WASHINGTON STATE HIGHWAY DEPARTMENT RESEARCH PROGRAM REPORT **9.3**

STUDDED TIRE PAVEMENT WEAR REDUCTION & REPAIR

PHASE 3
FINAL REPORT

RESEARCH PROJECT

Y-1439

DECEMBER 1973

PREPARED FOR
WASHINGTON STATE HIGHWAY COMMISSION
IN COOPERATION WITH
U.S. DEPARTMENT OF TRANSPORTATION
ERAL HIGHWAY ADMINISTRATION
D IDAHO DEPARTMENT OF HIGHWAYS

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16. Abstract

This report presents results obtained from the analyses of data which were collected during the performance of Phase I and Phase II of this project. The data were collected at the G. A. Riedesel Pavement Testing Facility which is operated by Washington State University and is located in Pullman, Washington. Regression analyses were performed in order to relate various factors to each other.

The factors used in the analyses included stud type, stud protrusion, speed, air temperature, pavement temperature, environmental conditions, stud hardness and tire tread depth. The purpose was to evaluate the relative importance of these factors on pavement wear. It was found that the type of overlay, the type of stud and the stud protrusion length were the most important factors affecting pavement wear under WSU Test Track conditions. The other factors could not be sufficiently isolated to determine their relative importance.

Average wear rates were calculated for the different types of pavements and overlays caused by the different stud types. A formula was developed which can be used to calculate pavement life under certain conditions.

The results obtained for Phase I and Phase II were compared and the difference in these results is discussed. Some of the difference was due to the different testing conditions between the two phases. A comparison with other associated research was also made.

A striping paint study was made and the results are included in this report.

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PAVEMENT RESEARCH
performed at the
G. A. RIEDESEL PAVEMENT TESTING FACILITY
Pullman, Washington

STUDDED TIRE PAVEMENT WEAR REDUCTION AND REPAIR

Phase III: Composite presentation of Phase I and Phase II results and extrapolation of the conclusions to real world conditions.

The Final Report to the Washington State Department of Highways
for Research Project Y-1439.

by

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December 31, 1973

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Department of Highways
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and the
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Transportation Systems Section Publication H-41

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Dave Heinen and Ed Ellis, students in Electrical Engineering, deserve special credit for programming the equations used in the regression analyses and doing all the legwork involved.

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Other students involved in the tedious task of reducing the raw data to more usable form include Chuck West and Barbara J. Krukar.

Photographs were taken and processed by the Engineering Photographic Laboratory's staff-Herb Howard, Bill Hawkins and Glenn Sprouse.

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SUMMARY OF RESULTS

INTRODUCTION

This project, entitled "Studded Tire Pavement Wear Reduction and Repair" and designated Y-1439, was initiated by the Transportation Systems Section of the College of Engineering Research Division, Washington State University, and is financed by the Washington State Highway Commission, Department of Highways; by the U.S. Department of Transportation, Federal Highway Administration, as an HPR federal aid research project; and by the Idaho Department of Highways.

The project was divided into three phases: Phase I involved different types of pavements and surface textures; Phase II involved different types of overlays and surfacings; and Phase III involved complete regression analyses of the data, interpretations and discussions of the results of the analyses, comparison of the results with other research, correlations of the results to existing Washington State Department of Highways data, and extrapolation of the results for use in predicting pavement life due to the effects of tire studs.

Phase I started on October 1, 1971 with the construction of Experimental Ring No. 5 at the G.A. Riedesel Pavement Testing Facility at Washington State University. The traffic simulator was operated and test measurements were made during the period February 11, 1972 - May 4, 1972. The data obtained during this period is displayed and discussed in the final Phase I report dated December 30, 1972.

Phase II started on August 8, 1972 with the construction of Experimental Ring No. 6 at the test track. The testing period was from November 20, 1972 to May 1, 1973. The final report for Phase II was dated August 15, 1973.

The contents of this present report are founded on the experimental data collected during both Phase I and Phase II of the project. This present report exhibits the objectives of Phase III of the project and constitutes the Final Report for Project Y-1439.

DESCRIPTION OF THE TRAFFIC SIMULATOR

The traffic simulator at the G.A. Riedesel Pavement Testing Facility is a truss with three legs, each leg supported by a set of dual truck tires. The legs are attached to and support a water tank at the center of the apparatus. A 60 hp electric motor on each leg provides the power to move the simulator on a circular path. A mechanism built into the apparatus produces an eccentric rotation so that the simulator has radial movement across each wheel path.

Passenger tires may be mounted on the three legs in various positions to provide separate test wheel paths. For this project, four separate wheel paths outside of the dual truck tires and two separate wheel paths inside of the dual truck tires were used. One tire traveled in each of the four outside wheel paths, while three tires traveled in each of the inside wheel paths. A total of 16 tires were mounted on the simulator for each of the two experimental rings. Each passenger car tire carried a 1000 lb load which was applied through an air load cell, and each set of dual truck tires carried 6,600 lbs. A hydraulic braking system was installed on the simulator for use on the inside tires in Ring No. 5, but continual operational problems with the system precluded its use.

DESCRIPTION OF THE PAVEMENT TEST FACILITY

a) Experimental Ring No. 5

Experimental Ring No. 5 consisted of three concentric rings or tracks. The center track was 3.0 feet wide and was that portion of the ring on which the dual truck tires traveled. The outside and inside tracks, each 3.5 feet wide, were those portions of the ring on which the outside and inside passenger tires traveled, respectively. The individual concentric rings consisted of different pavement materials placed in sections with different longitudinal lengths.

The pavement structure consisted of an asphalt-treated base 6 inches thick and a 6-inch surface course composed of different pavement materials. The center ring was constructed of reinforced portland cement concrete and was finished with twelve different surface textures. The outside and inside rings were constructed of various mixes of asphalt concrete and of portland cement concrete covered with different types of overlays. Thirty-four sections with various combinations of different pavement materials were constructed: 20 sections in the outside ring and 14 sections in the inside ring.

b) Experimental Ring No. 6

Experimental Ring No. 6 was constructed from the remains of Ring No. 5. The existing pavement structure from Ring No. 5 was used as a base and was overlaid with different materials in thicknesses varying from 3/4 to 2 inches. The concrete pavement wheel paths were patched with various materials prior to the placement of the overlay materials.

In this experimental ring, the overlay material was placed continuously across the width of the roadway. Hence, the outside, center and inside tracks were covered with the same overlay material in any particular section of the ring. A total of 22 longitudinal sections containing different overlay materials were placed on top of the existing pvavement structure.

PRESENTATION OF RESULTS

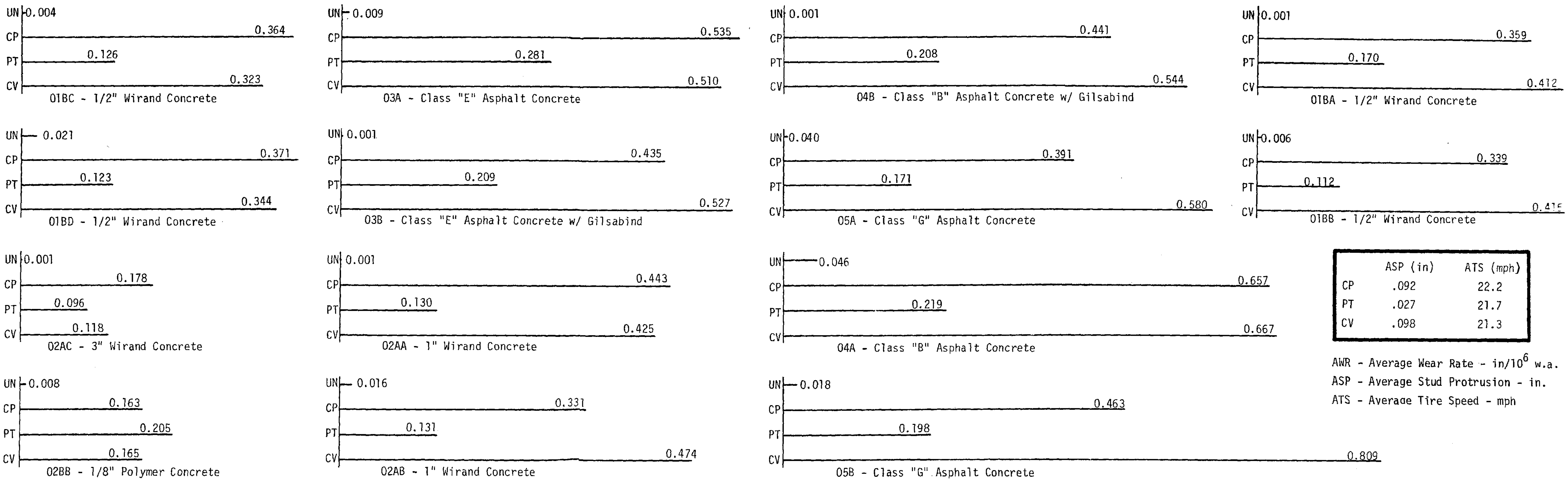
a) Experimental Ring No. 5

Figure 5 shows the relative effects of the various types of studs on the materials used in the outside track. Each tire with a different stud type traveled in a different track. Hence, each tire traveled at a slightly different speed. Associated with each type of stud is an average stud protrusion length. The average tire speeds (ATS) and average stud protrusion lengths (ASP) are given in the figure. With few exceptions, the PT stud caused the lowest wear rate, while the CP and the CV studs alternated for the second and third places. It is important to note the magnitudes of the wear rates for the three different studs. The effect of the difference in the average tire speed on the average wear rates can be assumed negligible, since the difference in speeds is so small, but the effect of the different ASP's cannot be overlooked. The PT stud has the smallest ASP, hence the smallest AWR's. The CP and CV studs exhibit similar ASP's and, thus, similar AWR's. All of the studded tires caused considerably higher AWR's on all of the materials than the unstudded tires.

Figure 6 displays the AWR's for the various materials resulting from the passage of the CP stud. These materials were on the outside and inside tracks of the ring. The average AWR for all of these sections for the unstudded tire paths is given for comparative purposes. Note the differences in ATS and ASP for the various outside track and inside track sections.

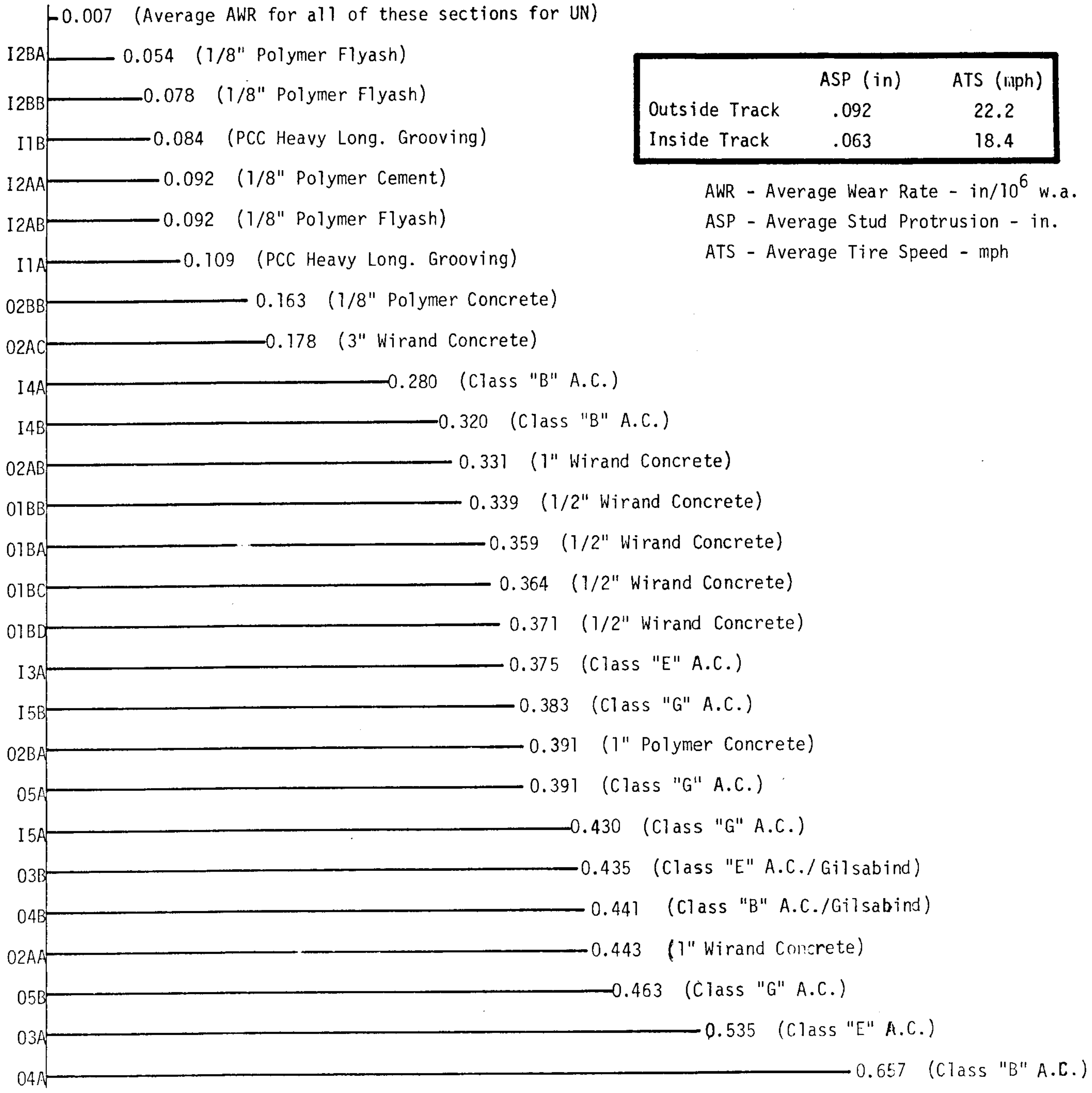
Figure 7 is similar to Figure 6 and presents the AWR's attributed to the PT stud.

FIGURE 5: AWR Value Comparisons for the Materials in the Outside Track in Ring No. 5.



	ASP (in)	ATS (mph)
CP	.092	22.2
PT	.027	21.7
CV	.098	21.3

AWR - Average Wear Rate - in/10^6 w.a.
ASP - Average Stud Protrusion - in.
ATS - Average Tire Speed - mph



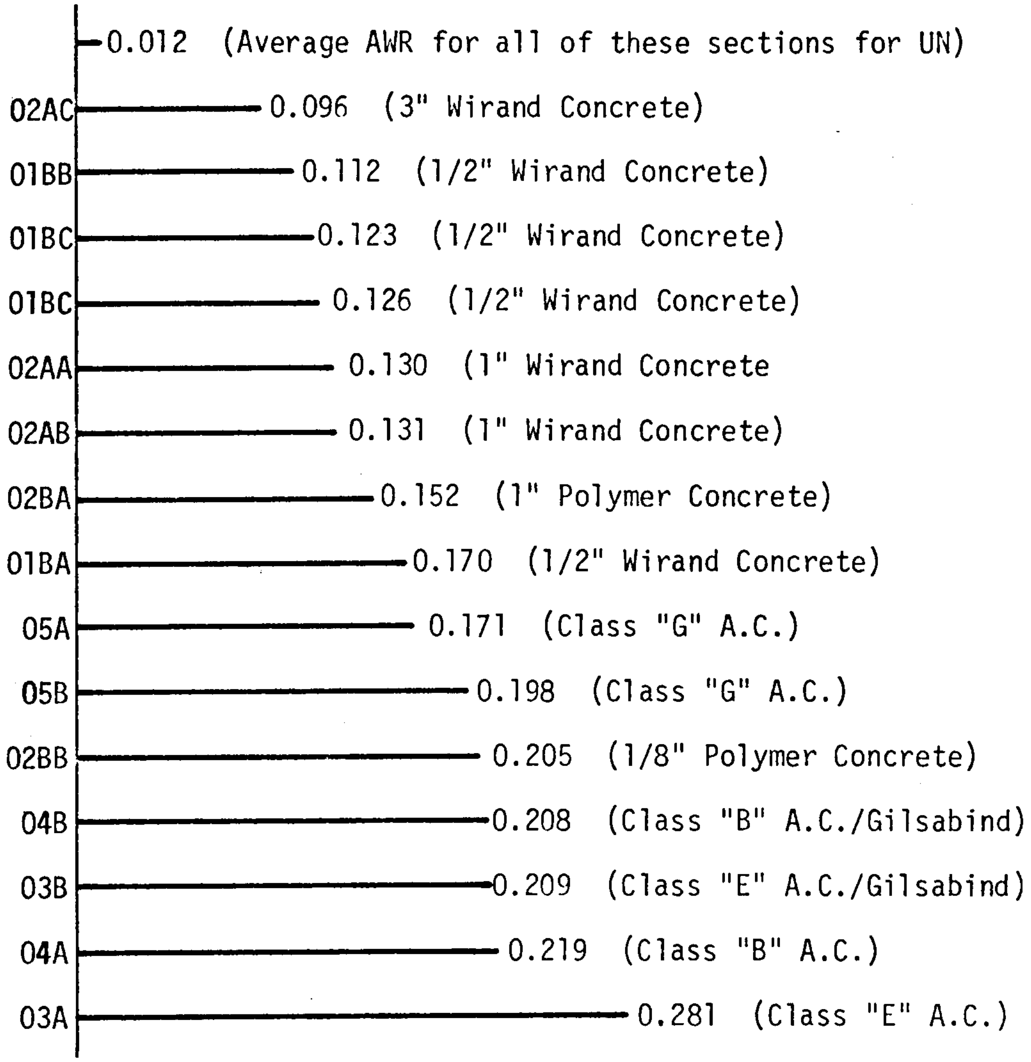
	ASP (in)	ATS (mph)
Outside Track	.092	22.2
Inside Track	.063	18.4

AWR - Average Wear Rate - in/10^6 w.a.

ASP - Average Stud Protrusion - in.

ATS - Average Tire Speed - mph

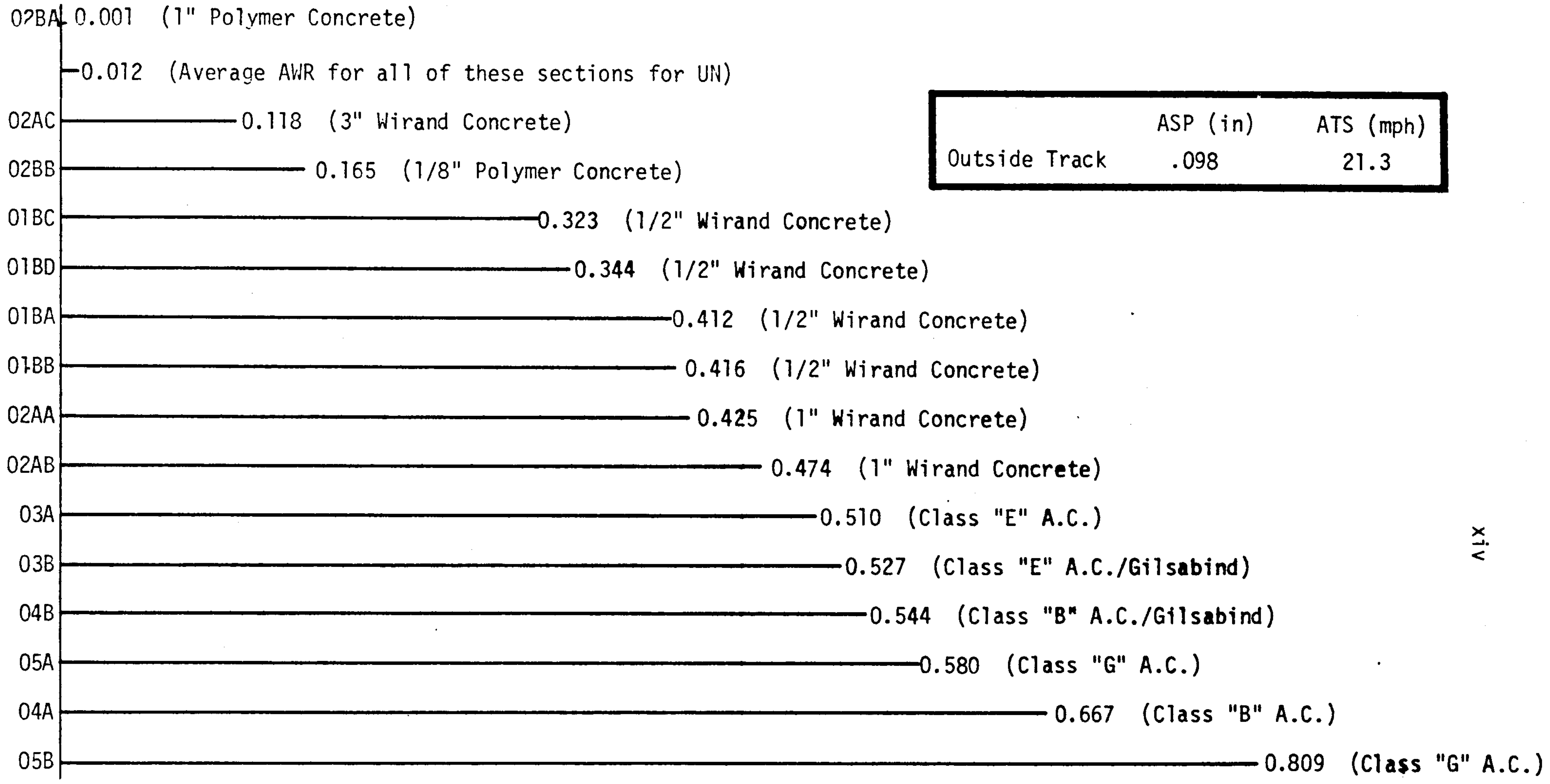
FIGURE 6: AWR Values Determined for the Controlled Protrusion Stud from Ring No. 5 Data.



	ASP (in)	ATS (mph)
Outside Track	.027	21.7

AWR - Average Wear Rate - in/10^6 w.a.
ASP - Average Stud Protrusion - in.
ATS - Average Tire Speed - mph

FIGURE 7: AWR Values Determined for the Perma-T Gripper Stud from Ring No. 5 Data.



AWR - Average Wear Rate - in/10^6 w.a.
ASP - Average Stud Protrusion - in.
ATS - Average Tire Speed - mph

FIGURE 8: AWR Values Determined for the Conventional Stud from Ring No. 5 Data. (Passenger Tires)

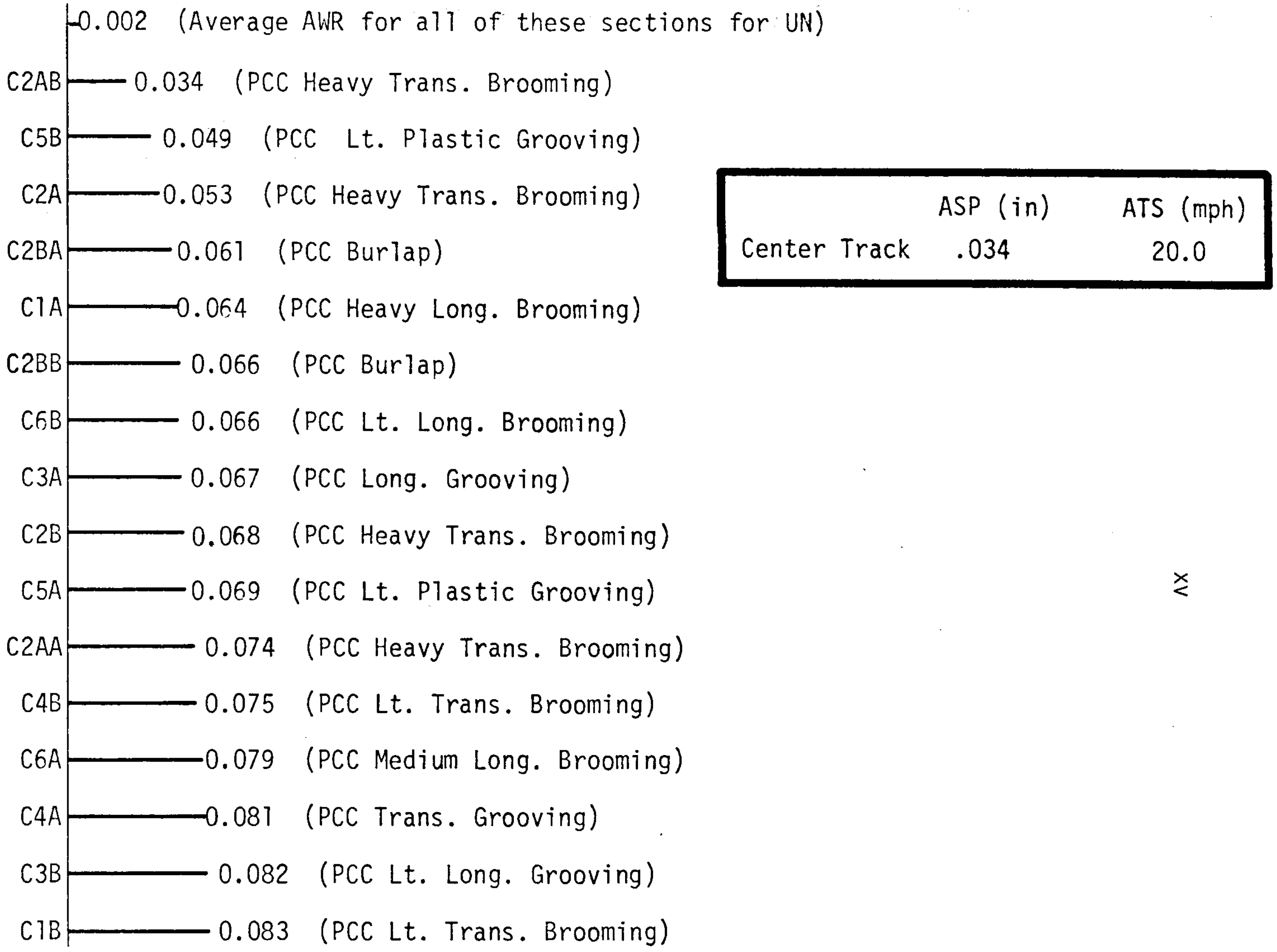


FIGURE 8 (Cont.): AWR Values Determined for the Conventional Stud from Ring No. 5 Data. (Truck Tires)

Figure 8 is similar to Figure 6 and presents the AWR's attributed to the CV stud. Since there are different types of tires associated with this figure, a separate average AWR for the unstudded tire path is given for comparison purposes within each group.

b) Experimental Ring No. 6

Figures 10, 11 and 12 display the calculated AWR's for the surfacing group, the concrete overlay group and the asphalt overlay group, respectively. In general the shorter the ASP, the smaller the AWR value. The differences in the tire speeds are so small that no conclusions can be reached concerning the effect of speed on the average wear rates.

