average Flange Thickness = $A_0 + B$ (mileage)

where: $B = b_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_4 X_4 + b_5 X_5 + b_6 X_6$

where:

X_1 = 1 if wheel is heat treated
0 if wheel is untreated

X_2 = 1 if wheel is 1 wear
0 if wheel is 2 wear

X_3 = 1 if wheel is cast
0 if wheel is wrought

X_4 = 1 if wheel has CN profile
0 if wheel has AAR profile

X_5 = 1 if truck has 14-inch center plate
0 if truck has 16-inch center plate

X_6 = 1 if truck is type 1
0 if truck is type 2

The results of this regression are given in table 3.

TABLE 3. RESULTS OF REGRESSION ON MODEL

Flange Thickness =

$A_0 + (b_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_4 X_4 + b_5 X_5 + b_6 X_6)$ Mileage

Correlation coefficient R = 0.6820

Variable	Coefficient Value	"F"	Statistical Significance
Intercept (A_0)	1.376		
Mileage (b_0)	-0.00001367	845.76	0.9999
X_1 (b_1)	0.0000082	599.25	0.9999
X_2 (b_2)	-0.00000024	1.11	0.7085
X_3 (b_3)	0.00000036	2.75	0.9025
X_4 (b_4)	0.00000052	5.46	0.9804
X_5 (b_5)	0.00000051	5.12	0.9762
X_6 (b_6)	0.00000093	18.23	0.9999

It can be seen with this second formulation the secondary variables take on a much greater significance. However, it should also be noted that the overall regression coefficient R was only 0.682. Thus, this model only explains 46.5 percent of the variation observed in the data.

Based on the earlier findings that the shape of the flange thickness versus mileage curves tend to be non-linear, a non-linear regression was tried. This third formulation was:

$$\text{Average Flange Thickness} = A_0 \,(\text{Mileage} + 10{,}000)^B$$

where: $$B = b_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_4 X_4 + b_5 X_5 + b_6 X_6$$

where:

X_1 = 1 if wheel is heat treated
0 if wheel is untreated

X_2 = 1 if wheel is 1 wear
0 if wheel is 2 wear

X_3 = 1 if wheel is cast
0 if wheel is wrought

X_4 = 1 if wheel has CN profile
0 if wheel has AAR profile

X_5 = 1 if truck has 14-inch center plate
0 if truck has 16-inch center plate

X_6 = 1 if truck is type 1
0 if truck is type 2

As in the earlier formulation, 10,000 was added to the mileage in order to avoid taking the logarithm of zero.

The results of this regression are given in table 4.

TABLE 4. RESULTS OF REGRESSION ON MODEL

Flange Thickness =

$$A_0 \text{ (Mileage + 10,000)}^B$$

$$B = (b_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_4 X_4 + b_5 X_5 + b_6 X_6)$$

Correlation coefficient R = 0.7214

Variable	Coefficient Value	"F"	Statistical Significance
Intercept (A_0)	1.8026		
Mileage (b_0)	-0.1650	1621.00	0.9999
X_1 (b_1)	0.0106	555.92	0.9999
X_2 (b_2)	-0.0002	0.25	0.3830
X_3 (b_3)	0.0007	2.92	0.9124
X_4 (b_4)	0.0015	13.30	0.9997
X_5 (b_5)	0.0011	7.51	0.9938
X_6 (b_6)	0.0013	11.30	0.9992

The coefficient of regression R is now 0.7214, only slightly higher than that for the linear model. In this case 52 percent of the variation is explained by the model. Because the underlying distribution fits the data more closely, this model was chosen as the final study model. Since X_2 (1-wear, 2-wear) only had a statistical significance of 0.3830 it was decided that it should not be included in the model. X_3 which had a significance of 0.9124 was left in the model. When the variable X_2 was removed, the other coefficients and their statistical significance changed slightly leaving as the final model:

$$\text{Average Flange Thickness} = 6.056 \text{ (Mileage + 10,000)}^B$$

where: $B = -0.1649 + 0.0107 X_1 + 0.0007 X_3 + 0.0014 X_4 + 0.0011 X_5 + 0.0013 X_6$

where:

X_1 = 1 if wheel is heat treated
0 if wheel is untreated

X_3 = 1 if wheel is cast
0 if wheel is wrought

X_4 = 1 if wheel has CN profile
0 if wheel has AAR profile

CONCLUSIONS AND RECOMMENDATIONS

In summary, the analysis of experiment 1 data leads to several conclusions:

- The primary wear occurring on the heavily curved FAST track is flange wear.

- On the FAST track, treated wheels have shown significantly better flange wear performance than untreated wheels. Indications are that treated wheels provide on the order of two and one-third times as much wear life.

- Compared to the effect of heat treatment, the other test variables -- cast wheels versus wrought wheels, 1-wear wheels versus 2-wear wheels, AAR profile versus CN profile, type 1 truck versus type 2 truck, 14-inch center plate versus 16-inch center plate -- have relatively small effects on flange wear. However, there is some indication that CN profile, 14-inch center plates, cast wheels, and type 1 trucks tended to increase flange life slightly.

- Untreated wheels tended to be removed from the test for thin flange conditions, while treated wheels tended to be removed for cracks. It should be noted that these cracks were not at the AAR condemning limits and the heat-treated wheels had already traveled more miles (before cracks began to develop) than the non-heat-treated wheels had traveled before being removed for thin flange.

Also, several observations made during the course of this analysis lead to recommendations for changes and improvements in future wheel tests:

- New variables should be included in future experiments. The fact that there were wide differences in the performance of wheels of the same variable combinations indicates that there may be other significant variables. Examples of these could be a measure of the age of the rail, a measure of the level of lubrication of the rail, the chemical composition of the wheels, and the hardness of the rail and wheels. Provision has already been made to include data on the chemical composition of the wheels in the data base.

- In each future experiment, fewer variables should be tested using a larger number of test units for each variable. It has been seen that the practical operation of the FAST track can vary from the basic experiment design, and the problems with component supply or operations problems can lead to the loss of some test components.

- Efforts to improve the accuracy of the measurements should continue. At this point, many of the measurements are not accurate enough to yield detailed conclusions. Efforts are under way both to improve the profilometer measurements and to incorporate a more accurate hardness measure. These should proceed without delay. In addition, efforts should be begun to improve the measurements now being performed with the finger gage.

Analysis of Data From The First Wheel Experiment at the Facility For Accelerated Service Testing, US DOT, FRA, KW Larsen, 1979, 02-Track-Train Dynamics