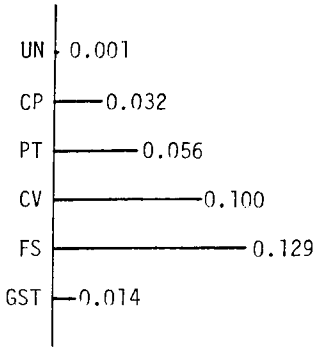
Figures 13, 14, 15 and 16 show the different AWR's for the different materials attributed to the CP stud, the PT stud, the CV stud and FS stud, respectively. Note that the average AWR for all of the unstudded tires in the respective groups is given for casual comparative purposes. It is obvious from these four figures that some materials resist the effects of tire studs more readily than others.

TRAFFIC PAINTS

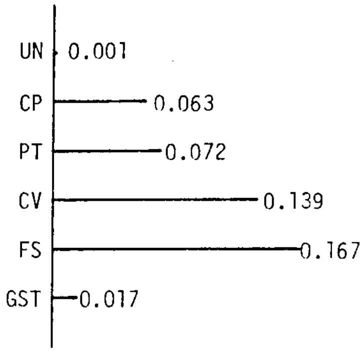
Four different types of traffic striping were tested to determine their resistance to wear from studded tires; three were paints applied with a constant-thickness paint applicator and the other was a thermoplastic white tape. The tests were made on sections 021 (the polymer cement concrete) and 100 (the class "G" asphalt concrete with Petroset AT). The initial measured thicknesses of the three paint stripes averaged 22 mils, while that of the thermoplastic white tape averaged 95 mils.

No quantitative measurements were made on the wear of the traffic stripes. Rather, visual observations were made and the stripes were ranked according to

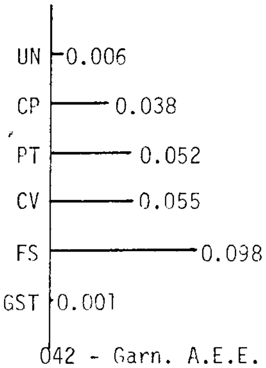
FIGURE 10: AWR Value Comparisons for the SURFACINGS GROUP in Ring No. 6.



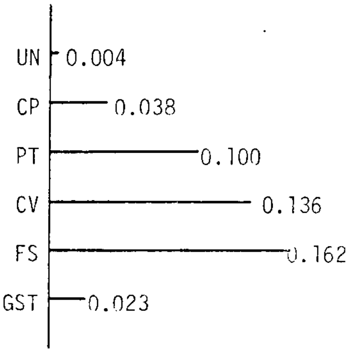
010 - Baux. A.E.E. Surf./High Al. C.C.



041 - Min. Slag A.E.E. Surf./PC Sand



042 - Garn. A.E.E. Surf./PC Sand



043 - Baux. A.E.E. Surf./PC Sand

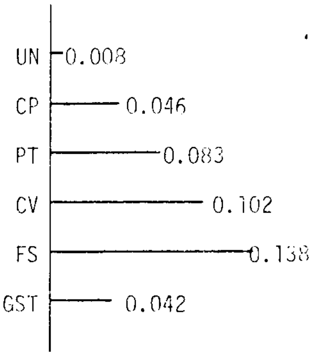
	ASP (in)	ATS (mph)
UN	---	18.0
CP	.020	18.4
PT	.017	21.7
CV	.030	21.3
FS	.029	22.2
GST	---	22.5

AWR - Average Wear Rate - in/10^6 w.a.

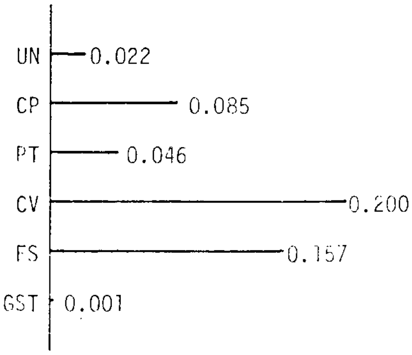
ASP - Average Stud Protrusion - in.

ATS - Average Tire Speed - mph

See Table 6 for Stud Types.

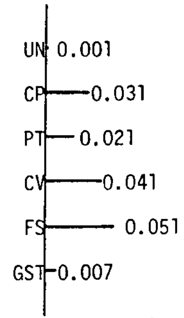


050 - Baux. A.E.E. Surf./Class "G" A.C.

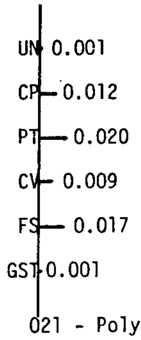


110 - Idaho Chip Seal/Class "G" A.C.

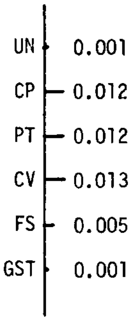
FIGURE 11: AWR Comparisons for the CONCRETE OVERLAY GROUP in Ring No. 6.



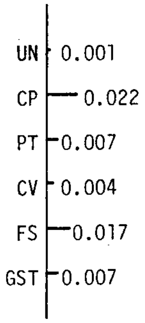
122 - Portland Cement Concrete



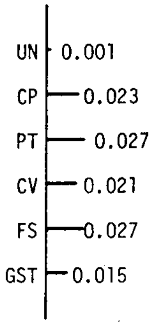
021 - Polymer Cement Concrete



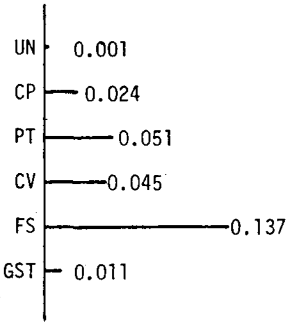
033 - Min. Slag-Sand on Polymer Conc.



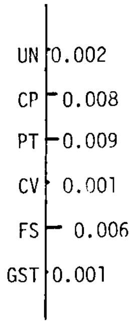
022 - Polymer Wirand Concrete



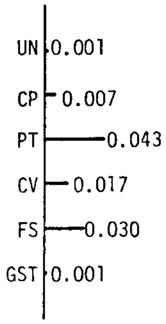
023 - Garnet on Polymer Cement Concrete



034 - Rubber Sand on Polymer Conc.



031 - Polymer Concrete



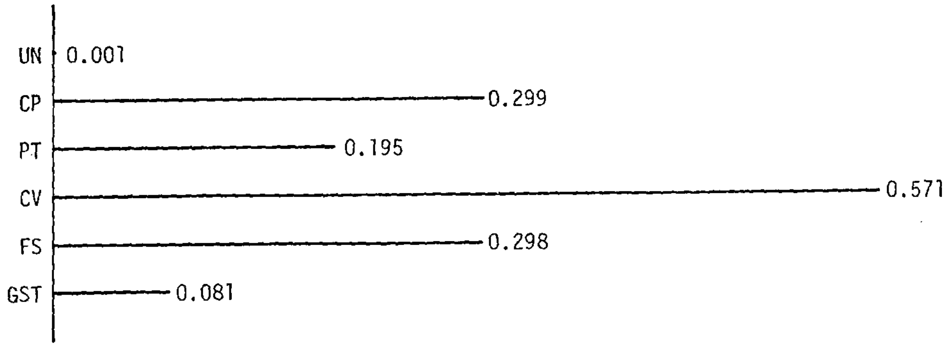
032 - Garnet on Polymer Concrete

	ASP (in)	ATS (mph)
UN	---	18.0
CP	.020	18.4
PT	.017	21.7
CV	.030	21.3
FS	.029	22.2
GST	---	22.5

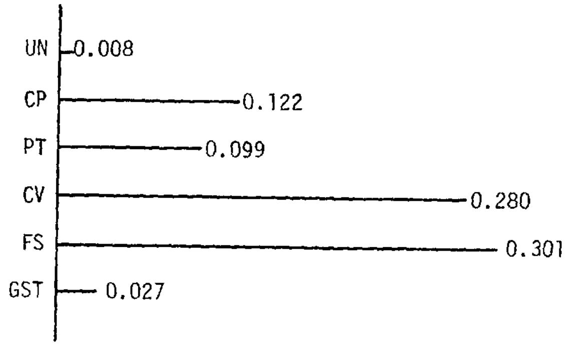
AWR - Average Wear Rate - in/10^6 w.a.
ASP - Average Stud Protrusion - in.
ATS - Average Tire Speed - mph

See Table 6 for Stud Types.

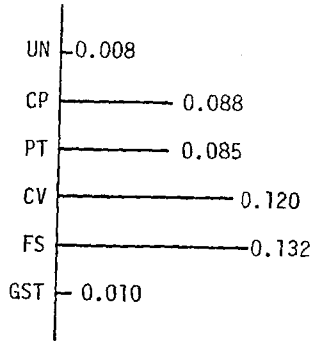
FIGURE 12: AWR Value Comparisons for the ASPHALT OVERLAY GROUP in Ring No. 6.



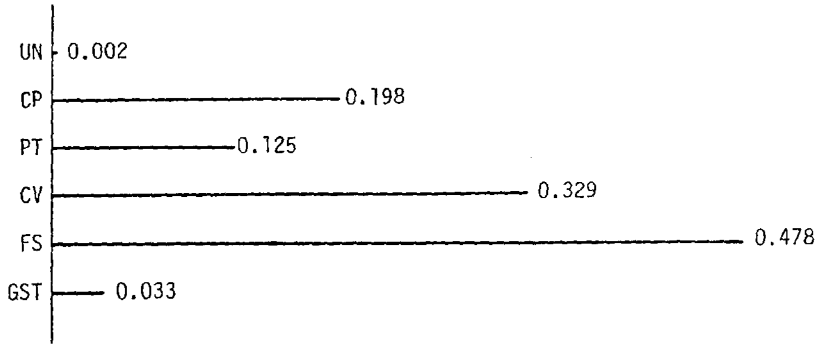
061 - Class "D" Asphalt Concrete



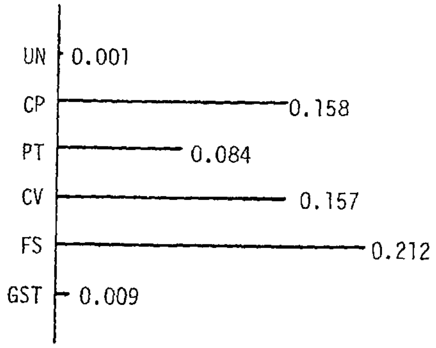
070 - Class "G" Asphalt Concrete/Pliopave



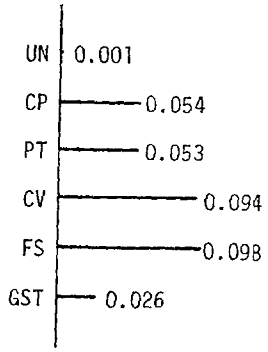
121 - Class "B" Asphalt Concrete



090 - Class "G" Asphalt Concrete



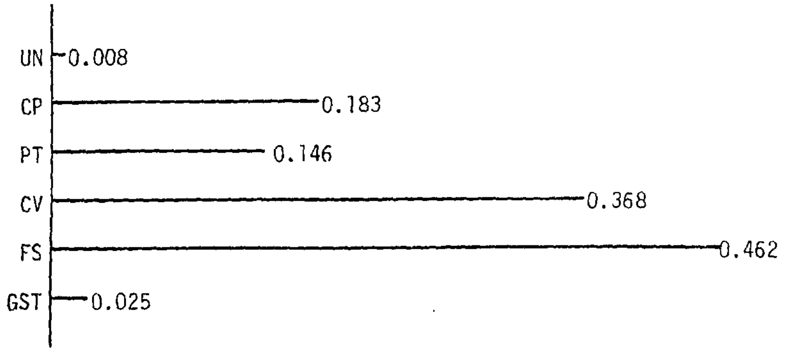
080 - Class "G" A.E.E. Concrete



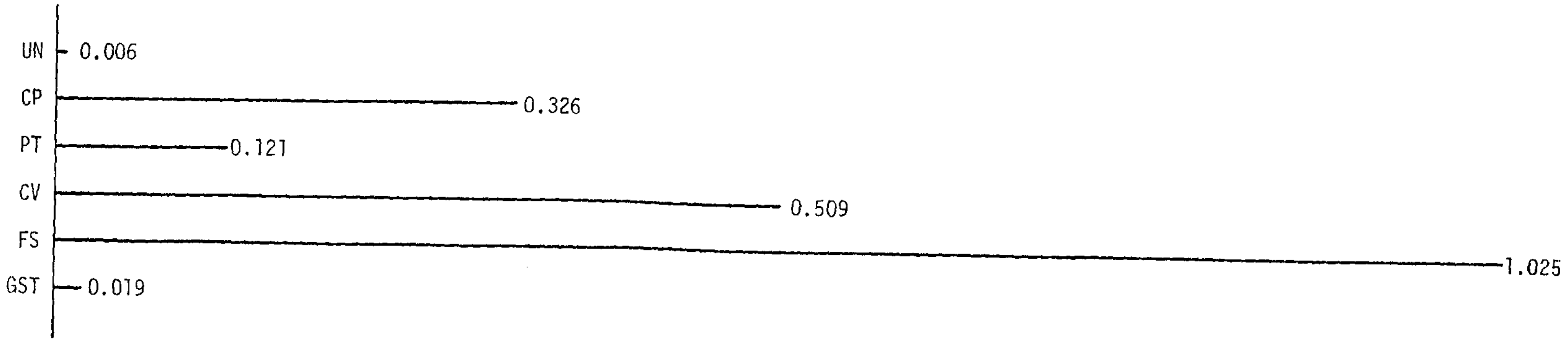
123 - Mastic Asphalt

	ASP (in)	ATS (mph)
UN	---	18.0
CP	.020	18.4
PT	.017	21.7
CV	.030	21.3
FS	.029	22.2
GST	---	22.5

AWR - Average Wear Rate - in/10^6 w.a.
ASP - Average Stud Protrusion - in.
ATS - Average Tire Speed - mph



100 - Class "G" Asphalt Concrete/Petroset AT



062 - Class "D" Asphalt Concrete/Petroset AT

FIGURE 13: AWR Values Determined for the Controlled Protrusion Stud from Ring No. 6 Data.

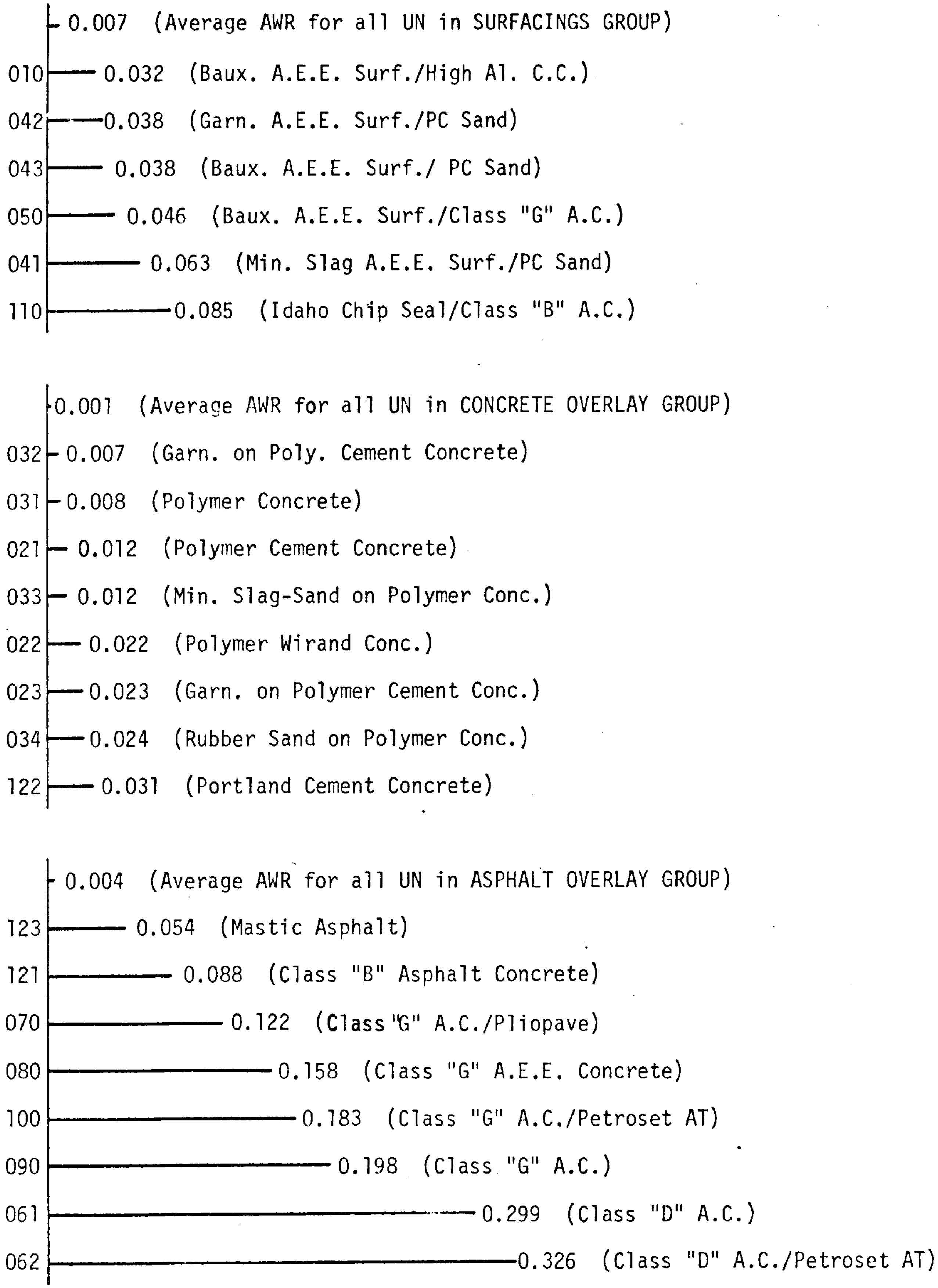


FIGURE 14: AWR Values Determined for the Perma-T Gripper Stud from Ring No. 6 Data.

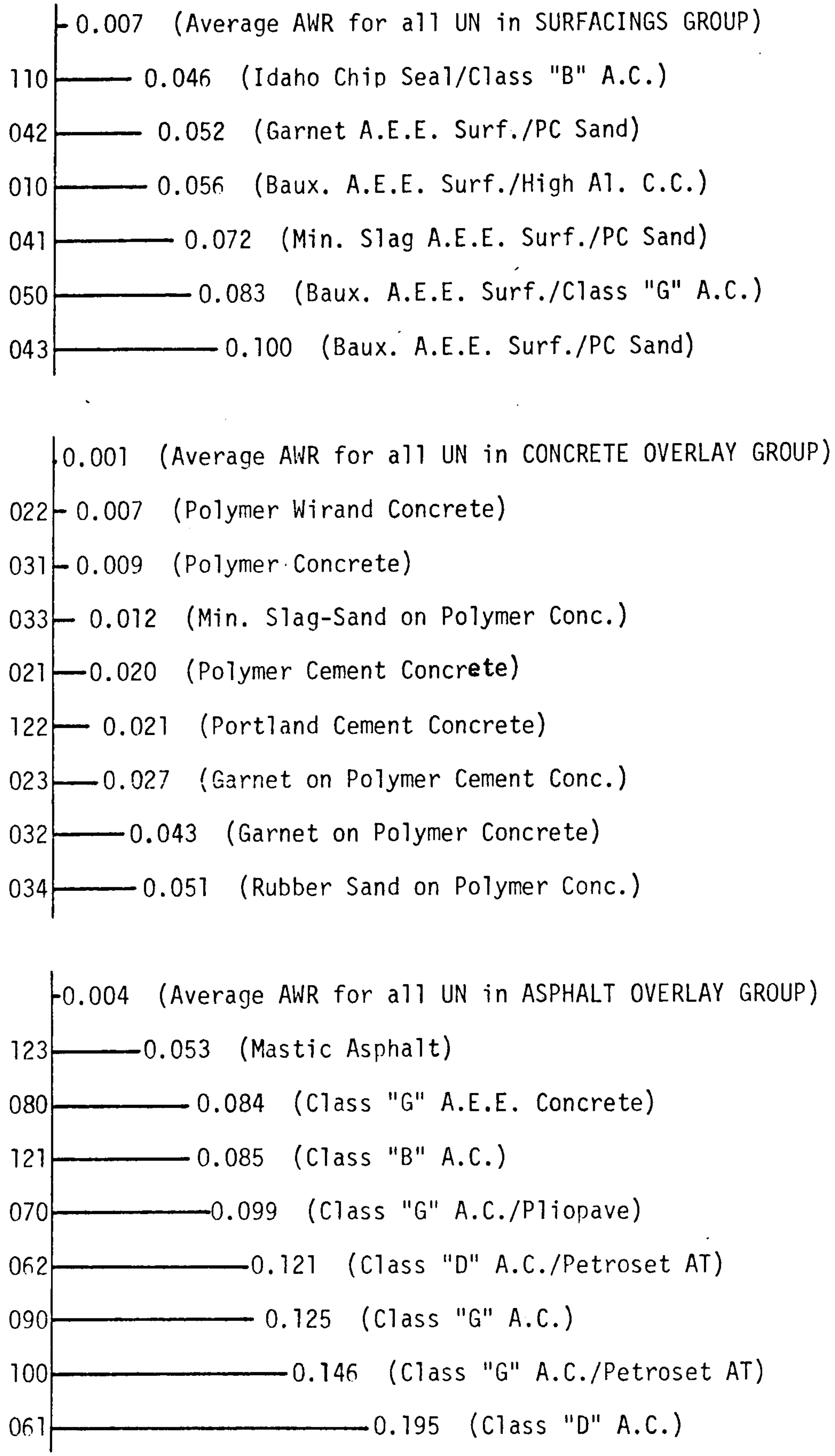


FIGURE 15: AWR Values Determined for the Conventional Stud from Ring No. 6 Data.

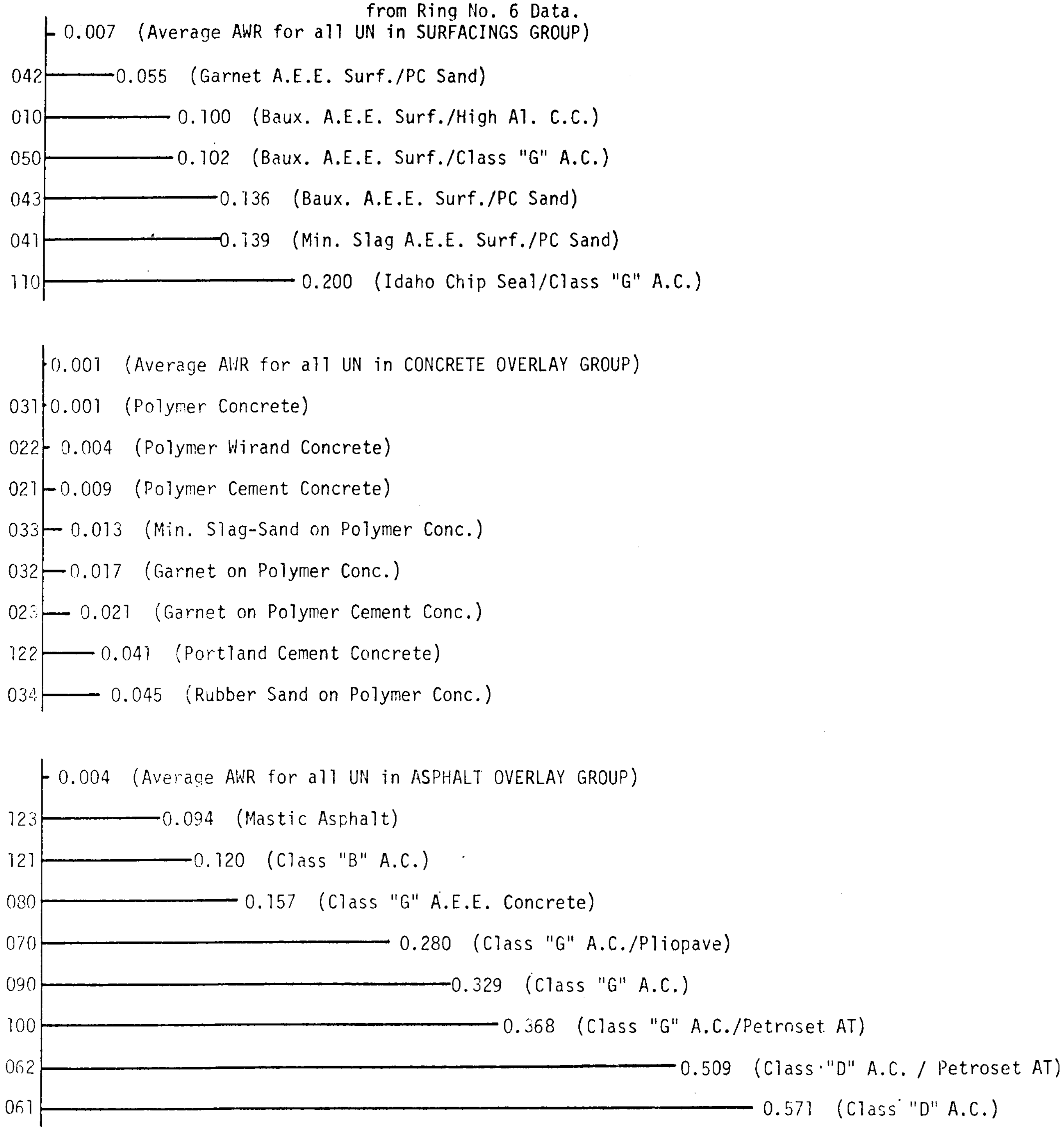
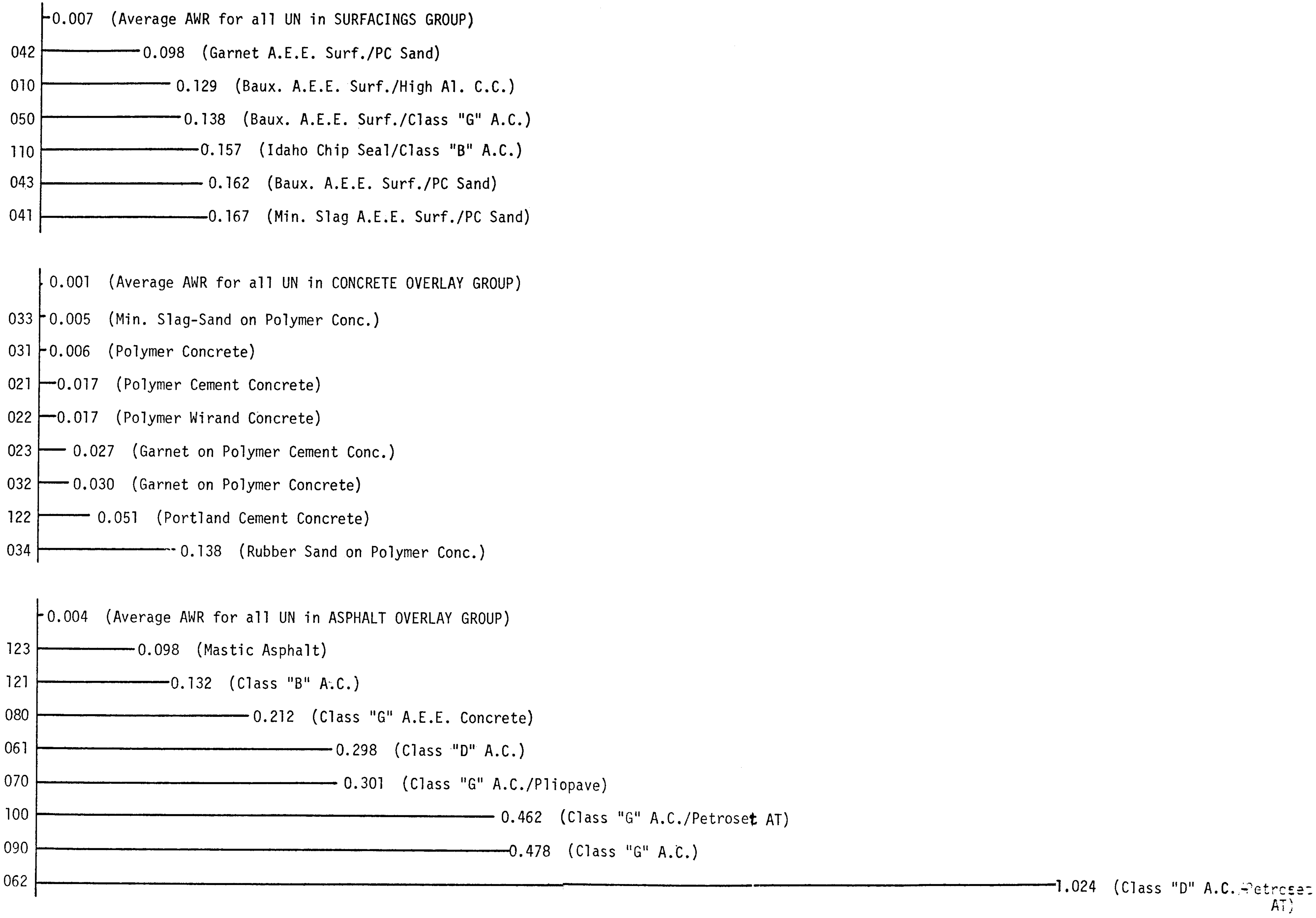


FIGURE 16: AWR Values Determined for the Finnish Stud from Ring No. 6 Data.



their appearance on the basis of whiteness and adherence. The rankings were made on the stripes relative to the different studs; e.g., each stripe was ranked versus the stud or tire type. The purpose of the test was to determine which stripe would have the most resistance to the various studs and tires. The rankings are more subjective than objective.

The thermoplastic white tape was the outstanding performer. This material consistently showed better adherence than did the other three stripes.

The reason for the phenomenal success of the striping tape in regard to its resistance to wear is its thickness and its composition; it was four times as thick as the paint stripes and it had an asphalt base. A disadvantage of this type of stripe is the possible lack of bond with the pavement. Thus, the stripe may become loose, which happened during the test. Another disadvantage is that snow plows may tear it off because of its thickness. One solution to the latter problem may be to apply this material into pre-recessed grooves to make it flush with the pavement.

GENERAL DISCUSSION AND RECOMMENDATIONS

A very definite conclusion which can be stated as a result of this project is that tires with tire studs cause much higher rates of wear in pavements than tires without tire studs.* It can also be concluded that the rate of wear is a function of the stud protrusion length, i.e., the longer the stud protrusion length, the higher the wear rate. These two conclusions may indicate that some kind of control on the stud protrusion length could lessen the wear effects due to studs. However, a law limiting the distance a tire stud could protrude from the tire tread surface would be of questionable value.

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* See Figures 25 and 26 which visually display the pavement wear through the use of plaster castings of the wheel paths.

The normal acceptable protrusion length for tire studs has been set at 0.040 inch. Stud protrusion lengths were monitored at various intervals throughout the test periods. For the most part, these values for each type of tire stud had a very wide range (e.g., 0 - .120 in.) for each set of measurements. Thus, unless some changes are made in the design of the tire to insure some control on stud protrusion lengths, it would be virtually impossible to stay within the law and to determine compliance with the law.

The speed with which the tires rotated was essentially constant for each tire and the variation in tire speed from one tire to another was very small. Thus speed was not a variable in this project. However, various researchers have demonstrated the effect of the speed of studded tires on the wear rate characteristics of various pavement materials (in general, as speed increases, wear rate increases). Based on the implications of this research, it could be possible to lessen the effects of tire studs on wear rates by limiting the speed at which those cars equipped with studded tires travel.

Pavement wear resistance, particularly for asphalt concretes, is greatly affected by temperature. It has been shown that the optimum pavement temperature for lowest wear effects is about 32°F. Based on this information, serious consideration should possibly be given to the modification of the existing calendar time period established for the legal use of studded tires. Perhaps the legal time period should coincide more closely with that time period which regional weather bureau records indicate has an average daily temperature close to 32°F.

FIGURE 25: Pavement Wear Displayed by the Use of Plaster Castings of the Wheel Paths. (Typical)

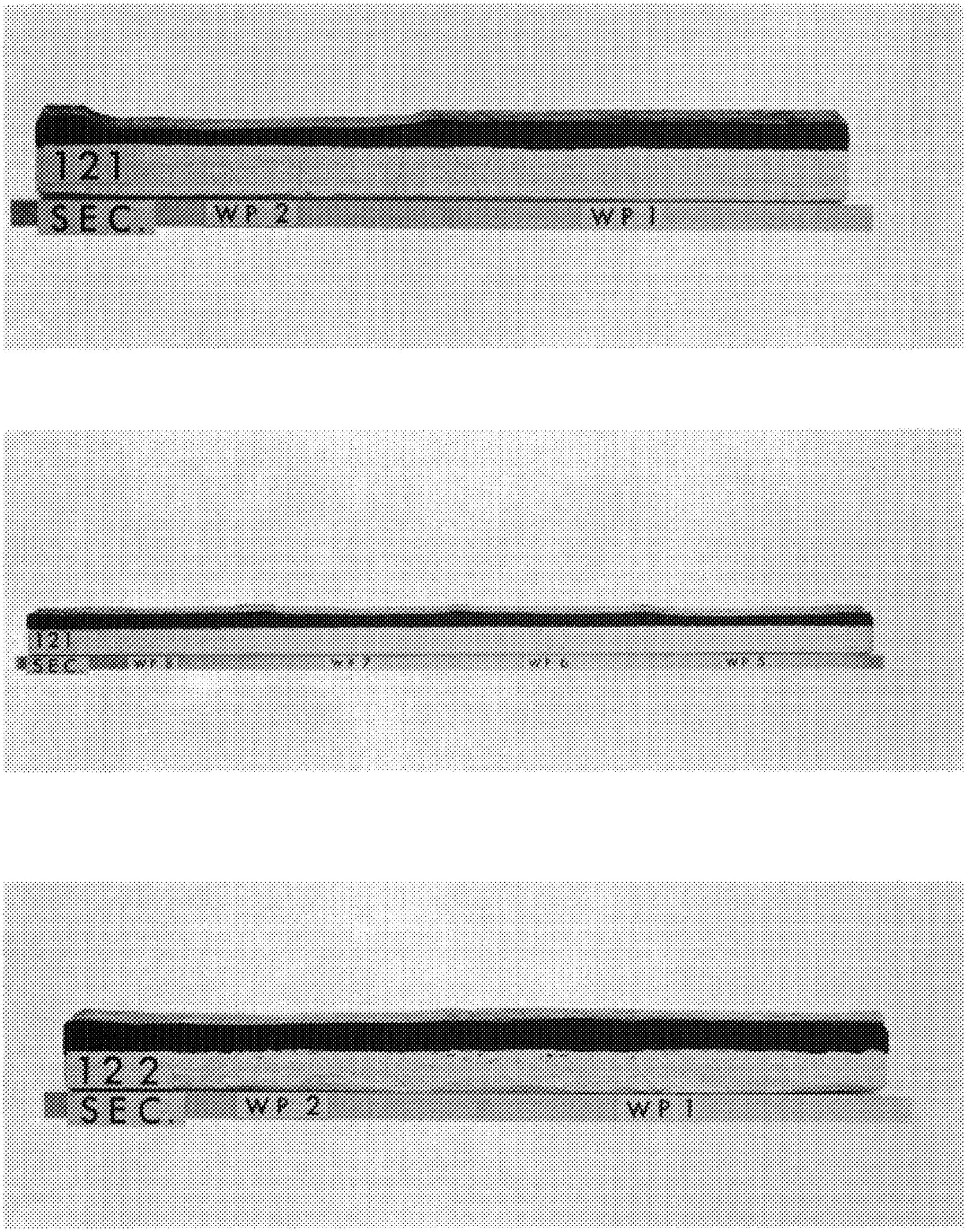
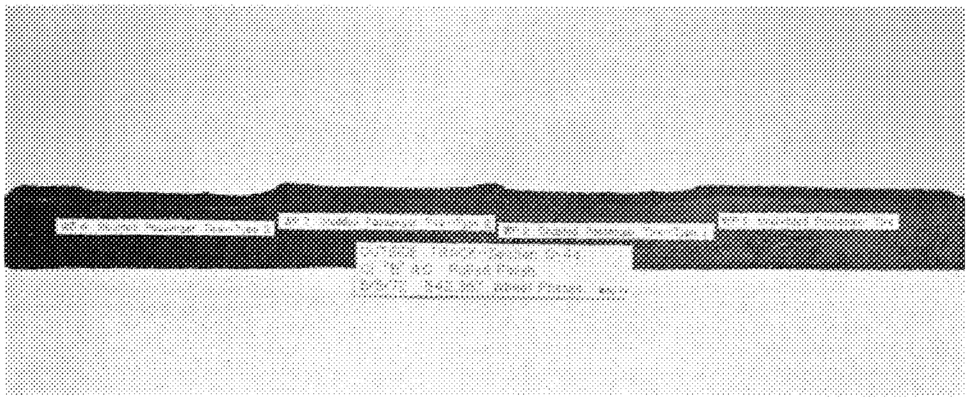
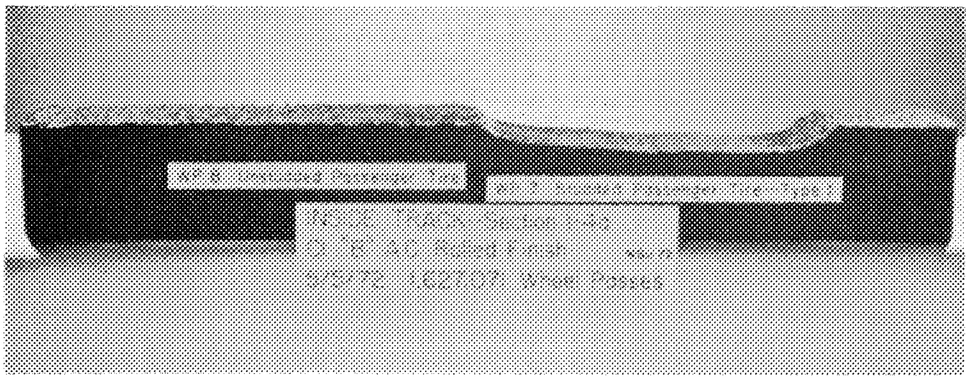
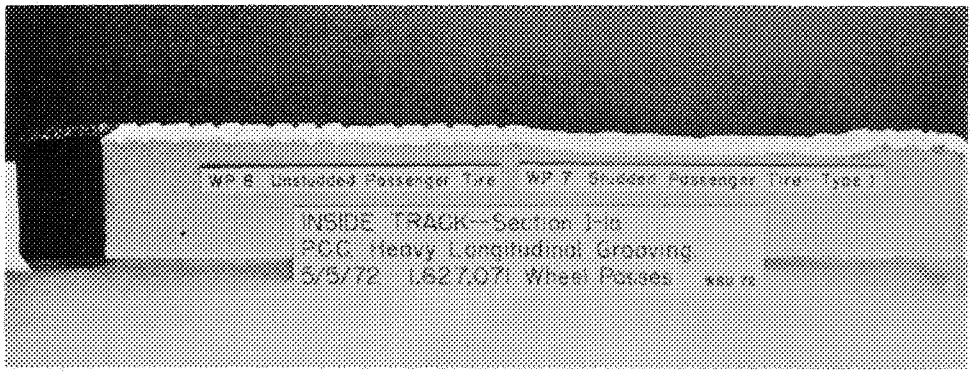


FIGURE 26: Pavement Wear Displayed by the Use of Plaster Castings of the Wheel Paths. (Typical)







STUDDED TIRE PAVEMENT WEAR REDUCTION AND REPAIR

INTRODUCTION

This project, entitled "Studded Tire Pavement Wear Reduction and Repair" and designated Y-1439, was initiated by the Transportation Systems Section of the College of Engineering Research Division, Washington State University and is financed by the Washington State Highway Commission, Department of Highways; by the U.S. Department of Transportation, Federal Highway Administration, as a HPR federal aid research project; and by the Idaho Department of Highways.

The project was divided into three phases: Phase I involved different types of pavements and surface textures; Phase II involved different types of overlays and surfacings; and Phase III involved complete regression analyses of the data, interpretations and discussions of the results of the analyses, comparison of the results with other research, correlations of the results to existing Washington State Department of Highways data, and extrapolation of the results for use in predicting pavement life due to the effects of tire studs.

Phase I started on October 1, 1971 with the construction of Experimental Ring No. 5 at the G.A. Riedesel Pavement Testing Facility at Washington State University. The traffic simulator was operated and test measurements were made during the period February 11, 1972 - May 4, 1972. The data obtained during this period is displayed and discussed in the final Phase I report (1)[1] dated December 30, 1972.

Phase II started on August 8, 1972 with the construction of Experimental Ring No. 6 at the test track. The testing period was from November 20, 1972 to May 1, 1973. The final report for Phase II (2) was dated August 15, 1973.

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[1] The numbers in parentheses refer to references listed at the end of this report.

The contents of this present report are founded on the experimental data collected during both Phase I and Phase II of the project. This present report exhibits the objectives of Phase III of the project and constitutes the Final Report for Project Y-1439.

LITERATURE SURVEY

Since their introduction in North America in the early nineteen sixties, studded tires have received general acceptance by the motoring public. A serious controversy exists between the purported increased safety effects resulting from the use of studded tires and the accelerated pavement damage and other non-desirable side effects which are known to exist.

There are definite viewpoints concerning the safety aspects of studded tire usage, both positive and negative. Numerous reports discussing the positive safety claims made for the use of studded tires have been published as well as a number of reports discussing the negative safety aspects associated with the use of studded tires. Many of these reports have been examined and investigated by Rosenthal, Haselton, Bird and Joseph (5). Another report, which covers all aspects of the studded tire controversy, was written by Petersen & Blake (6).

The safety claims attributed to studded tires are very difficult to quantify. It is relatively easy to measure stopping distances and maneuverability, but to quantify the number of accidents which may have been avoided due to the use of studded tires is another matter. Nevertheless, several studies have been conducted in order to evaluate the safety effectiveness of studded tires with regard to accidents (5,6,9,10,11,12). Overend (13) has attempted to present both sides of the controversy.

It is considerably easier to quantify the damage to pavements caused by studded tires. This damage has been discussed by Petersen and Blake (6) and in an OECD report (7). The OECD report also presents some experiences with studded tires in several European countries.

The Ontario Department of Highways expressed concern in regard to the economic consequences resulting from the use of studded tires (14,15, 16).

As a result of the Ontario Department of Highways' reports, Minnesota and other contributing states sponsored research directed toward the determination of wear effects of studded tires on different types of pavements. The results of that research were presented in a series of reports by Speer and Gorman (18,19,20,21). The results of this research dramatically showed the wear effects due to studded tires.

The Washington State Highway Commission also became very concerned about the effect of tire studs and sponsored research at Washington State University with regard to the effects of different types of studs on different types of pavements and pavement overlays using local aggregates. A partial presentation of this research is presented in a series of reports (1,2,3,4).

Research has also focused on the development of pavement materials which are more resistant to wear. Work done in this area is discussed in the OECD report (7). Smith and Schonfield (15), Fromm and Corkill (17), and Santucci (24) have done research for the development of better wear resistant pavements. Hode Keyser (22,23) concentrated on developing better design criteria for bituminous pavements. Although the results obtained by these researchers have been encouraging, high wear resistant pavements at reasonable cost for extensive use do not appear to be feasible in the very near future.

The tire stud manufacturing companies have also been involved in research with regard to the development of new types of studs which would minimize pavement wear but retain their safety features. These new developments have been reported (8,25,26). A majority of the research studies involving tire studs has been conducted using the standard or conventional stud in use prior to 1972. The research performed for the Minnesota Highway Department and that for the Washington State Highway Commission incorporated several of the new stud designs.

The National Swedish Road and Traffic Research Institute has been very active in research on studded tires effects using a traffic simulator. In 1968, they built the "Bromma Track" where automated vehicles with studded tires could be run on different pavements on straight ways. Their results, published in 1972, show similar rankings of the different pavements with respect to wear on the Bromma Test Track as in the road machine (31).

DESCRIPTION OF THE TRAFFIC SIMULATOR

The traffic simulator at the G.A. Riedesel Pavement Testing Facility is a truss with three legs, each leg supported by a set of dual truck tires. The legs are attached to and support a water tank at the center of the apparatus. A 60 hp electric motor on each leg provides the power to move the simulator on a circular path. A mechanism built into the apparatus produces an eccentric rotation so that the simulator has radial movement across each wheel path.

Passenger tires may be mounted on the three legs in various positions to provide separate test wheel paths.[2] For this project, four separate wheel paths outside of the dual truck tires and two separate wheel paths inside of the dual truck tires were used. One tire traveled in each of the four outside wheel paths, while three tires traveled in each of the inside wheel paths. A total of 16 tires were mounted on the simulator for each of the two experimental rings. Each passenger care tire carried a 1000 lb load which was applied through an air load cell, and each set of dual truck tires carried 6,600 lb. A hydraulic braking system was installed on the simulator for use on the inside tires in Ring No. 5, but continual operational problems with the system precluded its use.

An overall view of the G.A. Riedesel Pavement Testing Facility and the traffic simulator is given in Figure 1. A more detailed explanation of the simulator is given in references 1 and 2.

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[2] See Appendix A for general information on the tire arrangement.

DESCRIPTION OF THE PAVEMENT TEST FACILITY

a) Experimental Ring No. 5

Experimental Ring No. 5 consisted of three concentric rings or tracks. The center track was 3.0 feet wide and was that portion of the ring on which the dual truck tires traveled. The outside and inside tracks, each 3.5 feet wide, were those portions of the ring on which the outside and inside passenger tires traveled, respectively. The individual concentric rings consisted of different pavement materials placed in sections with different longitudinal lengths.

The pavement structure consisted of an asphalt treated base 6 inches thick and a 6 inch surface course composed of different pavement materials. The center ring was constructed of reinforced portland cement concrete and was finished with twelve different surface textures. The outside and inside rings were constructed of various mixes of asphalt concrete and of portland cement concrete covered with different types of overlays. Thirty-four sections with various combinations of different pavement materials were constructed: 20 sections in the outside ring and 14 sections in the inside ring. See Table 1 and Figure 2 for specific details. The design and construction details of the pavement structure are presented in reference 1.

b) Experimental Ring No. 6

Experimental Ring No. 6 was constructed from the remains of Ring No. 5. The existing pavement structure from Ring No. 5 was used as a base and was overlaid with different materials in thicknesses varying from 3/4 to 2 inches. The concrete pavement wheel paths were patched with various materials prior to the placement of the overlay materials.

In this experimental ring, the overlay material was placed continuously across the width of the roadway. Hence, the outside, center and inside tracks were covered with the same overlay material in any particular section of the ring. A total of 22 longitudinal sections containing different overlay materials were placed on top of the existing pavement structure. Table 2 and Figure 3 show these specific details. The design and construction details of the various overlays are presented in reference 2.

DESCRIPTION OF THE PROFILOMETER

The profilometer used in measuring the contour of the roadway surface was designed and built by engineers and engineering technicians at Washington State University. It has a crosshead scanner containing 10 fingers which moves on a support beam along a cross-section of the roadway. The values given by the individual fingers are averaged and this average value is recorded by the instrument. The predicted accuracy of the measurements made with the profilometer is ±1.0% in 1.0 inch. The profilometer is shown in Figure 4. The profilometer is discussed in greater detail in references 1 and 2.

DISCUSSION OF THE EXPERIMENTAL MEASUREMENTS

a) Pavement Rut Depth Measurements

Ring No. 5. The profile measurements on the pavement surfaces were made with the profilometer. The profilometer was positioned over the test section, and the crosshead scanner was moved through its length of travel. The output from the scanner was recorded on a strip chart. Various points of the trace on the strip chart were digitized for input to a digital computer with the use of a Benson-Lehner Model F Decimal Converter. The data was subsequently read into a digital computer, and the resulting output gave the average rut depth for the wheel paths corresponding to the appropriate number of wheel applications.[3]

There were no parmanent positive reference points available for the placement of the profilometer at the various test positions. Reference points were painted on the pavement and were used. As a result, the exact position of the profilometer could not be achieved for each successive measurement. In order to obtain meaningful results, each successive profile trace at any given section had to be aligned both vertically and horizontally before rut depth calculations could be made. This alignment adjustment was done by the computer program by matching up selected points in the profile which were outside of the wheel paths.

The lack of fixed reference pins for positioning the profilometer resulted in a loss of accuracy for these measurements. The cross beam which supported the scanner head sagged, which also contributed to a loss of accuracy for the measurements. It is estimated that the computer results based on the measurements made with the profilometer in Experimental Ring No. 5 had a total error of ±5.0% in 1.0 inch.

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[3] See Appendix B for a typical set of computer output.

Ring No. 6. Modifications in the procedure for taking profile measurements and modifications to the profilometer resulted in more precise measurements in this ring. The profilometer cross beam was strengthened to prevent sag, permanent fixed reference pins were installed in the test sections, and the profilometer output was simultaneously recorded on a strip chart and punched on paper tape.

The data contained on the paper tape was easily transferred to computer cards by means of a computer program, and, hence, eliminated one phase of the tedious task of data reduction. The profile recorded during each successive measurement was again adjusted for alignment, but the use of the reference pins and the stiffer cross beam made this task easier and reduced computer time considerably. It is estimated that the computer results based on the measurements made with the profilometer in Experimental Ring No. 6 had a total error of ±1.0% in 1.0 inch.

b) Tread Depth Measurements

A conventional tread depth gauge was used to measure the tread depth of the tires at a various times during the period of the test. It is estimated that these measurements are accurate to ±1/32 inch.

c) Tire Stud Protrusion Measurements

Tire stud protrusion measurements were made with a dial gauge at appropriate intervals during the test period. It is estimated that these measurements are accurate to ±.001 inch.

d) Temperature Measurements

Temperature readings were obtained at various positions around the test track by means of iron-constantan thermocouples. These readings were automatically recorded around the clock on a 24 point multi-channel Honeywell recorder. The accuracy of the measurements is ±1° F. Ambient temperatures were recorded at the test site by means of a Belfort Thermograph.

e) Precipitation Measurements

No measurements at the test site were taken in regard to precipitation. These data were obtained directly from the Palouse Conservation Field Station of the U.S. Department of Agriculture.

f) Skid Resistance Measurements

Skid resistance numbers for the various pavement surfaces were obtained with the use of a California Skid Tester and a British Portable Skid Tester. The latter was not available for use during the performance of test measurements on Ring No. 5. It is estimated that the skid resistance numbers obtained with the use of these two instruments are accurate to ±2.

ANALYSIS OF THE DATA

a) General Discussion

The quantity of data obtained during the conduct of this project was enormous. In Experimental Ring No. 5, forty-six different sections were investigated for the effects of three different types of studs, while in Experimental Ring No. 6, twenty-two different sections and four different types of tire studs were involved. Due to the array of pavement materials, overlays and tire studs considered, a relatively simple way of presenting the results had to be found. A detailed presentation of the data collected from Experimental Ring No. 5 is given in the Phase I Report (1) for this project, and one for Experimental Ring No. 6 is given in the Phase II Report (2) for this project.

A sampling of the computer output data from both experimental rings involving average rut depth (D) and the number of wheel applications (P) was subjected to regression analyses involving four different regression equations. These regression equations were:

a. $D = a_o + a_1P$ (a straight line on rectangular coordinate paper)
b. $D = a_o + a_1P + a_2P^2$ (a parabola on rectangular coordinate paper)
c. $D = a_oP^{a_1}$ (a straight line on log-log paper)
d. $D = a_oe^{a_1P}$ (a straight line on semi-log paper)

A regression analysis of the data using each of the four regression equations was carried out using a least squares procedure. The equation given in a) above was selected over those forms given in c) and d) because of its simple form and good representation of the data. The parabolic form given in b) was more representative of the data in some cases than the straight line given in a), but the parabolic form was not suitable for extrapolation beyond the limits of the data. Hence, the straight line $D = a_o + a_1P$ was chosen because of its simplicity, its representation of the data, and its desirable extrapolative qualities. Due to the nature of experimental measurements, the actual form of the equation used was

$$D = a_0 + a_1P \pm 2S$$

where a_0 represents the ordinate intercept or initial value of D, a_1 represents the slope of the straight line and the term 2S represents the 95% statistical limit for D as a function of P. If the regression line $D = a_0 + a_1P$ were plotted through the data points and if a straight line parallel to the regression line were plotted a distance of 2S away from and on each side of the regression line, theory predicts that 95% of the data points will lie between these two boundary lines if the points are normally distributed about the regression line. In other words, the value of D as predicted by the regression line is bounded such that

$$(D_{pred.} - 2S) < D_{pred.} < (D_{pred.} + 2S).$$

The value of the standard error of estimate S can also be used as an indicator of the fairness of the straight line representation for the data; the smaller the value of S, the better the straight line represents the data.[4]

The profilometer data was analyzed by using average rut depth as a function of the number of wheel applications. Each data set started at 0 wheel applications and included all points taken up to the conclusion of the tests. The analysis produced many regression lines with an ordinate intercept not equal to zero and, for the sections with very little wear, gave lines with negative slopes. For the non zero ordinate intercepts, it was concluded that these were due to the relatively high rut depths that were developed at the beginning of the tests and which were associated in the Phase I and Phase II reports with initial wear rates. These lines were not adjusted to zero, since the regression line as obtained gave a fair representation of the data at the higher number of wheel applications, which is the more useful segment of the curve. For those lines

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[4] See Appendix C for an illustrative sampling of the plotting of the data.

with negative slopes, it was concluded that the sensitivity of the recording instrument was not sufficiently accurate to discern minute rut depths, and, hence, these negative values should simply be interpreted as being associated with small rut depths and the negative value should not be considered as being critical.

b) Data From Experimental Ring No. 5

The regression analyses applied to the profilometer data give linear regression lines from which average rut depths may be predicted, within limits, as a function of the number of wheel applications. The coefficient of P in these regression equations represents the slope of the straight line or the average wear rate (AWR) for the material. The composite set of regression lines is presented in Table 3. The average wear rates for the individual sections and stud types have been reproduced in more convenient form in Table 4. To further aid in displaying the results for easy interpretation, the average wear rate values given in Table 4 are presented in the form of bar graphs in Figures 5, 6, 7 and 8.

c) Discussion of Experimental Ring No. 5 Data[5]

Figure 5 shows the relative effects of the various types of studs on the materials used in the outside track. Each tire with a different stud type traveled in a different track. Hence, each tire traveled at a slightly different speed. Associated with each type of stud is an average stud protrusion length. The average tire speeds (ATS) and average stud protrusion lengths (ASP) are given in the figure. With few exceptions, the PT stud caused the lowest wear rate, while the CP and the CV studs alternated for the second and third places. It is important to note the magnitudes of the wear rates for the three different studs. The effect of the difference in the average tire speed on the average wear rates can be assumed negligible, since the difference in speeds is so small, but the effect of the different ASP's cannot be overlooked.

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[5] See Appendix A for type of stud, wheel path and track correlation.

The PT stud has the smallest ASP, hence the smallest AWR's. The CP and CV studs exhibit similar ASP's, and, thus, similar AWR's. All of the studded tires caused considerably higher AWR's on all of the materials than the unstudded tires.

Figure 6 displays the AWR's for the various materials resulting from the passage of the CP stud. These materials were on the outside and inside tracks of the ring. The average AWR for all of these sections for the unstudded tire paths is given for comparative purposes. Note the differences in ATS and ASP for the various outside track and inside track sections.

Figure 7 is similar to Figure 6 and presents the AWR's attributed to the PT stud.

Figure 8 is similar to Figure 6 and presents the AWR's attributed to the CV stud. Since there are different types of tires associated with this figure, a separate average AWR for the unstudded tire path is given for comparison purposes within each group.

In Experimental Ring No. 5 there were only three materials for which a comparison could be made involving tires with the same type of stud but having different stud protrusion lengths and moving at different speeds. This comparison is given in Figure 9. The purpose of this comparison is to show the effects of speed and stud protrusion lengths on wear rates. There is insufficient data from this project to conclude anything definite as to the effects of the speed of the tire on the AWR, but the results do show that the AWR is definitely a function of the stud protrusion length to which the pavement material is subjected.

d) Data From Experimental Ring No. 6[6]

The profilometer data obtained from this experimental ring and which relate to various overlays and surfacings were regressed in a manner identical

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[6] See Appendix A for type of stud, wheel path and track correlation.

to that of the previous ring. Linear regression lines of the form

$$D = a_0 + a_1P \pm 2S$$

were obtained for each wheel path at each section of the ring. A composite listing of the equations resulting from the regression analysis is given in Table 5. The coefficient of P or the AWR associated with the stud type and overlay material is reproduced in more convenient form in Table 6. The information presented in Table 6 is again displayed in bar graph form for easier interpretation in Figure 10 through Figure 16.

e) Discussion Of Experimental Ring No. 6 Data

Figures 10, 11 and 12 display the calculated AWR's for the surfacing group, the concrete overlay group and the asphalt overlay group, respectively. In general the shorter the ASP, the smaller the AWR value. The differences in the tire speeds is so small that no conclusions can be reached concerning the effect of speed on the average wear rates.

Figures 13, 14, 15 and 16 show the different AWR's for the different materials attributed to the CP stud, the PT stud, the CV stud and FS stud, respectively. Note that the average AWR for all of the unstudded tires in the respective groups is given for casual comparative purposes. It is obvious from these four figures that some materials resist the effects of tire studs more readily than others. However, the AWR values do not tell the entire story by themselves as there are differences in the ordinate intercept values. That is, a material with a lower AWR may show a greater D after one million wheel applications than a material with a higher AWR due to the difference in the ordinate intercept constants. However, for comparative purposes throughout this report, only the calculated values of the AWR's will be used since, for most materials, the value of the ordinate intercept was less than .05 inch. In addition, if any linear regression line were used for extrapolation outside the finite range of given data, the ±2S bound on the predicted D more than offsets any effect due to the initial constant a_o.

f) Comparison Of Data From Both Experimental Rings

To demonstrate the effect that stud protrusion length has on wear rates, it is possible to compare the AWR's on several similar materials which were subjected to tires moving with the same speed and with the same type of stud but having different stud protrusion lengths. This comparison is shown in bar graph form in Figure 17. Note the difference in AWR's for materials for which the only dominate variable is the difference in ASP's. Note also that in general, as the difference in the ASP's increases or decreases, the difference in the AWR's increases or decreases, correspondingly.

g) Discussion In Different ASP's For The Various Studs

The results show conclusively that the AWR for any particular material is a function of the ASP. The various types of studs display different ASP's. One reason for these different ASP's could be associated with the design of the stud.

According to the manufacturer of the CP (controlled protrusion) stud, the carbide pin is pushed back into the stud body as a result of impact forces acting on the stud. The magnitude of the required impact force is a function primarily of the tire stud protrusion and partially of the speed of the vehicle (8). This means that the studs should maintain a certain protrusion level throughout their use essentially independent from the driving conditions and the wear resistance of the carbide pin and the tire. However, the force required to move the pin is assured by driving the tire at 60 mph at least 25% of the time. The tests performed on the WSU test track did not meet these requirements and stud protrusion measurements yielded the following results:

Exp. Ring	Tire Speed	Min SP[7]	Max SP	ASP[8]
5	22.2 mph	.045"	.122"	.092"
5	18.4 mph	.032"	.099"	.063"
6	18.4 mph	.012"	.042"	.020"

According to the manufacturer of the PT (Perma-t-gripper) stud, hard carbide chips are bonded together in a soft matrix. The soft matrix wears down allowing the carbide chips to fall off. Thus the stud and the tire tread wear down with the tendency for the stud protrusion to keep fairly uniform. Measurements on this stud yielded the following results:

Exp. Ring	Tire Speed	Min SP	Max SP	ASP
5	21.7 mph	.012"	.075"	.027"
6	21.7 mph	.002"	.085"	.017"

The CV (conventional stud) is a hard carbide pin encased in a steel jacket with no particular distinguishing characteristics except extensive prior use. Measurements on this type of stud yielded the following results:

Exp. Ring	Tire Speed	Min SP	Max SP	ASP
5	21.3 mph	.046"	.125"	.098"
5	20.0 mph	.025"	.064"	.034"
6	21.3 mph	.009"	.068"	.030"

The FS (Finnstop) stud is a carbide pin encased in a plastic jacket. The plastic jacket is claimed to dissipate the heat more readily and keep the stud more firmly in place. Measurements on this type of stud yielded the following results:

Exp. Ring	Tire Speed	Min SP	Max SP[7]	ASP[8]
6	22.2 mph	.009"	.070"	.029"

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[7] See Appendix D for a sample calculation for the SP (Stud Protrusion Length).

[8] See Appendix D for a sample calculation for the ASP (Average Stud Protrusion Length).

GENERAL DISCUSSION OF RESULTS

There are various factors which contributed to the difference in the AWR's between Ring No. 5 and Ring No. 6 as displayed in Figure 17. Some of these factors are listed in the table below.

Factor	Ring No. 5
Average Stud Protrusion Length	Longer than those in Ring No. 6
Tire Stud Hardness	Same as in Ring No. 6
Tire Stud Sharpness	Same as in Ring No. 6
Speed of Comparable Tires	Same as in Ring No. 6
Pavement Surface Temperature	Higher than in Ring No. 6
Surface Moisture[9]	Same as in Ring No. 6

Each factor except tire stud hardness and tire stud sharpness is discussed elsewhere in the report and those discussions will not be repeated here.

Knoop hardness tests were performed on the various tire studs by the Materials Chemistry Section, Research Division, College of Engineering. All tire studs tested exhibited an average Knoop Hardness number in the range 1670-1817. It was concluded on the basis of these hardness numbers that the tire studs were all of the same general hardness category.

Before and after pictures of the tire studs are shown in Figure 18. It should be particularly noted, that regardless of the initial shape of the tire stud, the worn shape is essentially identical.

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[9] See Appendix E.

ANALYSIS OF SKID RESISTANCE DATA

The skid resistance data obtained with the use of the California Skid Tester and the British Portable Skid Tester (Ring No. 6 only) were subjected to linear regression analyses. The skid resistance number (SRN) as a function of the number of wheel applications was obtained for each wheel path in each section. The results of the analyses on the skid resistance data are presented here in condensed form.

Tables 7, 8 and 9 contain the values of the average rate of change in the skid resistance number for the various sections and appropriate types of stud. Also present in these tables for comparison purposes is the predicted value of the skid resistance number for the appropriate section and stud type after one million wheel applications as obtained from the regression line for the respective data.

As seen from Tables 7 and 8, every material exhibited some decrease in its California skid resistance number with increasing wheel applications except one: namely, the Class "B" Asphalt Concrete with Gilsabind (Section 04B) used in Ring No. 5. This material displayed an increase in its skid resistance in all four wheel paths (3 tires with studs, one tire without studs) in the section. A few isolated wheel paths in other sections showed a positive rate of change in the skid resistance while other wheel paths in the same section showed a negative change. This difference could simply be experimental error or a result of the linear regression analysis.

Table 9 developed from data obtained with the use of the British Portable Skid Tester is presented for information only. No attempt is made in this report to correlate the skid numbers obtained by use of the California Skid Tester with those obtained by use of the British Portable Skid Tester because of the incompleteness of the data and the variability of the results.

The values given in the CSRN or BSRN columns in these three tables are indicative of the skid resistance characteristics of the material after one million wheel applications. The numbers have been obtained from the linear regression lines. The negative signs on some of these values are, of course, unrealistic, but are given simply to show how the skid resistance characteristics of the various materials compare with each other.

The Washington State Department of Highways considers any pavement with a California skid resistance number (CSRN) less than 25 to be less than desirable in regard to maneuverability of an automobile on the pavement during adverse weather conditions. All but two of the materials tested exhibited a CSRN of 25 or more before traffic started: namely, a Polymer concrete section (I2BA) in Ring No. 5 and a Polymer concrete section (031) in Ring No. 6. As one can discern from Tables 7 and 8, a majority of the materials tested did not exhibit a CSRN greater than 25 after one million wheel passes.

The AWR's obtained from the analyses of the data for Ring No. 6 are also shown in Table 8 along with the skid resistance data. No definite conclusions are made from the numbers in this table, but the optimum pavement material would exhibit the *lowest* rate of surface wear in conjunction with the *highest* skid resistance characteristics.

The equations relating skid resistance number to the number of wheel applications are not given in this report because of the large number of equations. They are on file in the Transportation Section, College of Engineering, Washington State University. Each equation is of the form

$$SRN = a_0 + a_1 P \qquad 2S$$

the terms of which were described earlier in this report.

ANALYSIS OF TREAD DEPTHS AND STUD PROTRUSION LENGTHS

The tread depth measurements and stud protrusion length measurements taken during the test period for the two experimental rings were subjected to the same linear regression analyses as the other data. Average rates of change in the individual tire tread depths (ATDR) and in the stud protrusion lengths (ASPR) were determined. These values are presented below.

	TYPE OF STUD	ASPR (in/10^6 w.a.)	ATDR (in/10^6 w.a.)
Ring No. 5	UN	---	-5.730
	CP	+.170	- .413
	PT	-.009	- .188
	CV	+.072	- .275
	CP	+.136*	- .145*
	UN	---	-2.846*
Ring No. 6	GST	---	-15.416
	FS	-.148	- .171
	PT	-.057	- .089
	CV	-.156	- .147
	CP	-.091*	- .213*
	UN	---	-2.938*

*Average of the data for 3 tires

As one would expect, the rate of wear of the tread was much less for the studded tires than for the unstudded tires. The GST showed the most tread wear. This tire was a retread tire impregnated with garnet pebbles and this process has not as yet been perfected. The value of the rank correlation coefficient for these two columns of numbers indicates that there is insufficient data to conclude that there is an association between the ranks of the ASPR's and those of the ATDR's.

COMPARISON WITH OTHER STUDIES

a) The Minnesota Study

The Minnesota study (20, 21) was done in two parts by the American Oil Company. Test conditions in the Minnesota Study were completely different than those at the WSU Test Track. The American Oil Company Test Track is smaller and completely indoors where the environment can be controlled. The WSU Test Track is completely open to all elements. The test speeds were completely different: 35 m.p.h. for the Minnesota Study versus 20 m.p.h. for the WSU study. The temperature was kept at 25°F ± 5° and the track was kept continuously wet for the Minnestoa study, while these factors varied with the weather in the WSU study. The pavements were different to some extent as far as aggregates and mix designs were concerned. The pavements at WSU were built using normal construction equipment whenever possible, while those at the American Oil Company Test Track were built in the laboratory. The edges of the channels worn in the pavements during testing were ground down in the Minnesota study to avoid tire edge wear while the edges of the channels worn in the pavements were left to develop naturally in the WSU study. Tires were changed frequently in the Minnesota study as compared to those at the WSU Test Track. All these differences in test conditions contributed to results which make direct comparisons difficult. The results can only be compared in a relative sense.

Two studies were done for the State of Minnesota Department of Highways: one on the CV (conventional) stud (20) and the other on the CP (controlled protrusion) stud (21). It is interesting to note that the AMOCO research results show a large variation in the stud protrusion length for the CP stud as did the WSU research results.

Tables 10 and 11 show the values of the average wear rates for the CV and CP studs, respectively, for the Minnesota and WSU studies. The values are only informative in nature. Correlation between the WSU Phase I values and the Minnesota study values is fair, but there appears to be no correlation between the WSU Phase II values and the Minnesota study values. Apparently the differences reflect the different conditions of the tests. The disparity of the results between the WSU Phase II test values and the Minnesota study values may be due for the most part to the difference in stud protrusion lengths between the two tests.

b) Other Studies

It is difficult to compare the results obtained from the Ontario studies (14, 15, 16) to the WSU results, because the Ontario tests were made in the field. Rates of wear were estimated by assuming an ADT with an estimated percentage of cars having studded tires and then adjusting these estimated wear rates by factors accounting for acceleration, deceleration and speed which were obtained from experimental curves.

Other studies have also been made. As previously stated, there are differences in results due to speed, environmental conditions, differences in pavement aggregates and mix, variations in types and numbers of studs, etc. All these studies used some form of the CV stud. Table 12 presents the average wear rates obtained for portland cement concrete pavement from some of these studies. Table 13 shows the average wear rates obtained from other studies for bituminous concrete pavements.

Many of the wear rates presented in Tables 12 and 13 were given in inches for 100,000 wheel applications and extrapolating these values to a million wheel applications may give exaggerated wear rates, since wear rates, in general, start to stabilize at about 100,000 wheel applications. Some of the wear rate values were also measured in the field.

An interesting conclusion obtained from Tables 12 and 13 is that deceleration increases the wear rate about three times on portland cement concrete pavements and on bituminous concrete pavements. Areas such as bridge ramps, toll gates and stop areas may experience these very high accelerated wear rates from studded tire usage.

EFFECT OF PAVEMENT TEMPERATURE ON PAVEMENT WEAR

a) General Discussion

Several researchers have noted a relationship between pavement temperature and pavement wear from bituminous pavements. Tappert and Kohler (29) in their research in Germany have stated that the most important factor affecting pavement wear appears to be temperature and that significantly higher values of wear are achieved on pavements at 50°F than on pavements at 32°F. Hode Keyser (23), using a small traffic simulator in Montreal, Quebec, found similar results. Hode Keyser obtained a U-shaped curve which indicated that the wear is generally lowest near the freezing temperature, and the wear increases as the temperature increases or decreases. His test results, however, were limited and showed considerable scatter.

As a secondary objective of Phase III of Project Y-1439, an attempt was made to try to isolate the effects of pavement temperature on pavement wear resulting from the passage of studded tires using data from Ring No. 6. All the pavements in Ring No. 6 had thermocouples embedded in them. The thermocouples were continuously monitored for environmental records and to correlate pavement wear with pavement temperature. The temperature data was reduced to a 24-hour average value and averaged again on a weekly basis. The measurements for wear were taken at certain numbers of wheel applications, and an average wear rate was calculated for each interval of wheel applications, thus including a wide range of pavement temperatures. Regression analyses relating pavement temperature and wear rates were made for two types of pavements--the class "G" asphalt concrete (090) and the portland cement concrete (122)--for the CP (controlled protrusion) stud.

For the class "G" asphalt concrete section, using a sample of 22 data points which had a wide scatter, the least squares parabolic equation is

$$Y = 0.585 - 0.0128X + 0.0002X^2 \pm 0.621$$

where Y = average pavement wear in inches/10^6 w.a.

and X = pavement temperature in °F

The standard error of estimate on the 95% confidence level is ±0.621 in/10^6 w.a. The coefficient of correlation is 0.218. This equation is plotted in Figure 19 as curve A.

If the data points with the widest scatter are omitted from the data sample, the following equation, illustrated in Figure 19 as curve B, is given by the regression analysis:

$$Y = 0.902 - 0.411X + 0.0006X^2 \quad \pm 0.308$$

The standard error of estimate on the 95% confidence level becomes ±0.308 in/10^6 w.a., and the coefficient of correlation is 0.739. Since the correlation coefficient for the reduced data sample is closer to 1.0, curve B is more representative of the data points than curve A. Both curves, which are U-shaped, show that the least pavement wear occurs at about 35°F and increases as the temperature changes in either direction. These results tend to confirm the conclusions presented by Hode Keyser (23) and Tappert and Kohler (29).

The reasons why pavement wear increases as pavement temperatures go below 30°F are associated with the tire hardness and the pavement stiffness. Tire hardness and pavement stiffness increase as temperatures decrease. Thus, the force required to push the stud into the tire so that it is flush with the pavement surface depends on the temperature. At these low temperatures, the unit pressure is higher, and, since the pavement is stiffer, it is more brittle. Hence, the combination of higher unit pressure and more pavement brittleness at temperatures below 30°F results in more pavement wear.

The stiffness of asphalt varies with temperature since asphalt cement is a viscoelastic, semi-solid material with less cohesion at 70°F that at lower temperatures. Thus, as the temperature of the pavement rises, the stud penetrates deeper and deeper into the pavement thereby displacing the aggregate particles and thus, producing more wear by shear and dislodgment.

A regression analysis performed on the data points for the portland cement concrete overlay (122) yielded an equation of the following form:

$$Y = 0.159 - 0.0018X \pm 0.232$$

The standard error of estimate for the 95% confidence level was ± 0.232 in/10^6 w.a. and the coefficient of correlation was 0.520. The results are shown in Figure 20, and they indicate that pavement temperature had little, if any, effect on pavement wear for the portland cement concrete pavement under the WSU test conditions.

b) Comparison of Surface Temperatures

Since both rings had thermocouples embedded in the pavement surfaces, an examination of the surface temperatures for two typical pavements tested in both rings was made to determine whether or not a difference in surface temperatures existed.

The two types of pavement studied for surface temperatures were portland cement concrete and class "G" asphalt concrete. These pavements were tested in both rings and therefore could be compared.

The readings of the thermocouples were recorded automatically and continuously. This data was then reduced to 24-hour periods for the time the apparatus was in operation. Then the surface temperature was averaged for the entire testing period. The results are presented below.

COMPARISON OF AVERAGE SURFACE PAVEMENT TEMPERATURES - °F

Ring No.	TYPE OF PAVEMENT	
	PORTLAND CEMENT CONCRETE	CLASS "G" ASPHALT CONCRETE
5	47.2	49.2
6	41.4	41.6

Both types of pavements in Ring No. 5 had higher surface pavement temperatures than in Ring No. 6. There was about 6°F difference in surface temperature for the portland cement concrete between the rings and about 8°F difference for the class "G" asphalt concrete pavement between the rings. The asphalt concrete also exhibited higher surface temperatures than the portland cement concrete pavement, especially in Ring No. 5.

This temperature variation may be one of the factors causing the differences in pavement wear between the two rings particularly in the asphalt sections.

GENERAL DISCUSSION AND RECOMMENDATIONS

Figures 6 and 7 display the AWR values for the various sections in Ring No. 5 for the Controlled Protrusion and Perma-T-Gripper Studs, respectively. Figures 13 and 14 display the AWR values for the various sections in Ring No. 6 for the CP and PT studs, respectively.

Each of these figures depicts the effects of only one kind of stud on various pavement materials. However, on a typical section of real highway, the type of tire stud to which the pavement is subjected is not controlled. As a consequence of this fact, the effects of the combined action of the CP tire stud and the PT tire stud have been postulated. For illustrative purposes, it is assumed that only CP and PT tire studs are available to the motoring public and that the pavement is subjected to an equal number of wheel applications from each type of stud. Based on these assumptions the AWR values for the CP and PT studs were simply averaged together for both experimental rings and the results displayed in Figures 21 and 22.

A comparison of Figures 13 and 14 with Figure 22 shows a slightly different order in the resistability of the various pavement materials when subjected to the combined action of the studs as opposed to the action of the individual studs. Perhaps more research should be performed using more tires with different types of studs in the same wheel paths or possibly prohibiting the sale of those types of studs which are associated with very high wear rates. More extensive research could also be performed on some of the pavement materials which appeared in this study to be more favorable towards resisting wear than others.

A very definite conclusion which can be stated as a result of this project is that tires with tire studs cause much higher rates of wear in pavements than tires without tire studs.[10] It can also be concluded that the

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[10] See Figure 25 and 26 which visually display the pavement wear through the use of plaster castings of the wheel paths.

rate of wear is a function of the stud protrusion length, i.e., the longer the stud protrusion length, the higher the wear rate. These two conclusions may indicate that some kind of control on the stud protrusion length could lessen the wear effects due to studs. However, a law limiting the distance a tire stud could protrude from the tire tread surface would be of questionable value.

The normal acceptable protrusion length for tire studs has been set at 0.040 inch. Stud protrusion lengths were monitored at various intervals throughout the test periods. For the most part, these values for each type of tire stud had a very wide range (e.g., 0 - .120 in.) for each set of measurements. Thus, unless some changes are made in the design of the tire to insure some control on stud protrusion lengths, it would be virtually impossible to stay within the law and to determine compliance with the law.

The speed with which the tires rotated was essentially constant for each tire and the variation in tire speed from one tire to another was very small. Thus speed was not a variable in this project. However, various researchers have demonstrated the effect of the speed of studded tires on the wear rate characteristics of various pavement materials (in general, as speed increases, wear rate increases). Based on the implications of this research, it could be possible to lessen the effects of tire studs on wear rates by limiting the speed at which those cars equipped with studded tires travel. In Europe, where cars may be equipped with 4 studded tires, there is a speed limit for these vehicles different from the speed limit for vehicles without tire studs. In Switzerland, for example, cars on which there are studded tires must carry a sign indicating studded tires so that other motorists know why they are traveling slower. Additional research into the effect of speed on wear rates from studded tires could also be performed.

Pavement wear resistance, particularly for asphalt concretes, is greatly affected by temperature. It has been shown that the optimum pavement temperature for lowest wear effects is about 32°F. Based on this information, serious consideration should possibly be given to the modification of the existing calendar time period established for the legal use of studded tires. Perhaps the legal time period should coincide more closely with that time period which regional weather bureau records indicate has an average daily temperature close to 32°F.

TRAFFIC PAINTS

Four different types of traffic striping were tested to determine their resistance to wear from studded tires; three were paints applied with a constant-thickness paint applicator and the other was a thermoplastic white tape. The tests were made on sections 021 (the polymer cement concrete) and 100 (the class "G" asphalt concrete with Petroset AT). The initial measured thicknesses of the three paint stripes averaged 22 mils, while that of the thermoplastic white tape averaged 95 mils.

Kennametal, Inc., of Latrobe, Pennsylvania, supplied the paints. The company does not manufacture paint but was interested in determining the effect of their tire studs on the life of pavement traffic striping. Table 14 shows the brands of paint which were tested and their corresponding code numbers. A full report on the paints is given in Reference 30.

No quantitative measurements were made on the wear of the traffic stripes. Rather, visual observations were made and the stripes were ranked according to their appearance on the basis of whiteness and adherence. The rankings were made on the stripes relative to the different studs; e.g., each stripe was ranked versus the stud or tire type. The purpose of the test was to determine which stripe would have the most resistance to the various studs and tires. The rankings are more subjective than objective.

The rankings are presented in Tables 15 through 22 for the polymer cement concrete section (021) and the class "G" A.C. with Petroset AT section (100) determined at wheel applications of 10,000; 25,000; 50,000; and 150,000+. A series of pictures was taken but only those taken at 50,000 wheel applications are included in this report as Figures 23 and 24. These figures show the appearance of the stripes. Rankings were based on such appearances.

One can see from Tables 15 through 22 that striping material no. 4 was the outstanding performer. This material consistently showed better adherence than did the other three stripes.

The traffic striping materials performed differently on the polymer cement concrete than on the asphalt concrete. The stripes wore off more rapidly on the polymer cement concrete. As can be seen from Tables 15, 17, 19, and 21, stripe no. 4 was superior to the other three stripes followed by no. 1, no. 2, and no. 3 in that order. After 50,000 wheel applications most of these stripes (1, 2, and 3) were worn off. The CV stud caused the most damage followed by the FS, CP, PT, GST, UN, and UST, respectively.

The performance of the traffic striping materials on the asphalt concrete section is indicated in Tables 16, 18, 20, and 22. The no. 4 striping was again number one in ranking. The rankings of the remaining stripes varied with the number of wheel applications. Stripes no. 1 and no. 3 consistently vied for the number two ranking; stripe no. 2 was almost always ranked third or fourth. The CV stud caused the most wear followed by types FS, PT, CP, GST, UN, and UST, respectively.

After 150,000 wheel applications, almost all of each of the four stripes was worn off in the polymer concrete section (021) while portions of some of the stripes still remained in the class "G" A.C. with Petroset AT section (100).

The reason for the phenomenal success of the striping tape in regard to its resistance to wear is its thickness and its composition; it was four times as thick as the paint stripes and it had an asphalt base. A disadvantage of this type of stripe is the possible lack of bond with the pavement. Thus, the stripe may become loose, which happened during the test. Another disadvantage is that snow plows may tear it off because of its thickness. One solution to the latter problem may be to apply this material into pre-recessed grooves to make it flush with the pavement.

APPLICATION OF RESULTS

The results pertaining to the wear rates which were obtained in the analyses of the data collected in the performance of this project could be used to predict the useful lifetime of various pavement materials. This knowledge could be very valuable to persons responsible for highway maintenance schedules and, on the basis of replacing or repairing pavement surfaces, could be the foundation for a users' tax to those persons who want to drive with studded tires on their cars.

The results obtained from the test track data are not directly applicable to the real world. The types of modifications necessary to convert the test track results to real world situations depend on many factors. A few of these modifications will be used here for illustrative purposes. The modifications mentioned are in no way to be construed as all-inclusive.

Example of the use of the results of this project

Route: U.S. 195 between Pullman and Colfax (2 lanes)

ADT: 6000 vehicles (Approximated for 1973) (3000 vehicles per lane)

AWR: For unstudded tires -- AWR = 0.008 in./10^6 w.a.

For studded tires -- AWR = 0.087 in./10^6 w.a. (Combined effects of CP and PT studs)*

Pavement Material: Class "B" A.C. Overlay

Assumptions:

1) The ADT remains constant.
2) 30% of ADT have studded tires and these studded tires are on only the two rear wheels.
3) The legal period for studs is Nov. 1 to March 31.
4) The maximum allowable average rut depth before routine surfacing is required is 0.50 in.

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*The Average Wear Rates for the CP and PT studs are used in this example because the conventional stud (CV) is no longer on the market.

5) The real highway wheel path width equals 4 times the wheel path width on the test track.

6) The real highway wheel path wears evenly across its width.

If cars with tire studs are <u>not</u> permitted to travel on this segment of the highway throughout its useful lifetime, the value in years of the useful lifetime of the pavement may be determined as follows:

AYT = 3000 X 365 = 1,095,000 cars/year/lane

In one year, each wheel path will undergo 2,190,000 w.a. Average rut depth in the pavement per year would be equal to

$$2{,}190{,}000 \text{ w.a.} \times \frac{0.008 \text{ in.}}{10^6 \text{ w.a.}} \times \frac{1}{4} = 0.00438 \text{ in./year}$$

Note: The 1/4 is the wheel path conversion ratio of the test track wheel path width to the assumed real world wheel path width.

Hence, the useful predicted pavement lifetime $= \frac{0.50 \text{ in.}}{0.00438 \text{ in./year}} = 114.2$ years[11]

If cars with tire studs <u>are</u> permitted to travel on this segment of the highway throughout its useful lifetime, the calculations for the useful lifetime are as follows:

In seven months: 3000 X 7/12 (365) = 638,750 cars without tire studs

In five months: 3000 X 5/12 (365) = 456,250 cars including 319,375 without studs (70%) and 136,875 with studs (30%)

Thus in one year, each wheel path will be affected by 2,053,125 unstudded tires and 136,875 studded tires. The average rut depth per wheel path per year would now be equal to

$$2{,}053{,}125 \times \frac{0.008}{10^6} \times \frac{1}{4} + 136{,}875 \times \frac{0.087}{10^6} \times \frac{1}{4} = 0.0071 \text{ in./year}$$

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[11] This lifetime value is based solely on pavement wear caused by studded tires.

If a 0.50 inch rut depth is the controlling value for maintenance purposes, something would have to be done to this pavement surface in

$$\frac{0.50 \text{ in.}}{0.0071 \text{ in./year}} = 70.4 \text{ years}^{12}.$$

Thus, tire studs on the rear wheels only for 5 months out of the year on 30 percent of the cars traveling this highway section reduces the useful life of the pavement surface from 114 to 70 years or 39 percent. This is a very simple example, but it does demonstrate an application of the results obtained for this project. Other modification factors could be based on a speed ratio, a temperature ratio, a type of stud ratio, etc.

A general formula from which the useful lifetime of a pavement can be determined has been developed by the researchers working on this project from a procedure similar to that used in the example calculations for the studded tires. This formula has the form

$$L = \frac{D(R_W)(10^6)}{(LADT)\ \left\{730(AWR)^{UN}(R_S)^{UN} + 152(P)\ \left[(AWR)^{ST}(R_S)^{ST} - (AWR)^{UN}(R_S)^{UN}\right]\right\}}$$

in which

L = useful lifetime of the pavement

D = the maximum allowable wheel path rut depth

R_W = the ratio of the wheel path width of the real highway to the test track wheel path width

LADT = the average daily traffic volume per traffic lane

$(AWR)^{UN}$ = the average wear rate for the pavement material caused by unstudded tires at the WSU Test Track

$(AWR)^{ST}$ = the average wear rate for the pavement material caused by the studded tires at the WSU Test Track

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[12] This lifetime value is based solely on pavement wear caused by studded tires.

$(R_s)^{UN}$ = a wear rate factor for the unstudded tires caused by speeds different than those at the WSU Test Track

$(R_s)^{ST}$ = a wear rate factor for the studded tires caused by speeds different than those at the WSU Test Track

P = the percent of cars with tire studs in decimal form.

The above formula has been developed for cars with tire studs on the rear wheels only operating 5 months of the year and incorporates speed factors. Other modifications may be made as desired.

To illustrate the use of this formula, the data presented in the aforementioned example will be used, i.e.,

$D = 0.50$ in., LADT = 3000, $(AWR)^{UN} = 0.008$, $(AWR)^{ST} = 0.087$, $P = 30\% = .30$, $R_w = 4$, $(R_s)^{UN} = 1$, and $(R_s)^{ST} = 1$

Thus

$$L = \frac{0.50(4)(10^6)}{3000\ \left\{700(.008)(1) + 152(.30)\ \left[(.087)(1) - (.008)(1)\right]\right\}} = 70.4 \text{ years}$$

This lifetime is based on a tire speed of approximately 20 mph. Research indicates that wear rates increase with increasing speed. The actual correlation is not known, but if it is assumed that at 50 mph $(R_s)^{UN} = 2$ and $(R_s)^{ST} = 3$, the value of L = 29.2 years. As one can note, the pavement lifetime is inversely proportional to the LADT. Thus for a section of 4 lane highway in Spokane with an ADT = 36,000, i.e., a LADT = 9000, and the other values the same as given above, each value of L would be reduced by a factor of 3 to $\frac{70.4}{3} \approx 23$ years and and $\frac{29.2}{3} \approx 10$ years. There are many variables that could be incorporated in the above formula and each variable used must be evaluated in a realistic way in order to obtain valid pavement lifetimes.

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TABLES AND FIGURES

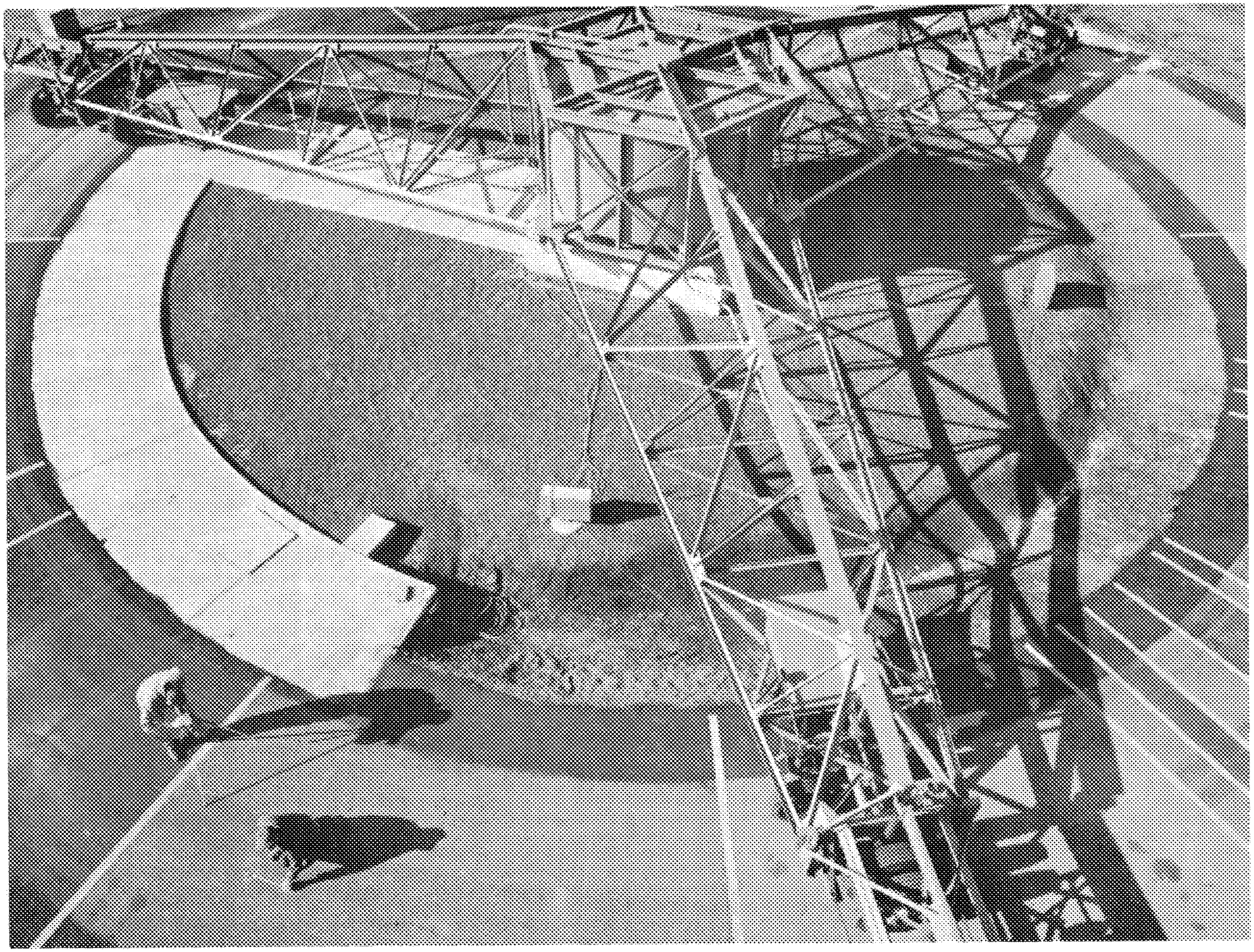


FIGURE 1: A view of the present G. A. Riedesel Pavement Testing Facility.

TABLE 1

EXPERIMENTAL RING NO. 5
Types of Pavement Materials and Textures

A) Outside Track

Section	Type	Texture
01AA	Polymer Concrete - 2" - Mix A	Hand Troweled Finish
01AB	Polymer Concrete - 2" - Mix A	Hand Troweled Finish
01AC	Polymer Concrete - 2" - Mix B	Hand Troweled Finish
01BA	1/2" Wirand Concrete - Mix 1	Light Transverse Brooming
01BB	1/2" Wirand Concrete - Mix 2a	Light Transverse Brooming
01BC	1/2" Wirand Concrete - Mix 2b	Light Transverse Brooming
01BD	1/2" Wirand Concrete - Mix 3	Light Transverse Brooming
02AA	1" Wirand Concrete - Mix 4	Light Transverse Brooming
02AB	1" Wirand Concrete - Mix 5	Light Transverse Brooming
02AC	3" Wirand Concrete - Mix 6	Plastic Grooving
02BA	1" Polymer Concrete - Mix C	Hand Troweled Finish
02BB	1/8" Polymer Concrete - Mix C	Hand Troweled Finish
03A	Class "E" A.C.	Rolled Finish
03B	Class "E" A.C. Gilsabind	Rolled Finish
04A	Class "B" A.C.	Rolled Finish
04B	Class "B" A.C. Gilsabind	Rolled Finish
05A	Class "G" A.C.	Rolled Finish
05B	Class "G" A.C.	Rolled Finish
06A	Idaho Chip Seal - Cl "B" A.C.	Rolled Finish
06B	Idaho Chip Seal - Cl "B" A.C.	Rolled Finish

TABLE 1 (Cont.)

EXPERIMENTAL RING NO. 5

Types of Pavement Materials and Textures

B) Center Track

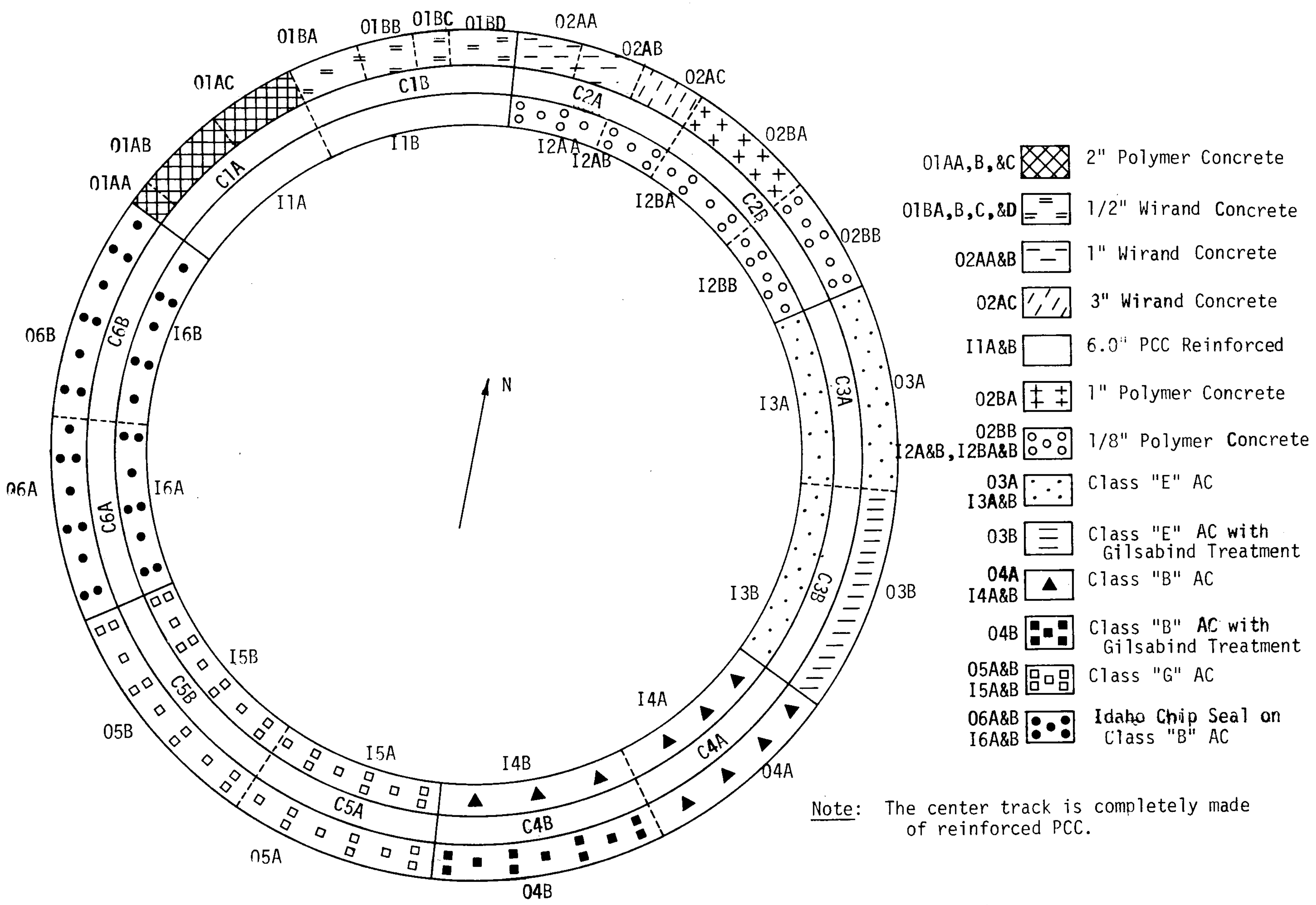
Section	Type	Texture
C1A	Portland Cement Concrete-Reinforced	Heavy Longitudinal Brooming
C1B	Portland Cement Concrete-Reinforced	Light Transverse Brooming
C2A	Portland Cement Concrete-Reinforced	Heavy Transverse Brooming
C2B	Portland Cement Concrete-Reinforced	Burlap
C3A	Portland Cement Concrete-Reinforced	Longitudinal Grooving
C3B	Portland Cement Concrete-Reinforced	Light Longitudinal Brooming
C4A	Portland Cement Concrete-Reinforced	Transverse Grooving
C4B	Portland Cement Concrete-Reinforced	Light Transverse Brooming
C5A	Portland Cement Concrete-Reinforced	Light Plastic Grooving
C5B	Portland Cement Concrete-Reinforced	Light Plastic Grooving
C6A	Portland Cement Concrete-Reinforced	Medium Longitudinal Brooming
C6B	Portland Cement Concrete-Reinforced	Light Longitudinal Brooming

TABLE 1 (Cont.)

EXPERIMENTAL RING NO. 5
Types of Pavement Materials and Textures

C) Inside Track

Section	Type	Texture
I1A	Portland Cement Concrete	Heavy Longitudinal Grooving
I1B	Portland Cement Concrete	Heavy Longitudinal Grooving
I2AA	1/8" Polymer Cement Conc.-Mix C	Hand Troweled Finish
I2AB	1/8" Polymer Cement Conc.-Mix D	Hand Troweled Finish
I2BA	1/8" Polymer Cement Conc.-Mix D	Hand Troweled Finish
I2BB	1/8" Polymer Cement Conc.-Mix C	Hand Troweled Finish
I3A	Class "E" A.C.	Rolled Finish
I3B	Class "E" A.C.	Rolled Finish
I4A	Class "B" A.C.	Rolled Finish
I4B	Class "B" A.C.	Rolled Finish
I5A	Class "G" A.C.	Rolled Finish
I5B	Class "G" A.C.	Rolled Finish
I6A	Idaho Chip Seal-Cl "B" A.C.	Rolled Finish
I6B	Idaho Chip Seal-Cl "B" A.C.	Rolled Finish



Note: The center track is completely made of reinforced PCC.

FIGURE 2: Plan View of the Pavement Sections Tested in Ring No. 5 (Phase I).

TABLE 2

EXPERIMENTAL RING NO. 6
Types of Overlays

SECTION	TYPE OF OVERLAY
010	Bauxite Asphalt Extended Epoxy Surfacing/High Alumina Cement Concrete
021	Polymer Cement Concrete
022	Polymer Steel Fibrous Concrete
023	Garnet Surfacing on Polymer Cement Concrete
031	Polymer Concrete
032	Garnet Surfacing on Polymer Concrete
033	Mineral Slag-Sand on Polymer Concrete
034	Rubber-Sand on Polymer Concrete
041	Mineral Slag Asphalt Extended Epoxy Surfacing/Portland Cement Sand Mix
042	Garnet Asphalt Extended Epoxy Surfacing/Portland Cement Sand Mix
043	Bauxite Asphalt Extended Epoxy Surfacing/Portland Cement Sand Mix
050	Bauxite Asphalt Extended Epoxy Surfacing/Class "G" Asphalt Concrete
061	Class "D" Asphalt Concrete
062	Class "D" Asphalt Concrete with Petroset AT
070	Class "G" Asphalt Concrete with Pliopave
080	Class "G" Asphalt Extended Epoxy Concrete
090	Class "G" Asphalt Concrete
100	Class "G" Asphalt Concrete with Petroset AT
110	Idaho Chip Seal on Class "B" Asphalt Concrete
121	Class "B" Asphalt Concrete
123[1]	Mastic Asphalt (Gussasphalt)
122	Portland Cement Concrete

[1] Placed on outside and inside tracks only.

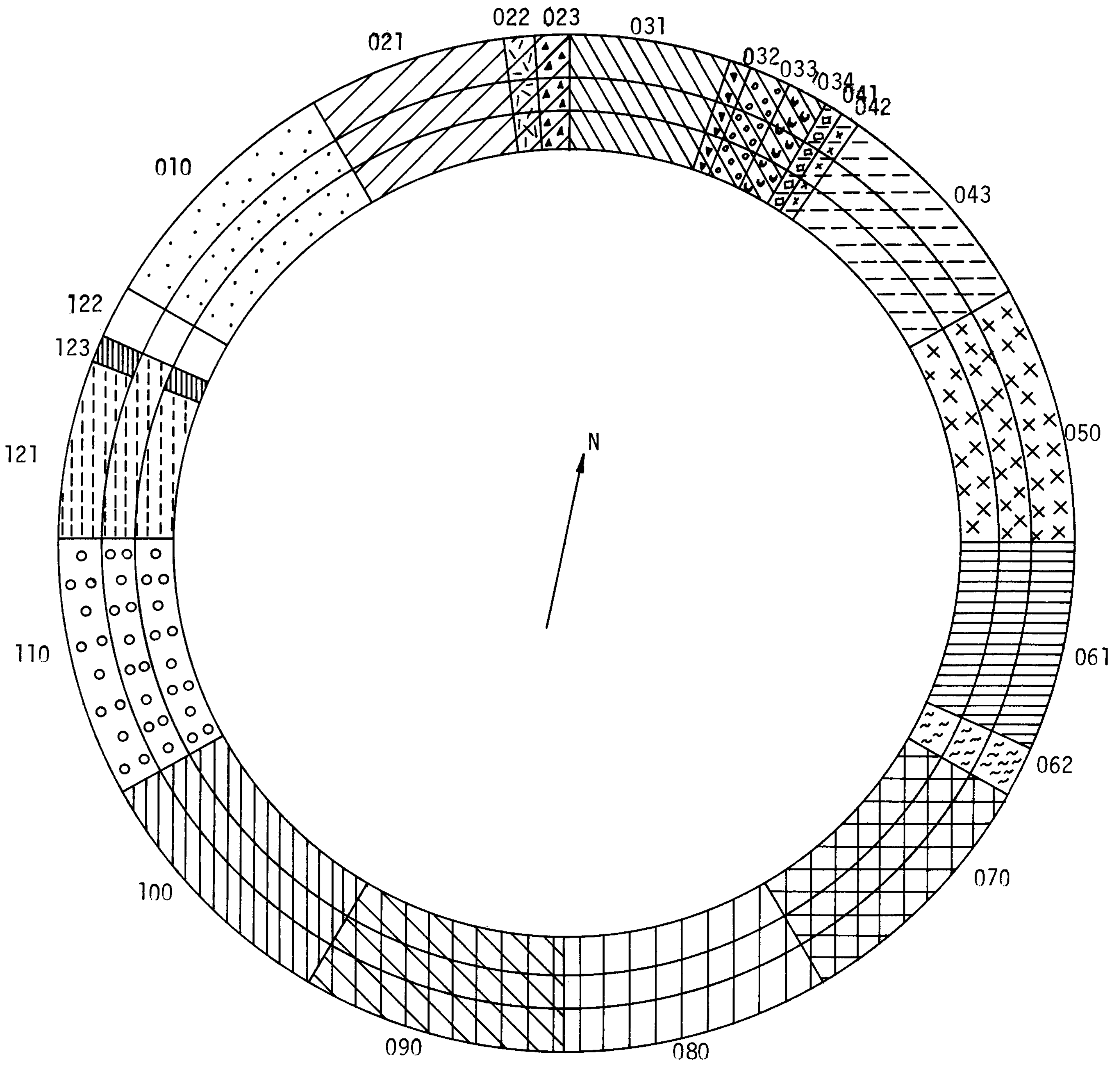
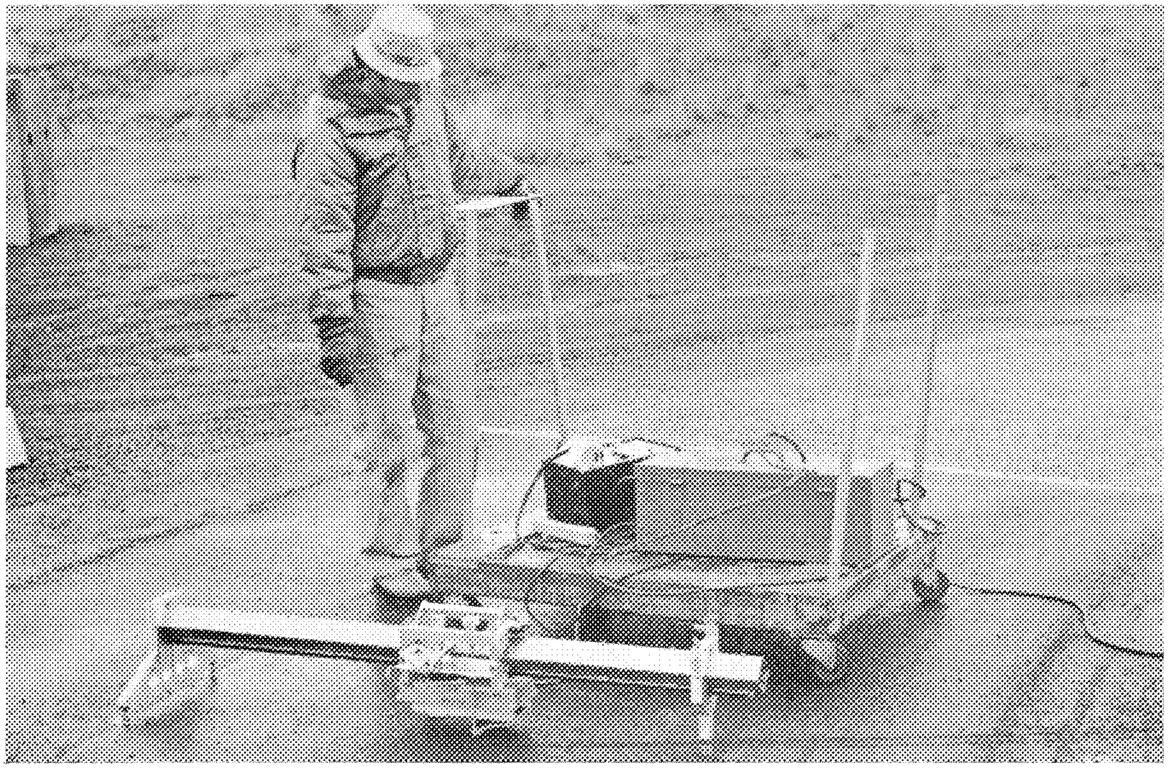
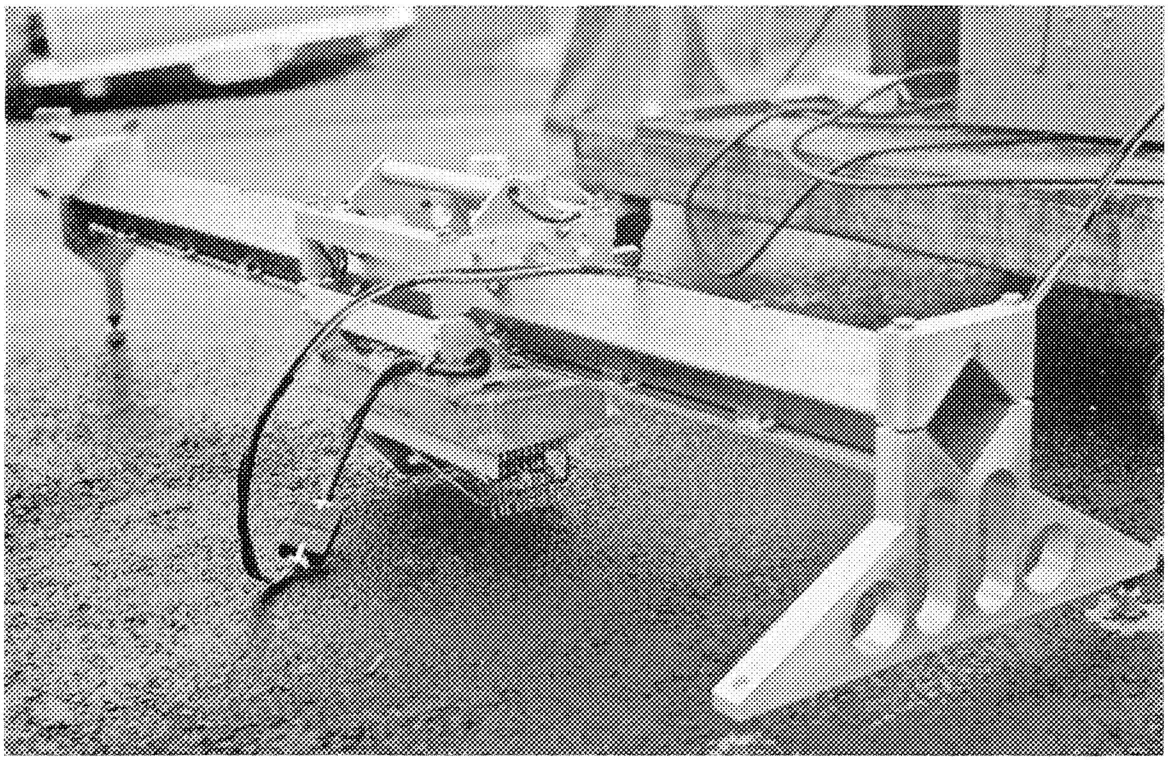


FIGURE 3: Plan View of the Pavement Overlays Tested in Ring No. 6 (Phase II).

010	Bauxite Agg. A.E.E./ High Alumina C.C. Base
021	Polymer Cement Concrete
022	Polymer Steel Fibrous Concrete
023	Poly. C.C. with Garnet Agg. Surfacing
031	Polymer Concrete
032	Poly. C. with Garnet Agg. Surfacing
033	Poly. C. with Mineral Slag Agg. Surfacing
034	Poly. C. with Rubber-Sand Surfacing
041	Mineral Slag Agg. A.E.E./ P.C. Sand Base
042	Garnet Agg. A.E.E./ P.C. Sand Base
043	Bauxite Agg. A.E.E./ P.C. Sand Base
050	Bauxite Agg. A.E.E./Class "G" A.C. Base
061	Class "D" A.C.
062	Class "D" A.C. with Petro-set AT Surface Treatment
070	Class "G" A.C. with Pliopave
080	Class "G" A.E.E. Concrete
090	Class "G" A.C.
100	Class "G" A.C. with Petro-set AT Treatment
110	Idaho Chip Seal/Class "B" A.C.
121	Class "B" A.C.
123	Mastic Asphalt Concrete
122	P.C.C. Type III



(a)



(b)

FIGURE 4: Views of the WSU Profilometer

TABLE 3

PREDICTOR EQUATIONS ($D = a_0 + a_1P \pm 2S$)

Experimental Ring No. 5

A) Outside Track

SECTION	TYPE OF PAVEMENT MATERIAL	AVERAGE RUT DEPTH UN	CP	PT	CV
01BA	1/2" Wirand Conc. - Mix 1	-0.02 - 0.046P ± 0.03	0.02 + 0.359P ± 0.05	0.03 + 0.170P ± 0.03	0.04 + 0.412P ± 0.07
01BB	1/2" Wirand Conc. - Mix 2a	-0.01 + 0.006P ± 0.01	0.01 + 0.339P ± 0.03	0.02 + 0.112P ± 0.03	0.03 + 0.416P ± 0.05
01BC	1/2" Wirand Conc. - Mix 2b	0.00 + 0.004P ± 0.01	0.01 + 0.364P ± 0.03	0.00 + 0.126P ± 0.01	0.01 + 0.323P ± 0.04
01BD	1/2" Wirand Conc. - Mix 3	0.01 + 0.021P ± 0.02	0.00 + 0.371P ± 0.01	0.03 + 0.123P ± 0.03	0.03 + 0.344P ± 0.04
02AA	1" Wirand Conc. - Mix 4	0.01 - 0.004P ± 0.03	0.01 + 0.443P ± 0.04	0.03 + 0.130P ± 0.04	0.01 + 0.425P ± 0.05
02AB	1" Wirand Conc. - Mix 5	-0.01 + 0.016P ± 0.02	0.01 + 0.331P ± 0.03	0.02 + 0.131P ± 0.02	0.01 + 0.474P ± 0.05
02AC	3" Wirand Conc. - Mix 6	-0.01 - 0.004P ± 0.04	0.01 + 0.178P ± 0.04	0.02 + 0.096P ± 0.02	0.02 + 0.118P ± 0.03
02BA	1" Polymer Conc. - Mix C	0.00 - 0.014P ± 0.02	0.02 + 0.391P ± 0.05	0.02 + 0.152P ± 0.03	0
02BB	1/8" Polymer Conc. - Mix C	-0.02 + 0.008P ± 0.02	0.01 + 0.163P ± 0.02	0.03 + 0.205P ± 0.05	0.02 + 0.165P ± 0.03
03A	Class "E" A.C.	0.00 + 0.009P ± 0.02	0.02 + 0.535P ± 0.05	0.02 + 0.281P ± 0.03	0.04 + 0.510P ± 0.07
03B	Class "E" A.C. Gilsabind	0.00 - 0.005P ± 0.02	0.03 + 0.435P ± 0.06	0.02 + 0.209P ± 0.02	0.03 + 0.527P ± 0.09
04A	Class "B" A.C.	0.00 + 0.046P ± 0.02	0.02 + 0.657P ± 0.07	0.02 + 0.219P ± 0.04	0.04 + 0.667P ± 0.12
04B	Class "B" A.C. Gilsabind	0.02 - 0.001P ± 0.02	0.02 + 0.441P ± 0.05	0.01 + 0.208P ± 0.03	0.02 + 0.544P ± 0.09
05A	Class "G" A.C.	0.00 + 0.040P ± 0.01	0.01 + 0.391P ± 0.04	0.03 + 0.172P ± 0.03	0.02 + 0.580P ± 0.06
05B	Class "G" A.C.	0.00 + 0.018P ± 0.02	0.03 + 0.463P ± 0.06	0.03 + 0.198P ± 0.03	0.04 + 0.809P ± 0.10
06A	Idaho Chip Seal on Class "B" A.C.	---	---	---	---
06B	Idaho Chip Seal on Class "B" A.C.	---	---	---	---

UN - Unstudded Tire CP - Controlled Protrusion Tire Stud PT - Perma-T Gripper Tire Stud CV - Conventional Stud

TABLE 3 (Cont.)

PREDICTOR EQUATIONS $(D = a_o + a_1P \pm 2S)$

Experimental Ring No. 5

B) Center Track

SECTION	TYPE OF MATERIAL AND TEXTURE	AVERAGE RUT DEPTH UN	AVERAGE RUT DEPTH CV
C1A	PCC-Reinforced - Heavy Long. Brooming	0.01 - 0.002P ± 0.01	0.04 + 0.064P ± 0.05
C1B	PCC-Reinforced - Light Trans. Brooming	0.00 - 0.005P ± 0.01	0.03 + 0.083P ± 0.05
C2A	PCC-Reinforced - Heavy Trans. Brooming	0.01 - 0.024P ± 0.08	0.02 + 0.053P ± 0.05
C2B	PCC-Reinforced - Burlap	0.02 - 0.017P ± 0.05	0.03 + 0.068P ± 0.05
C3A	PCC-Reinforced - Long. Grooving	-0.01 - 0.013P ± 0.02	0.04 + 0.067P ± 0.05
C3B	PCC-Reinforced - Light Long. Brooming	0.00 + 0.010P ± 0.02	0.03 + 0.082P ± 0.07
C4A	PCC-Reinforced - Transverse Grooving	0.00 - 0.003P ± 0.02	0.03 + 0.081P ± 0.06
C4B	PCC-Reinforced-- Light Trans. Brooming	0.00 + 0.005P ± 0.01	0.04 + 0.075P ± 0.06
C5A	PCC-Reinforced - Light Plastic Grooving	0.03 - 0.005P ± 0.04	0.03 + 0.069P ± 0.06
C5B	PCC-Reinforced - Light Plastic Grooving	0.01 - 0.002P ± 0.05	0.02 + 0.049P ± 0.02
C6A	PCC-Reinforced - Medium Long. Brooming	0.01 = 0.001P ± 0.06	0.03 + 0.079P ± 0.06
C6B	PCC-Reinforced - Light Long. Brooming	0.01 - 0.009P ± 0.06	0.03 + 0.066P ± 0.05

UN - Unstudded Tire

CV - Conventional Tire Stud

TABLE 3 (Cont.)

PREDICTOR EQUATIONS ($D = a_o + a_1P \pm 2S$)

Experimental Ring No. 5

C) Inside Track

SECTION	TYPE OF PAVEMENT MATERIAL	AVERAGE RUT DEPTH CP	AVERAGE RUT DEPTH UN
I1A	Portland Cement Concrete	0.02 + 0.109P ± 0.03	0
I1B	Portland Cement Concrete	0.01 + 0.084P ± 0.01	-0.01 - 0.037P ± 0.03
I2AA	1/8" Poly. Cement Conc. - Mix C	-0.01 + 0.092P ± 0.03	0
I2AB	1/8" Poly. Cement Conc. - Mix D	0.00 + 0.092P ± 0.03	0
I2BA	1/8" Poly. Cement Conc. - Mix D	0.01 + 0.054P ± 0.01	0
I2BB	1/8" Poly. Cement Conc. - Mix C	0.00 + 0.078P ± 0.01	0
I3A	Class "E" A.C.	0.02 + 0.375P ± 0.03	0
I3B	Class "E" A.C.	---	---
I4A	Class "B" A.C.	0.00 + 0.280P ± 0.01	0.00 + 0.001P ± 0.01
I4B	Class "B" A.C.	0.02 + 0.320P ± 0.02	0
I5A	Class "G" A.C.	0.00 + 0.430P ± 0.05	0
I5B	Class "G" A.C.	0.00 + 0.383P ± 0.04	0.01 - 0.005P ± 0.01
I6A	Idaho Chip Seal on Class "B" A.C.	---	---
I6B	Idaho Chip Seal on Class "B" A.C.	---	---

CP - Controlled Protrusion Tire Stud

UN - Unstudded Tire

TABLE 4

AVERAGE WEAR RATE VALUES
in inches per million wheel applications

Experimental Ring No. 5

A) Outside Track

SECTION	MATERIAL	UN	CP	PT	CV
01AA	2" Polymer Concrete	--	--	--	--
01AB	2" Polymer Concrete	--	--	--	--
01AC	2" Polymer Concrete	--	--	--	--
01BA	1/2" Wirand Concrete	0.001[1]	0.359	0.170	0.412
01BB	1/2" Wirand Concrete	0.006	0.339	0.112	0.416
01BC	1/2" Wirand Concrete	0.004	0.364	0.126	0.323
01BD	1/2" Wirand Concrete	0.021	0.371	0.123	0.344
02AA	1" Wirand Concrete	0.001	0.443	0.130	0.425
02AB	1" Wirand Concrete	0.016	0.331	0.131	0.474
02AC	3" Wirand Concrete	0.001	0.178	0.096	0.118
02BA	1" Polymer Concrete	0.001	0.391	0.152	0.001
02BB	1/8" Polymer Concrete	0.008	0.163	0.205	0.165
03A	Class "E" A.C.	0.009	0.535	0.281	0.510
03B	Class "E" A.C./Gilsabind	0.001	0.435	0.209	0.527
04A	Class "B" A.C.	0.046	0.657	0.219	0.667
04B	Class "B" A.C./Gilsabind	0.001	0.441	0.208	0.544
05A	Class "G" A.C.	0.040	0.391	0.172	0.580
05B	Class "G" A.C.	0.018	0.463	0.198	0.809
06A	Idaho Chip Seal	--	--	--	--
06B	Idaho Chip Seal	--	--	--	--

UN - Unstudded Tire

CP - Controlled Protrusion Tire Stud

PT - Perma-T Gripper Tire Stud

CV - Conventional Tire Stud

[1] The AWR value for any material for which the regression analysis yielded a negative slope was arbitrarily set to 0.001. This value should be interpreted as being indicative of a small AWR value.

TABLE 4 (Cont.)

AVERAGE WEAR RATE VALUES
in inches per million wheel applications

Experimental Ring No. 5

B) Center Track

SECTION	MATERIAL AND TEXTURE	UN	CV
C1A	PCC - Heavy Long. Brooming	0.001	0.064
C1B	PCC - Light Trans. Brooming	0.001	0.083
C2A	PCC - Heavy Trans. Brooming	0.001	0.053
C2B	PCC - Burlap	0.001	0.068
C3A	PCC - Long. Grooving	0.001	0.067
C3B	PCC - Light Long. Brooming	0.010	0.082
C4A	PCC - Trans. Grooving	0.001	0.081
C4B	PCC - Light Trans. Brooming	0.005	0.075
C5A	PCC - Light Plastic Grooving	0.001	0.069
C5B	PCC - Light Plastic Grooving	0.002	0.049
C6A	PCC - Medium Long. Brooming	0.001	0.079
C6B	PCC - Light Long. Brooming	0.001	0.066

UN - Unstudded Tire

CV - Conventional Tire Stud

TABLE 4 (Cont.)

AVERAGE WEAR RATE VALUES
in inches per million wheel applications

Experimental Ring No. 5

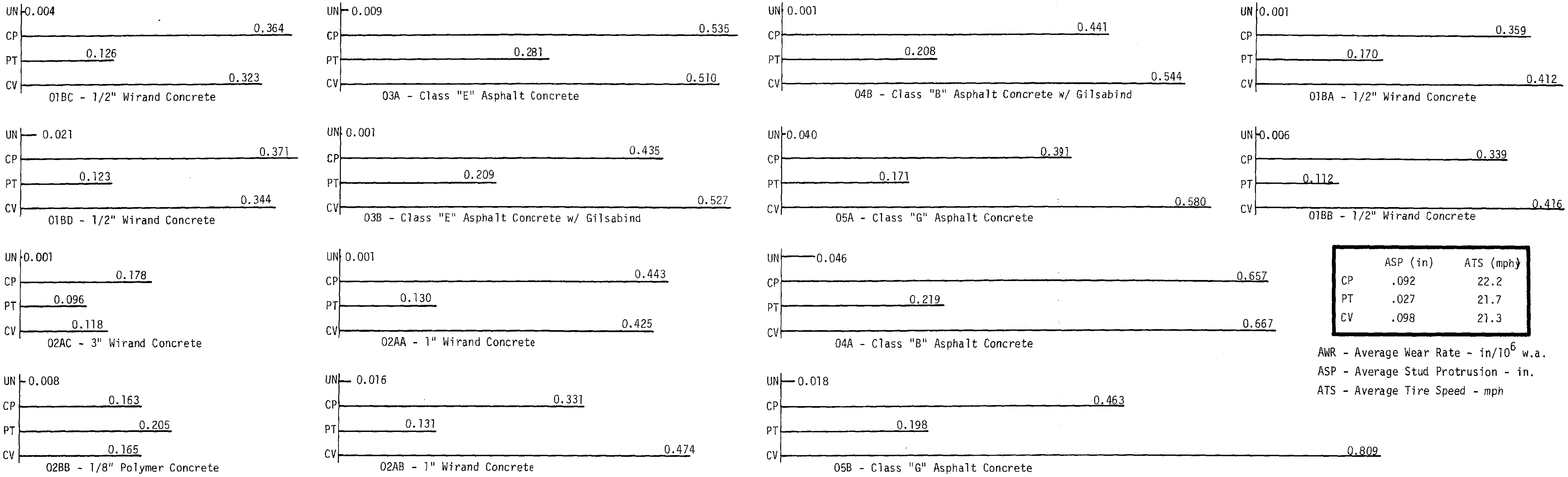
C) Inside Track

SECTION	MATERIAL	CP	UN
I1A	PCC	0.109	0.001
I1B	PCC	0.084	0.001
I2AA	1/8" Polymer Cement Conc.	0.092	0.001
I2AB	1/8" Polymer Flyash Conc.	0.092	0.001
I2BA	1/8" Polymer Flyash Conc.	0.054	0.001
I2BB	1/8" Polymer Cement Conc.	0.078	0.001
I3A	Class "E" A.C.	0.375	0.001
I3B	Class "E" A.C.	--	--
I4A	Class "B" A.C.	0.280	0.001
I4B	Class "B" A.C.	0.320	0.001
I5A	Class "G" A.C.	0.430	0.001
I5B	Class "G" A.C.	0.383	0.001
I6A	Idaho Chip Seal	--	--
I6B	Idaho Chip Seal	--	--

CP - Controlled Protrusion Tire Stud

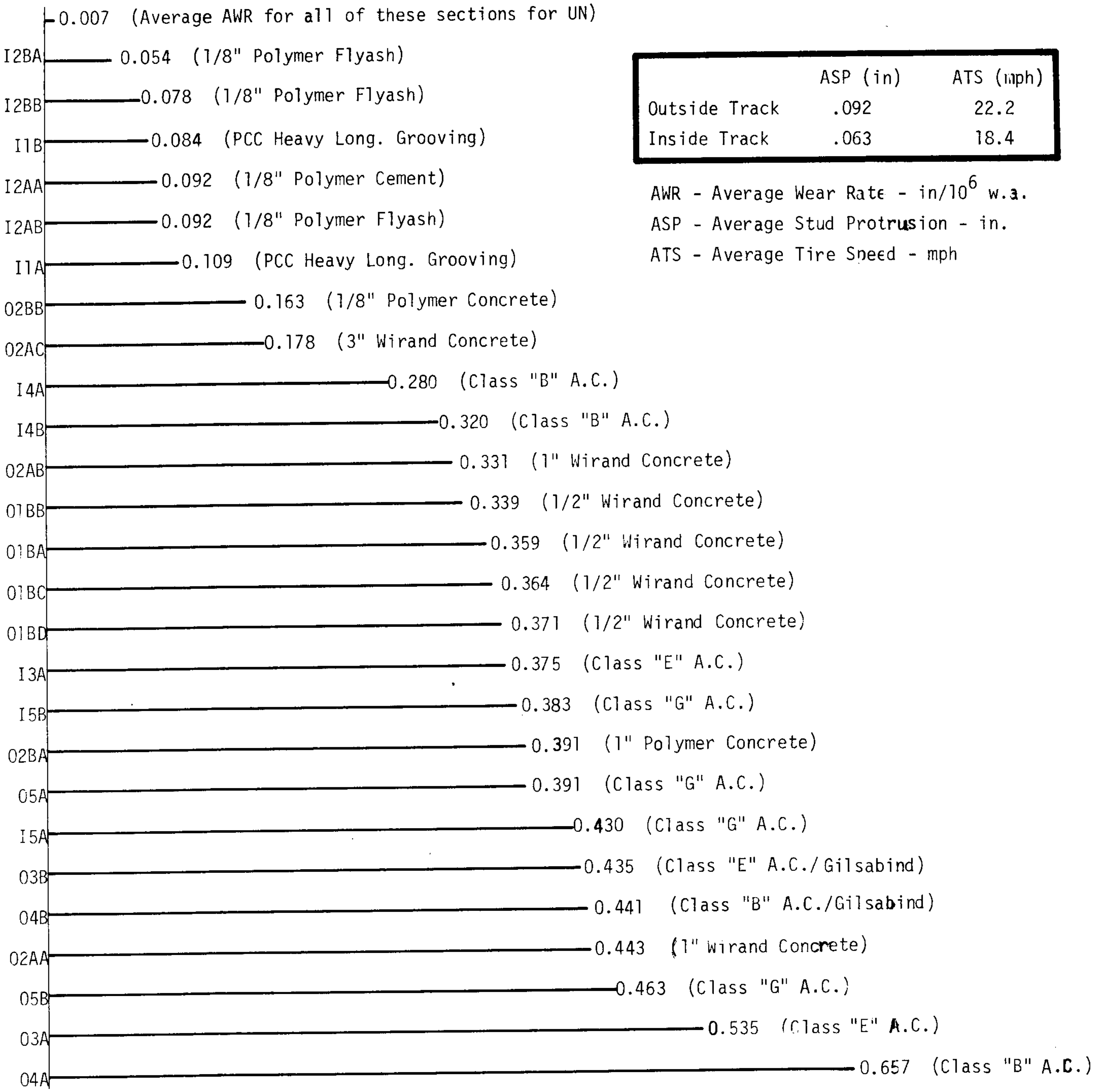
UN - Unstudded Tire

FIGURE 5: AWR Value Comparisons for the Materials in the Outside Track in Ring No. 5.



	ASP (in)	ATS (mph)
CP	.092	22.2
PT	.027	21.7
CV	.098	21.3

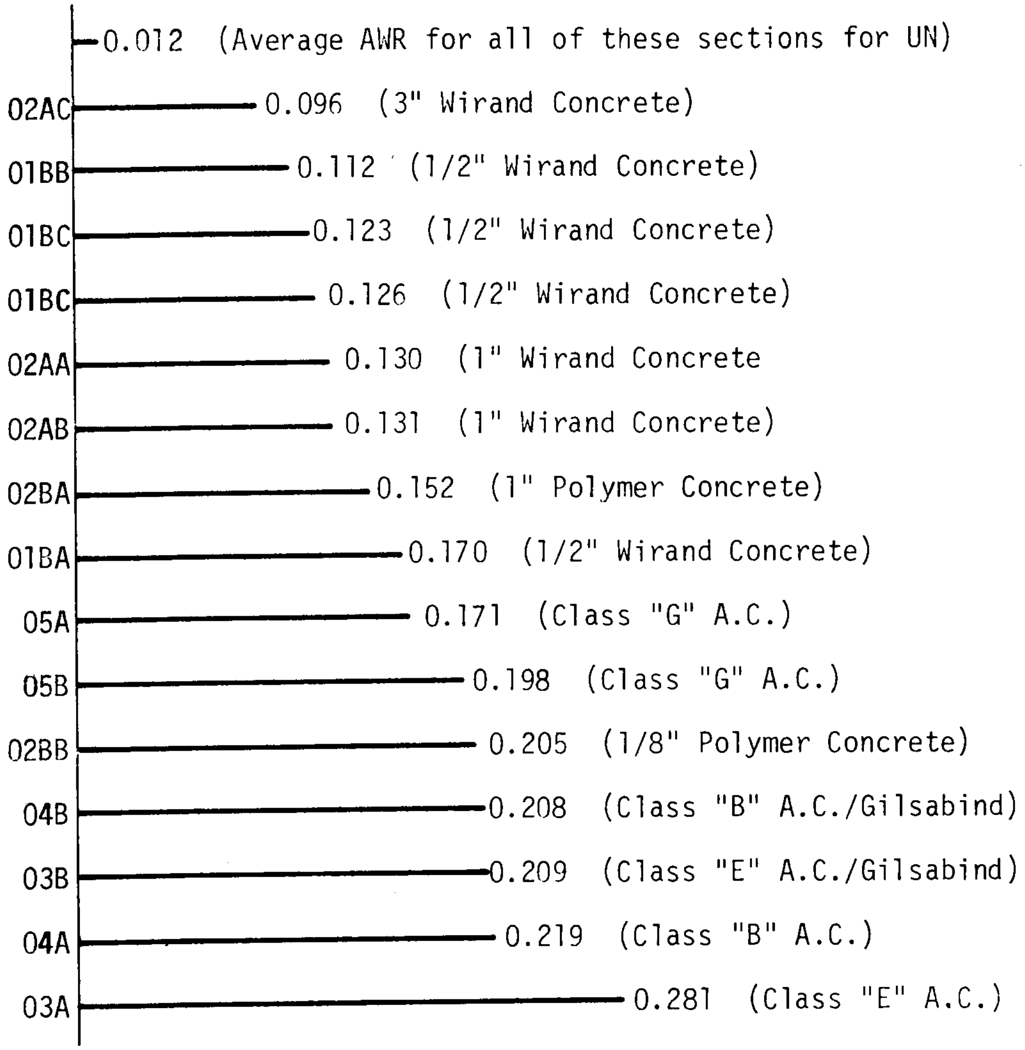
AWR - Average Wear Rate - in/10^6 w.a.
ASP - Average Stud Protrusion - in.
ATS - Average Tire Speed - mph



	ASP (in)	ATS (mph)
Outside Track	.092	22.2
Inside Track	.063	18.4

AWR - Average Wear Rate - in/10^6 w.a.
ASP - Average Stud Protrusion - in.
ATS - Average Tire Speed - mph

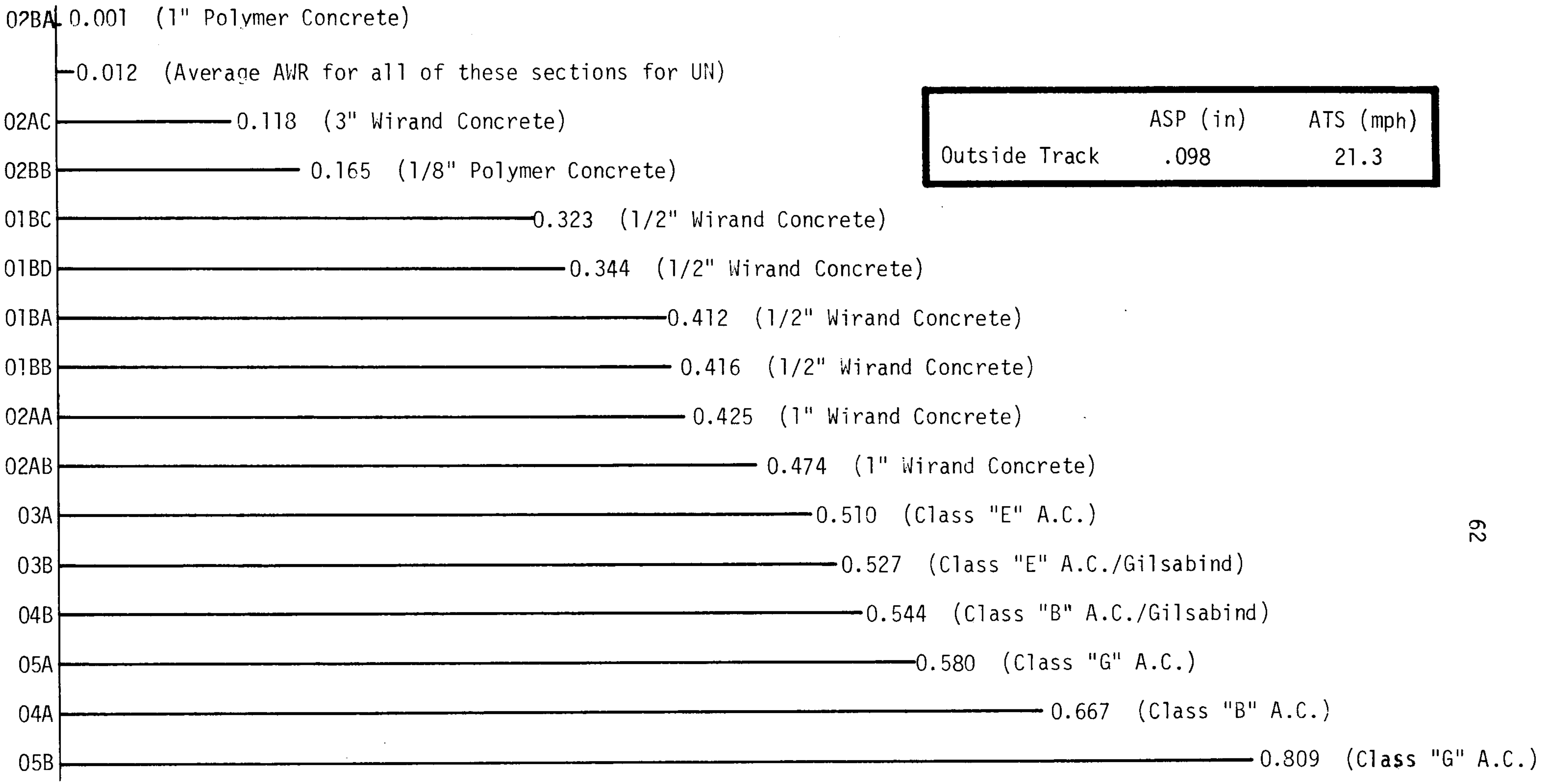
FIGURE 6: AWR Values Determined for the Controlled Protrusion Stud from Ring No. 5 Data.



	ASP (in)	ATS (mph)
Outside Track	.027	21.7

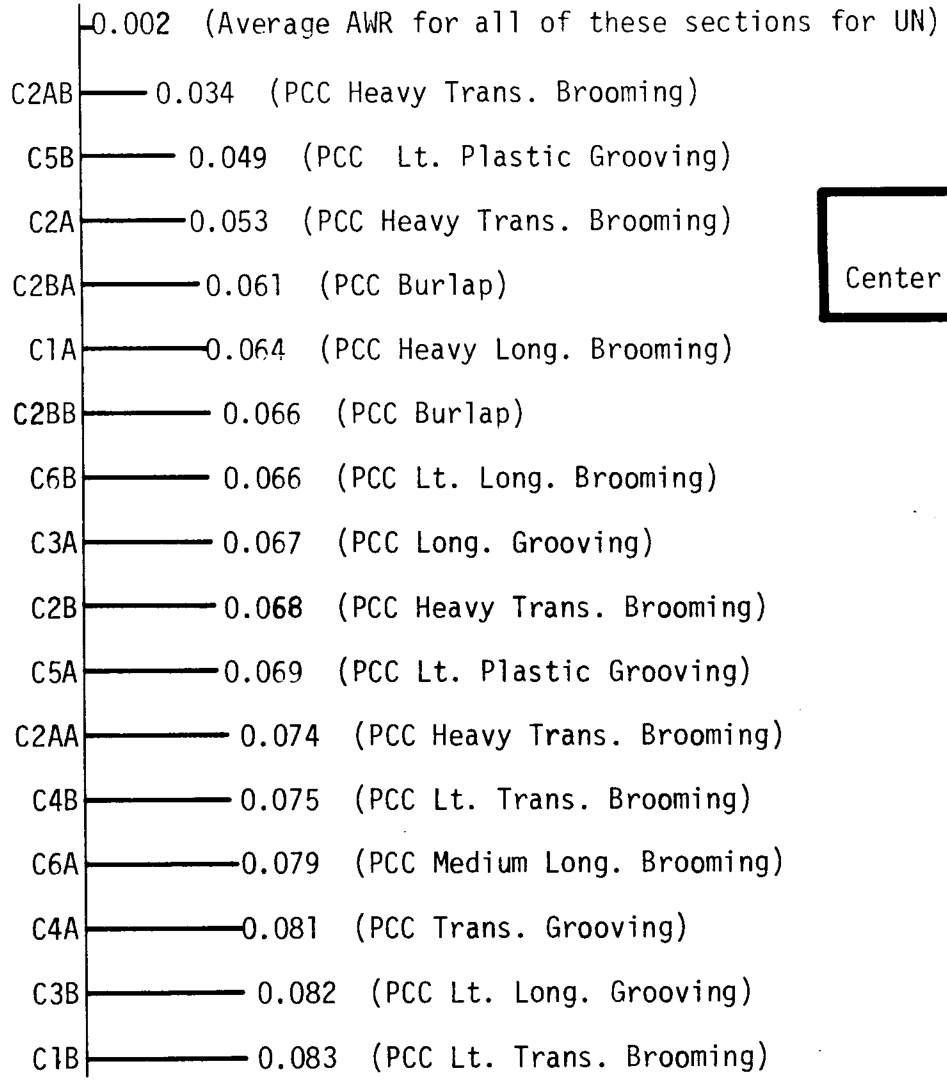
AWR - Average Wear Rate - in/10^6 w.a.
ASP - Average Stud Protrusion - in.
ATS - Average Tire Speed - mph

FIGURE 7: AWR Values Determined for the Perma-T Gripper Stud from Ring No. 5 Data.



AWR - Average Wear Rate - in/10^6 w.a.
ASP - Average Stud Protrusion - in.
ATS - Average Tire Speed - mph

FIGURE 8: AWR Values Determined for the Conventional Stud from Ring No. 5 Data. (Passenger Tires)



	ASP (in)	ATS (mph)
Center Track	.034	20.0

FIGURE 8 (Cont.): AWR Values Determined for the Conventional Stud from Ring No. 5 Data. (Truck Tires)

FIGURE 9: Comparison of AWR Values on Similar Materials for Tires With the Controlled Protrusion Stud but with Different Stud Protrusion Lengths and Moving at Different Speeds.

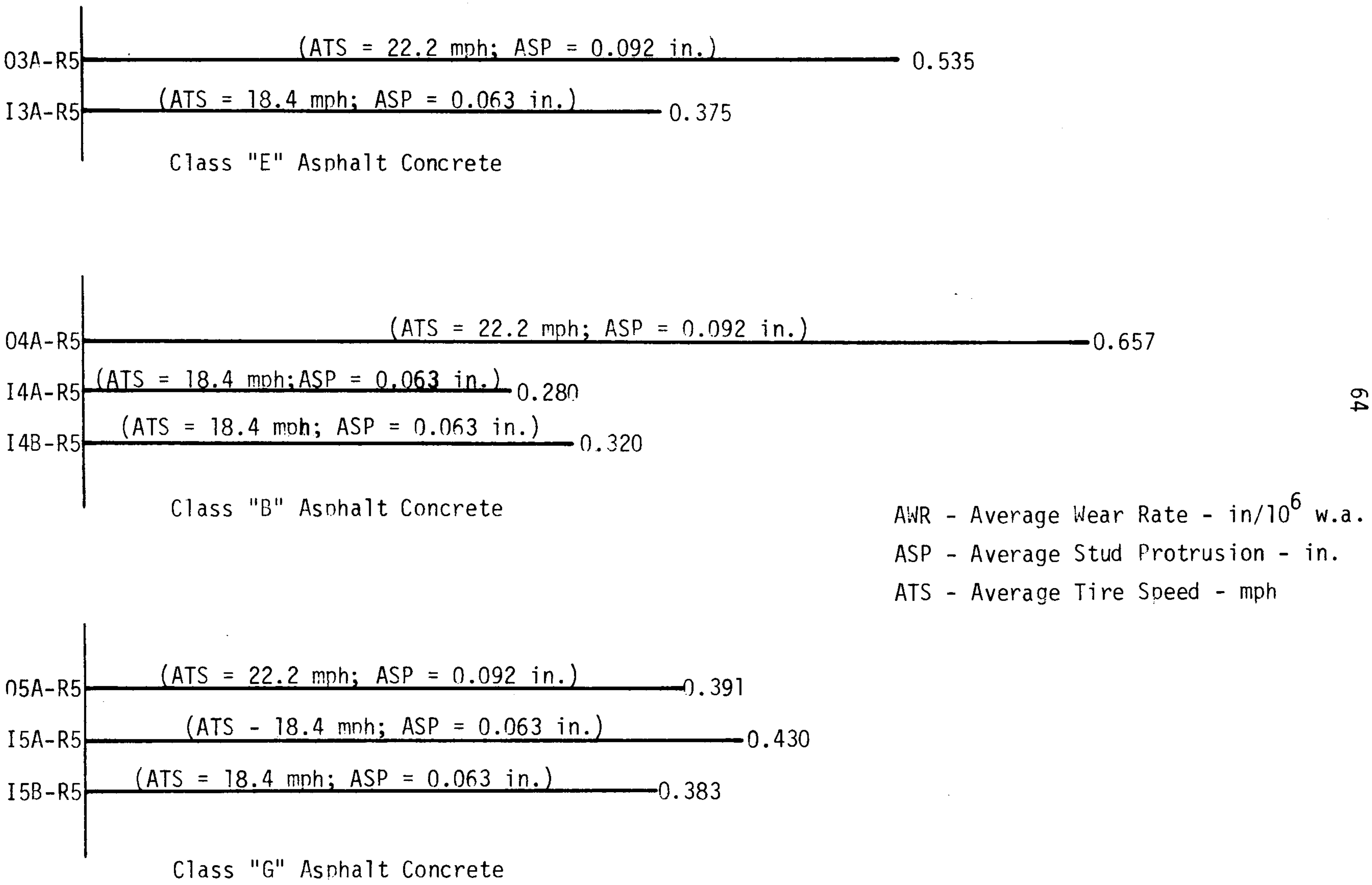


TABLE 5

PREDICTOR EQUATIONS (D = $a_o + a_1P \pm 2S$)

Experimental Ring No. 6

SECTION	TYPE OF OVERLAY	AVERAGE RUT DEPTH					
		GST	FS	PT	CV	CP	UN
010	Baux. A.E.E. Surf./High Al. C. C.	0.00 + 0.014P ± 0.01	0.02 + 0.129P ± 0.02	0.02 + 0.056P ± 0.02	0.02 + 0.100P ± 0.02	0.03 + 0.032P ± 0.03	0.00 + 0.001P ± 0.01
021	Polymer Cement Concrete	0.00 - 0.004P ± 0.01	0.00 + 0.017P ± 0.00	0.00 + 0.020P ± 0.01	0.01 + 0.009P ± 0.01	0.01 + 0.012P ± 0.01	0.01 + 0.001P ± 0.01
022	Polymer Steel Fibrous Conc.	-0.01 + 0.007P ± 0.02	0.00 + 0.017P ± 0.03	0.01 + 0.007P ± 0.03	0.01 + 0.004P ± 0.03	0.02 + 0.022P ± 0.02	0.00 + 0.000P ± 0.00
023	Garnet Surf. on Poly. C. C.	0.00 + 0.015P ± 0.01	0.01 + 0.027P ± 0.01	0.00 + 0.027P ± 0.01	0.00 + 0.021P ± 0.01	0.00 + 0.023P ± 0.01	0.00 - 0.002P ± 0.01
031	Polymer Concrete	0.00 - 0.005P ± 0.01	0.00 + 0.006P ± 0.00	0.00 + 0.009P ± 0.00	0.00 + 0.001P ± 0.01	0.00 + 0.008P ± 0.01	0.00 + 0.002P ± 0.01
032	Garnet Surf. on Poly. Conc.	0.00 - 0.011P ± 0.01	0.01 + 0.030P ± 0.01	0.00 + 0.043P ± 0.01	0.01 + 0.017P ± 0.01	0.00 + 0.007P ± 0.01	0.00 - 0.005P ± 0.01
033	Min. Slag-Sand on Poly. Conc.	-0.01 - 0.005P ± 0.01	0.00 + 0.005P ± 0.01	0.00 + 0.012P ± 0.01	0.00 + 0.013P ± 0.01	0.02 + 0.012P ± 0.02	0.01 - 0.006P ± 0.02
034	Rubber-Sand on Poly. Conc.	0.00 + 0.011P ± 0.01	0.00 + 0.137P ± 0.01	0.00 + 0.051P ± 0.02	0.01 + 0.045P ± 0.01	0.01 + 0.024P ± 0.01	0.00 - 0.002P ± 0.01
041	Min. Slag A.E.E. Surf./P.C. Sand Mix	0.00 + 0.017P ± 0.01	0.03 + 0.167P ± 0.03	0.02 + 0.072P ± 0.03	0.01 + 0.139P ± 0.03	0.05 + 0.063P ± 0.04	0.01 - 0.005P ± 0.03
042	Garn. A.E.E. Surf./P.C. Sand Mix	0.00 - 0.004P ± 0.01	0.01 + 0.098P ± 0.02	0.02 + 0.052P ± 0.02	-0.01 + 0.055P ± 0.01	0.01 + 0.038P ± 0.02	0.00 + 0.006P ± 0.01
043	Baux. A.E.E. Surf./P.C. Sand Mix	0.01 + 0.023P ± 0.01	0.03 + 0.162P ± 0.03	0.03 + 0.100P ± 0.03	0.04 + 0.136P ± 0.03	0.04 + 0.038P ± 0.04	-0.01 + 0.004P ± 0.01
050	Baux. A.E.E. Surf./Class "G" A.C.	0.00 + 0.042P ± 0.02	0.03 + 0.138P ± 0.03	0.03 + 0.083P ± 0.03	0.03 + 0.102P ± 0.03	0.03 + 0.046P ± 0.03	0.01 + 0.008P ± 0.01
061	Class "D" A.C.	0.04 + 0.081P ± 0.06	0.18 + 0.298P ± 0.20	0.02 + 0.195P ± 0.03	0.04 + 0.571P ± 0.05	0.05 + 0.299P ± 0.07	-0.01 - 0.002P ± 0.01
062	Class "D" A.C./Petroset AT	-0.01 + 0.019P ± 0.02	0.02 + 1.024P ± 0.08	0.02 + 0.121P ± 0.03	0.03 + 0.509P ± 0.04	0.10 + 0.326P ± 0.15	0.00 + 0.006P ± 0.01
070	Class "G" A.C./Pliopave	0.01 + 0.027P ± 0.01	0.06 + 0.301P ± 0.10	0.04 + 0.099P ± 0.03	0.06 + 0.280P ± 0.04	0.05 + 0.122P ± 0.06	0.00 + 0.008P ± 0.01
080	Class "G" A.E.E. Concrete	0.00 + 0.009P ± 0.01	0.01 + 0.212P ± 0.03	0.01 + 0.084P ± 0.02	0.01 + 0.157P ± 0.02	0.07 + 0.158P ± 0.08	-0.01 + 0.001P ± 0.02
090	Class "G" A.C.	0.01 + 0.033P ± 0.01	0.06 + 0.478P ± 0.07	0.03 + 0.125P ± 0.03	0.04 + 0.329P ± 0.04	0.11 + 0.198P ± 0.14	0.00 + 0.002P ± 0.01
100	Class "G" A.C./Petroset AT	0.01 + 0.025P ± 0.02	0.03 + 0.462P ± 0.05	0.03 + 0.146P ± 0.03	0.02 + 0.368P ± 0.03	0.07 + 0.183P ± 0.10	-0.01 + 0.008P ± 0.01
110	Idaho Chip Seal on Class "B" A.C.	0.01 - 0.047P ± 0.03	0.00 + 0.157P ± 0.04	0.01 + 0.046P ± 0.03	0.02 + 0.200P ± 0.05	0.00 + 0.085P ± 0.03	0.00 + 0.022P ± 0.03
121	Class "B" A.C.	0.00 + 0.010P ± 0.02	0.02 + 0.132P ± 0.03	0.02 + 0.085P ± 0.03	0.02 + 0.120P ± 0.03	0.05 + 0.088P ± 0.06	0.00 + 0.008P ± 0.01
123	Mastic Asphalt (Gussasphalt)	0.00 + 0.026P ± 0.01	0.02 + 0.098P ± 0.02	0.01 + 0.053P ± 0.02	0.01 + 0.094P ± 0.02	0.04 + 0.054P ± 0.06	0.01 + 0.001P ± 0.02
122	Portland Cement Concrete	0.01 + 0.007P ± 0.01	0.02 + 0.051P ± 0.02	0.01 + 0.021P ± 0.02	0.02 + 0.041P ± 0.02	0.03 + 0.031P ± 0.04	0.00 - 0.006P ± 0.02

GST - Garnet Impregnated Snow Tire

FS - Finnstop Tire Stud

PT - Perma-T Gripper Tire Stud

CV - Conventional Tire Stud

CP - Controlled Protrusion Tire Stud

UN - Unstudded Tire

TABLE 6

AVERAGE WEAR RATE VALUES

in inches per million wheel applications

Experimental Ring No. 6

SECTION	MATERIAL	GST	FS	PT	CV	CP	UN
010	Baux. A.E.E. Surf./High Al. C.C.	0.014	0.129	0.056	0.100	0.032	0.001
041	Min. Slag A.E.E. Surf./PC Sand	0.017	0.167	0.072	0.139	0.063	0.001
042	Garn. A.E.E. Surf./PC Sand	0.001	0.098	0.052	0.055	0.038	0.006
043	Baux. A.E.E. Surf./PC Sand	0.023	0.162	0.100	0.136	0.038	0.004
050	Baux. A.E.E. Surf./Class "G" A.C.	0.042	0.138	0.083	0.102	0.046	0.008
110	Idaho Chip Seal/Class "B" A.C.	0.001	0.157	0.046	0.200	0.085	0.022
021	Polymer Cement Conc.	0.001	0.017	0.020	0.009	0.012	0.001
022	Polymer Wirand Conc.	0.007	0.017	0.007	0.004	0.022	0.000
023	Garn. on Poly. Cem. Conc.	0.015	0.027	0.027	0.021	0.023	0.001
031	Polymer Concrete	0.001	0.006	0.009	0.001	0.008	0.002
032	Garn. on Poly. Concrete	0.001	0.030	0.043	0.017	0.007	0.001
033	Min. Slag-Sand on Poly. Conc.	0.001	0.005	0.012	0.013	0.012	0.001
034	Rubber Sand on Poly. Conc.	0.011	0.137	0.051	0.045	0.024	0.001
122	Portland Cement Concrete	0.007	0.051	0.021	0.041	0.031	0.001
061	Class "D" A.C.	0.081	0.298	0.195	0.571	0.299	0.001
062	Class "D" A.C./Petroset AT	0.019	1.024	0.121	0.509	0.326	0.006
070	Class "G" A.C./Pliopave	0.027	0.301	0.099	0.280	0.122	0.008
080	Class "G" A.E.E. Concrete	0.009	0.212	0.084	0.157	0.158	0.001
090	Class "G" A.C.	0.033	0.478	0.125	0.329	0.198	0.002
100	Class "G" A.C./Petroset AT	0.025	0.462	0.146	0.368	0.183	0.008
121	Class "B" A.C.	0.010	0.132	0.085	0.120	0.088	0.008
123	Mastic Asphalt	0.026	0.098	0.053	0.094	0.054	0.001

GST - Garnet Impregnated Snow Tire

FS - Finnstop Tire Stud

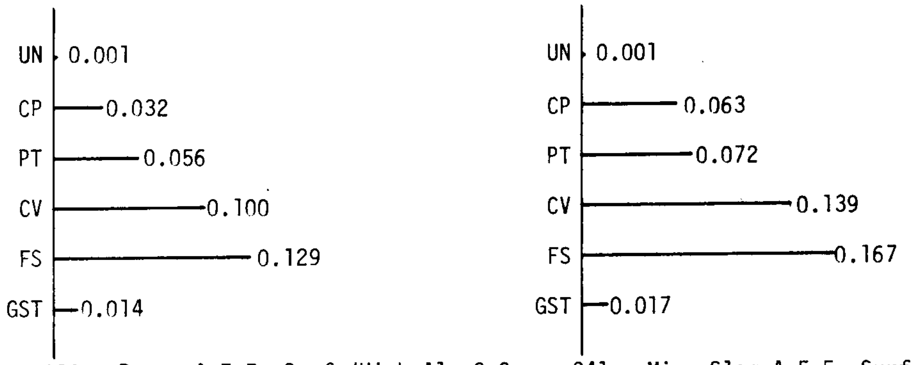
PT - Perma-T Gripper Tire Stud

CV - Conventional Tire Stud

CP - Controlled Protrusion Tire Stud

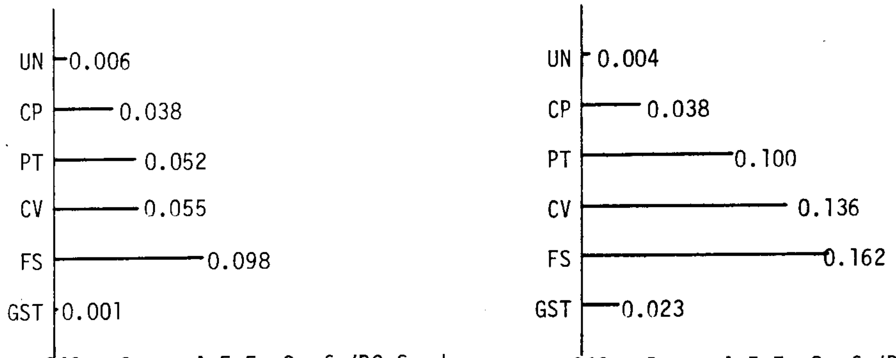
UN - Unstudded Tire

FIGURE 10: AWR Value Comparisons for the SURFACINGS GROUP in Ring No. 6.



010 - Baux. A.E.E. Surf./High Al. C.C.   041 - Min. Slag A.E.E. Surf./PC Sand

	ASP (in)	ATS (mph)
UN	---	18.0
CP	.020	18.4
PT	.017	21.7
CV	.030	21.3
FS	.029	22.2
GST	---	22.5



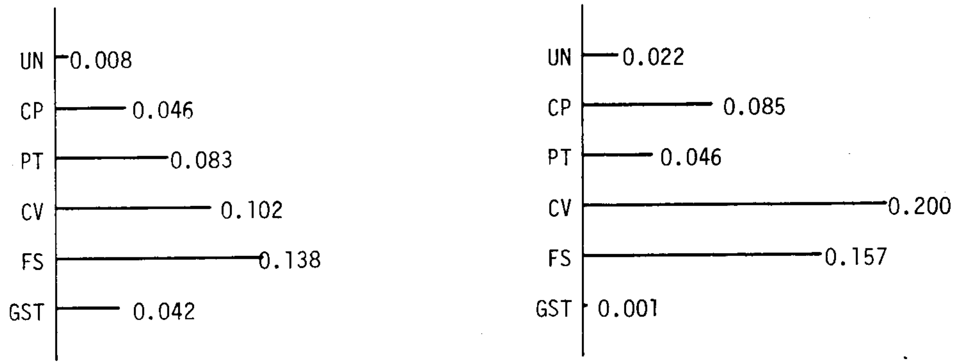
042 - Garn. A.E.E. Surf./PC Sand   043 - Baux. A.E.E. Surf./PC Sand

AWR - Average Wear Rate - in/10^6 w.a.

ASP - Average Stud Protrusion - in.

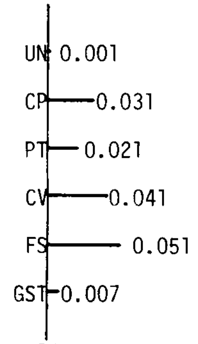
ATS - Average Tire Speed - mph

-See Table 6 for Stud Types-

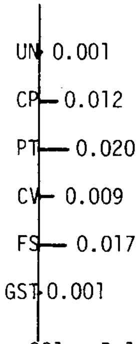


050 - Baux. A.E.E. Surf./Class "G" A.C.   110 - Idaho Chip Seal/Class "G" A.C.

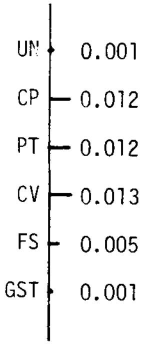
FIGURE 11: AWR Comparisons for the CONCRETE OVERLAY GROUP in Ring No. 6.



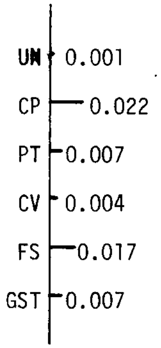
122 - Portland Cement Concrete



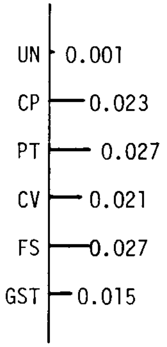
021 - Polymer Cement Concrete



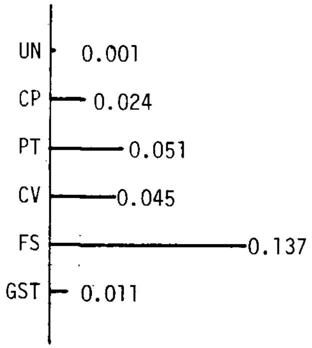
033 - Min. Slag-Sand on Polymer Conc.



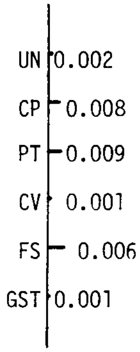
022 - Polymer Wirand Concrete



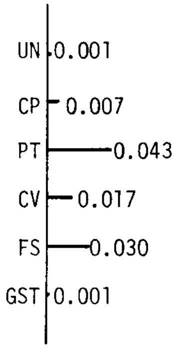
023 - Garnet on Polymer Cement Concrete



034 - Rubber Sand on Polymer Conc.



031 - Polymer Concrete



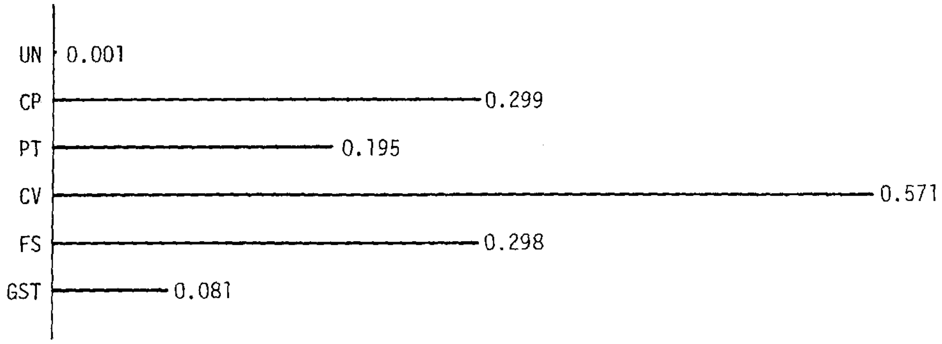
032 - Garnet on Polymer Concrete

	ASP (in)	ATS (mph)
UN	---	18.0
CP	.020	18.4
PT	.017	21.7
CV	.030	21.3
FS	.029	22.2
GST	---	22.5

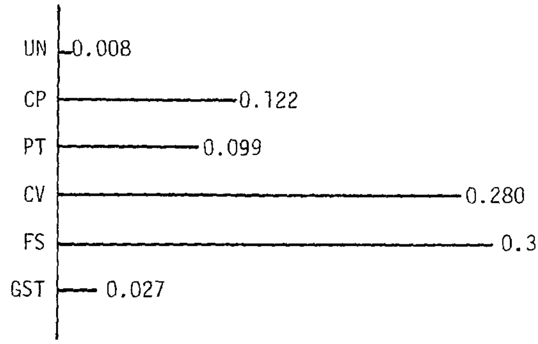
AWR - Average Wear Rate - in/10^6 w.a.
ASP - Average Stud Protrusion - in.
ATS - Average Tire Speed - mph

-See Table 6 for Stud Types and Tires-

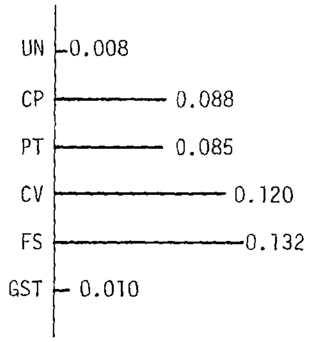
FIGURE 12: AWR Value Comparisons for the ASPHALT OVERLAY GROUP in Ring No. 6.



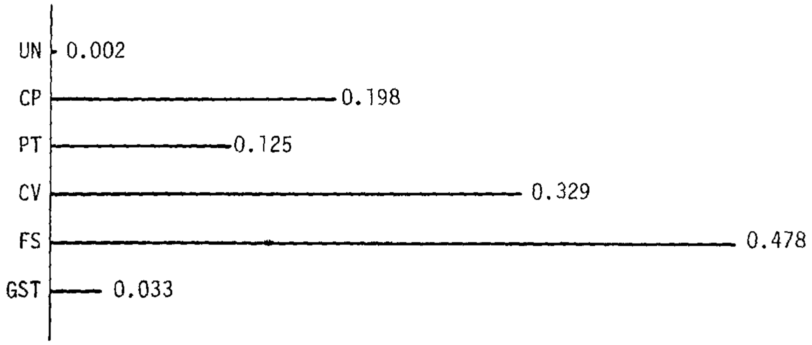
061 - Class "D" Asphalt Concrete



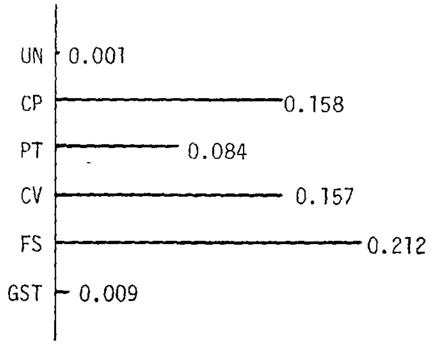
070 - Class "G" Asphalt Concrete/Pliopave



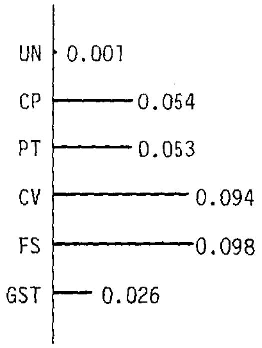
121 - Class "B" Asphalt Concrete



090 - Class "G" Asphalt Concrete



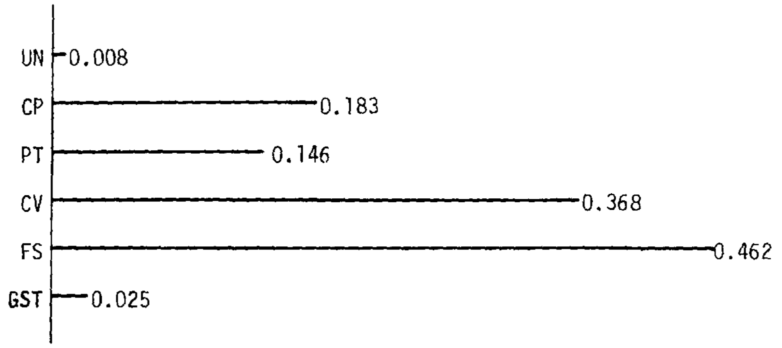
080 - Class "G" A.E.E. Concrete



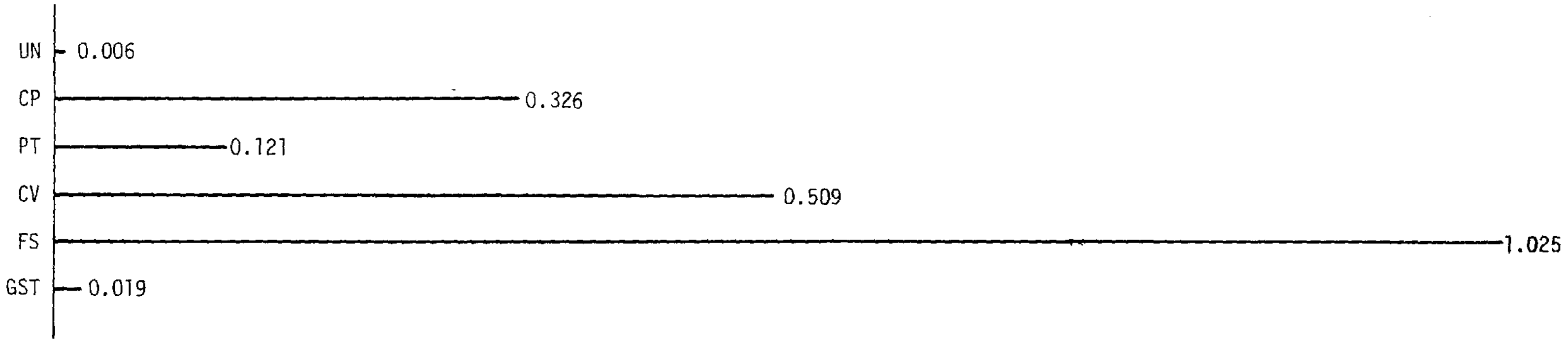
123 - Mastic Asphalt

	ASP (in)	ATS (mph)
UN	---	18.0
CP	.020	18.4
PT	.017	21.7
CV	.030	21.3
FS	.029	22.2
GST	---	22.5

AWR - Average Wear Rate - in/10^6 w.a.
ASP - Average Stud Protrusion - in.
ATS - Average Tire Speed - mph

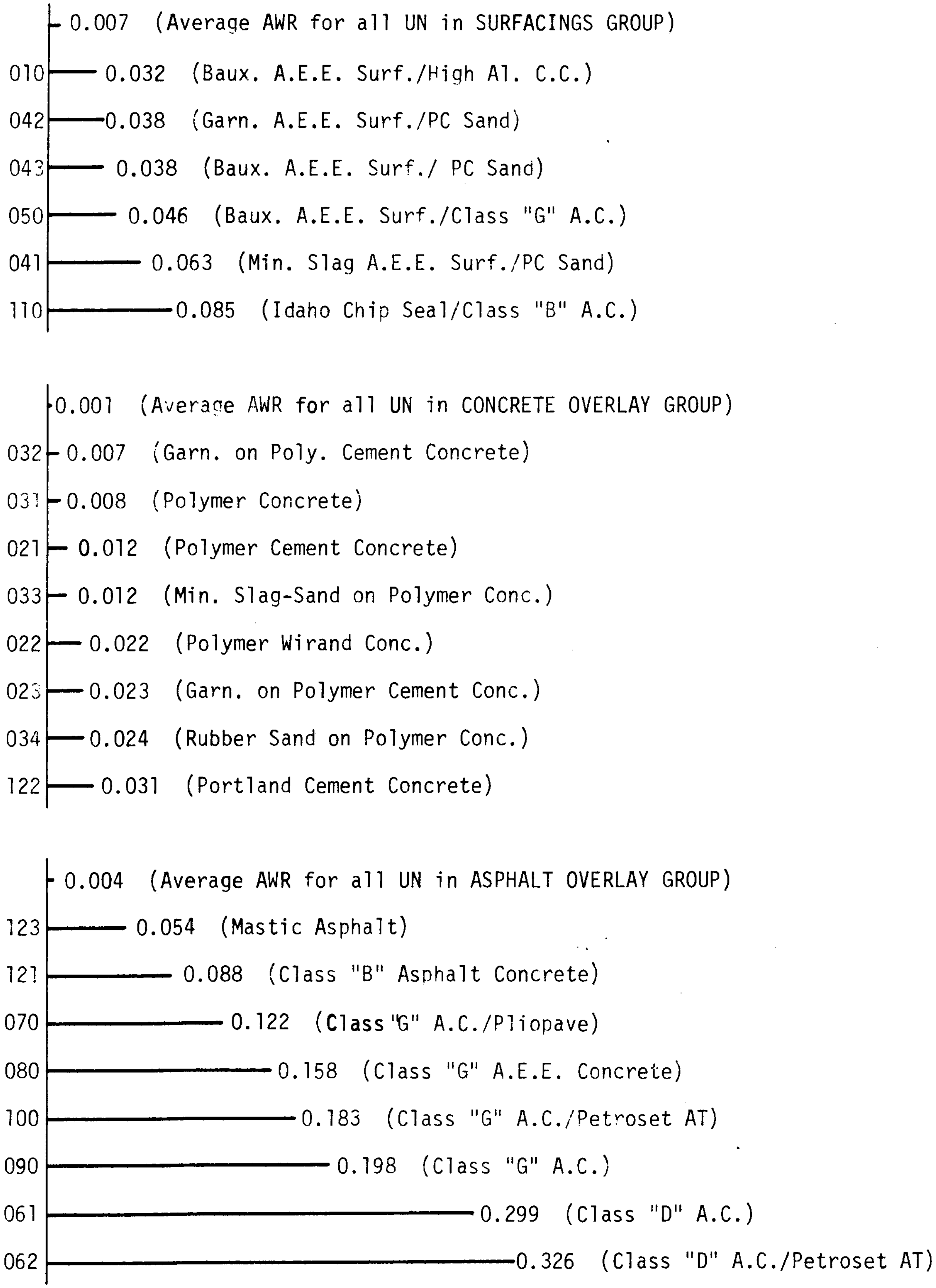


100 - Class "G" Asphalt Concrete/Petroset AT



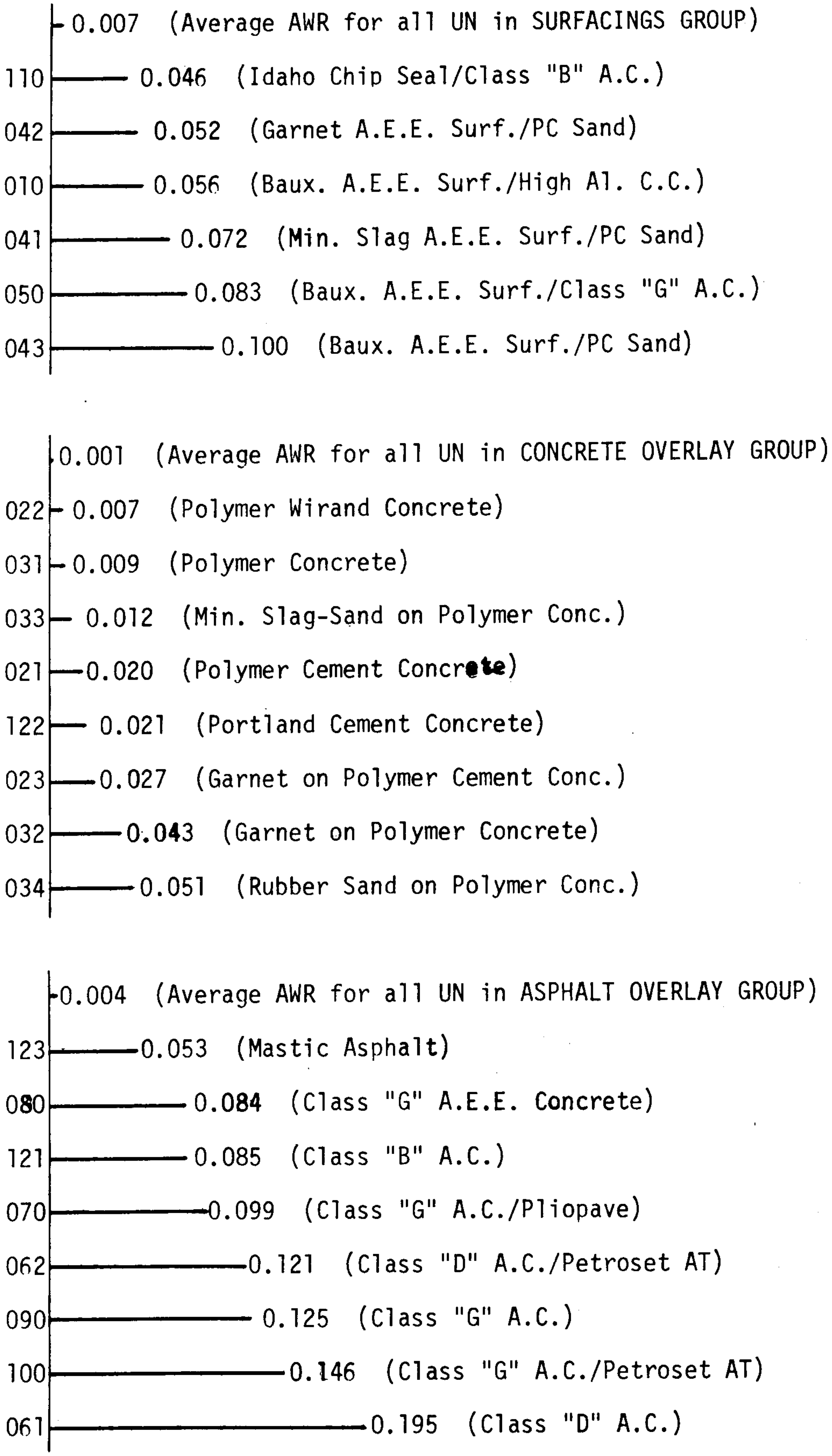
062 - Class "D" Asphalt Concrete/Petroset AT

FIGURE 13: AWR*Values Determined for the Controlled Protrusion Stud from Ring No. 6 Data.



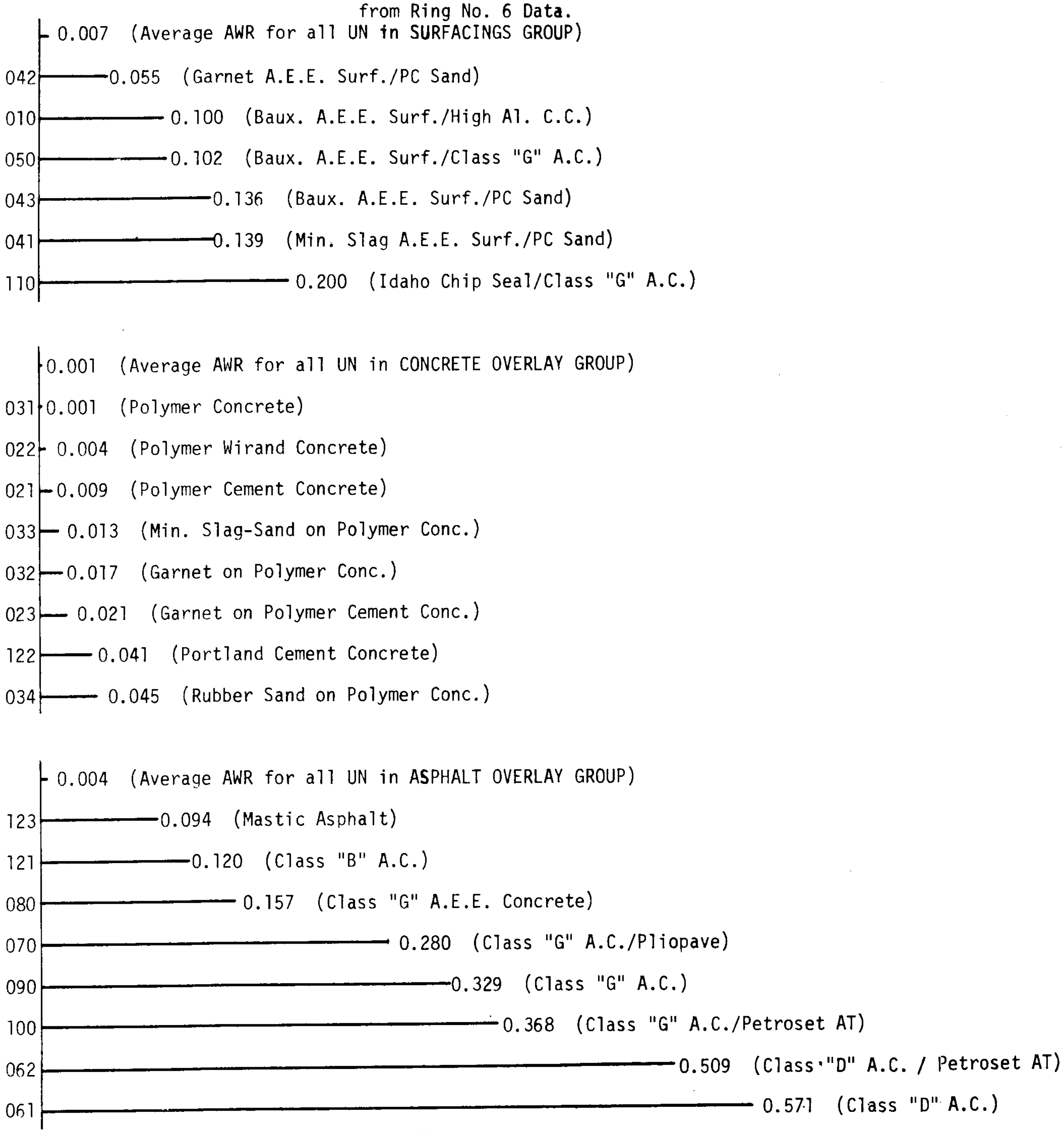
*AWR - Average Wear Rate - in/10^6 w.a.

FIGURE 14: AWR* Values Determined for the Perma-T Gripper Stud from Ring No. 6 Data.



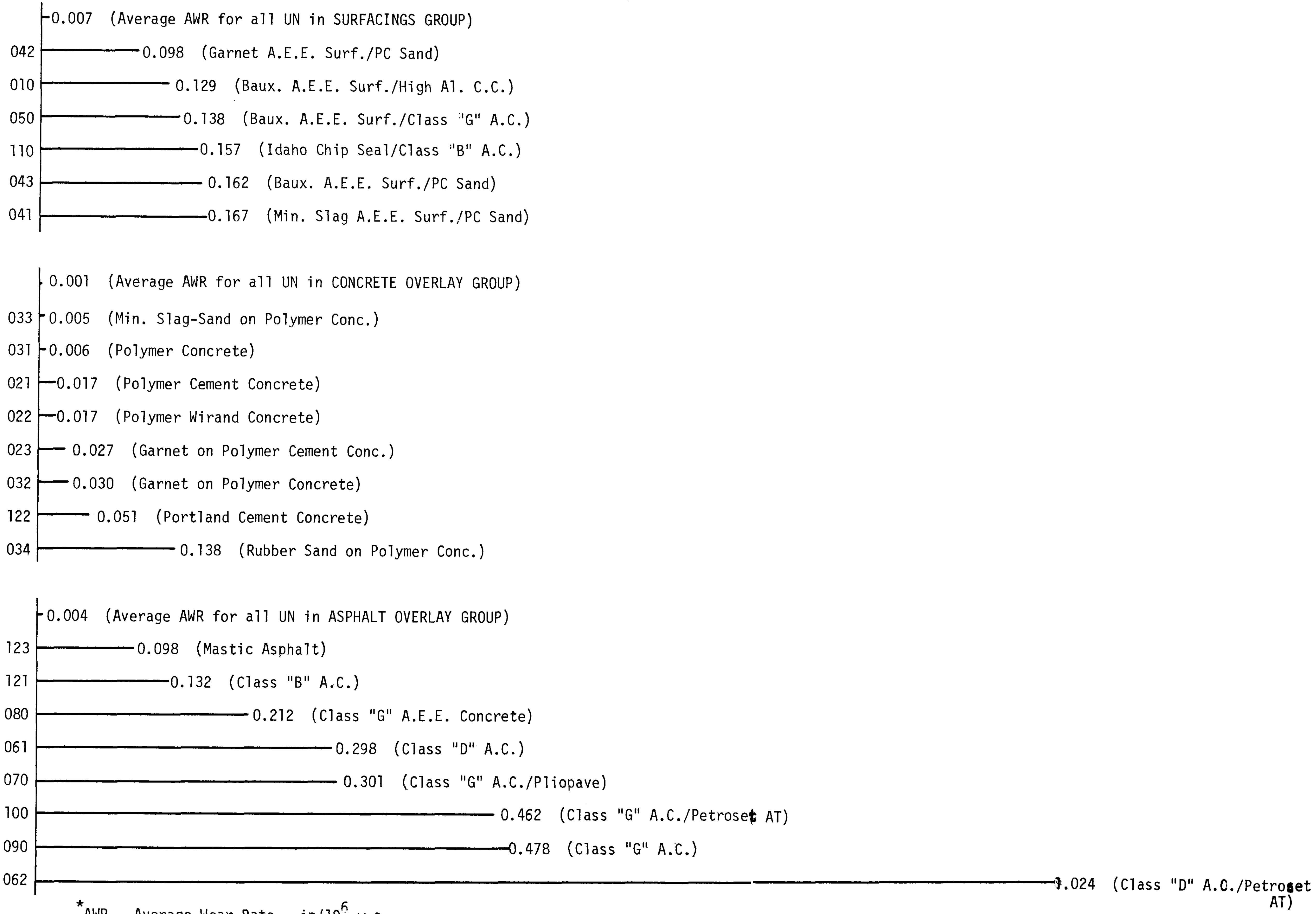
*AWR - Average Wear Rate - in/10^6 w.a.

FIGURE 15: AWR* Values Determined for the Conventional Stud from Ring No. 6 Data.



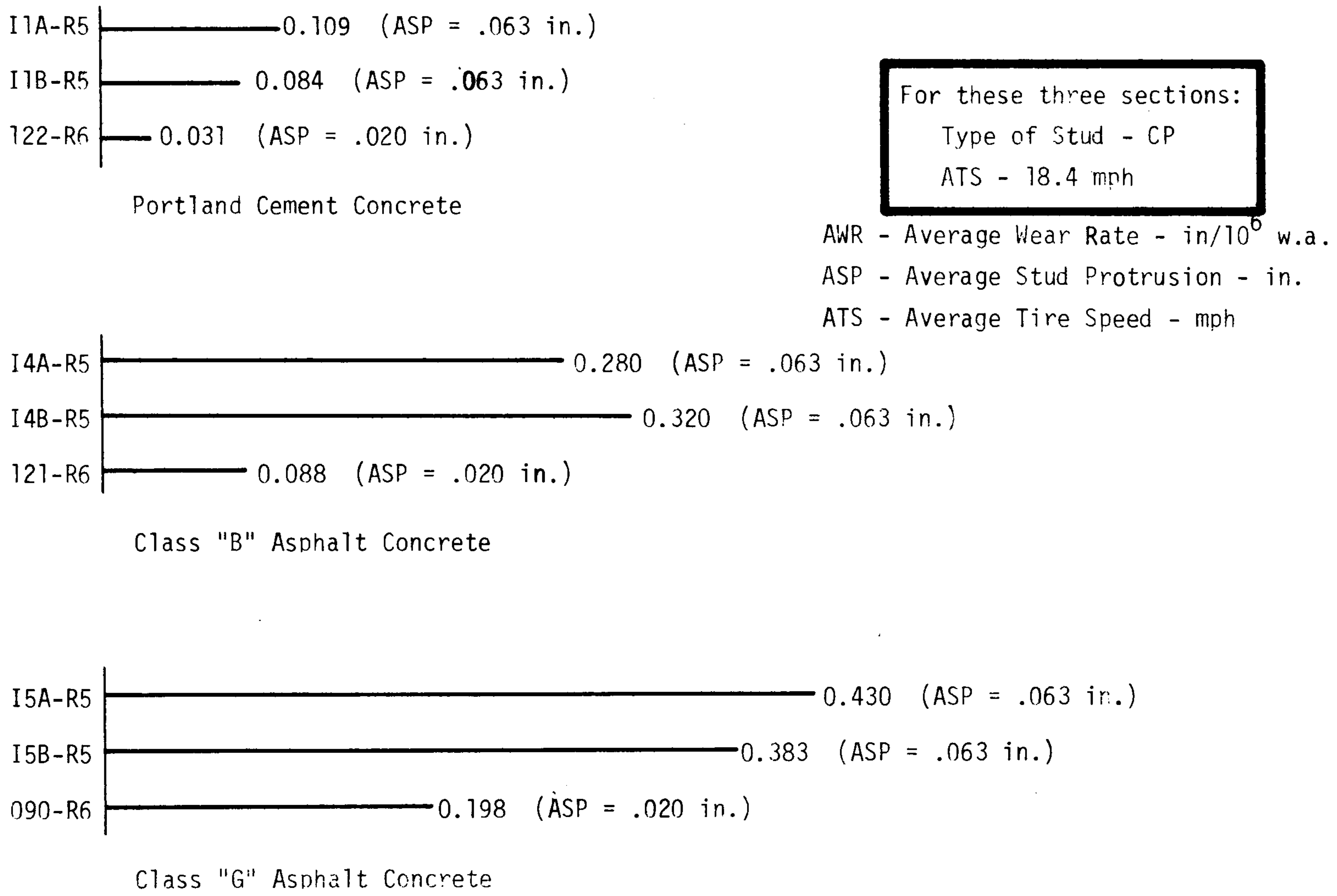
*AWR - Average Wear Rate - in/10^6 w.a.

FIGURE 16: AWR* Values Determined for the Finnish Stud from Ring No. 6 Data.



*AWR - Average Wear Rate - in/10^6 w.a.

FIGURE 17: Comparison of AWR Values on Similar Materials for Tires Moving at the Same Speed with the Same Type of Stud but with Different Stud Protrusion Lengths.



For these three sections:

Type of Stud - CP

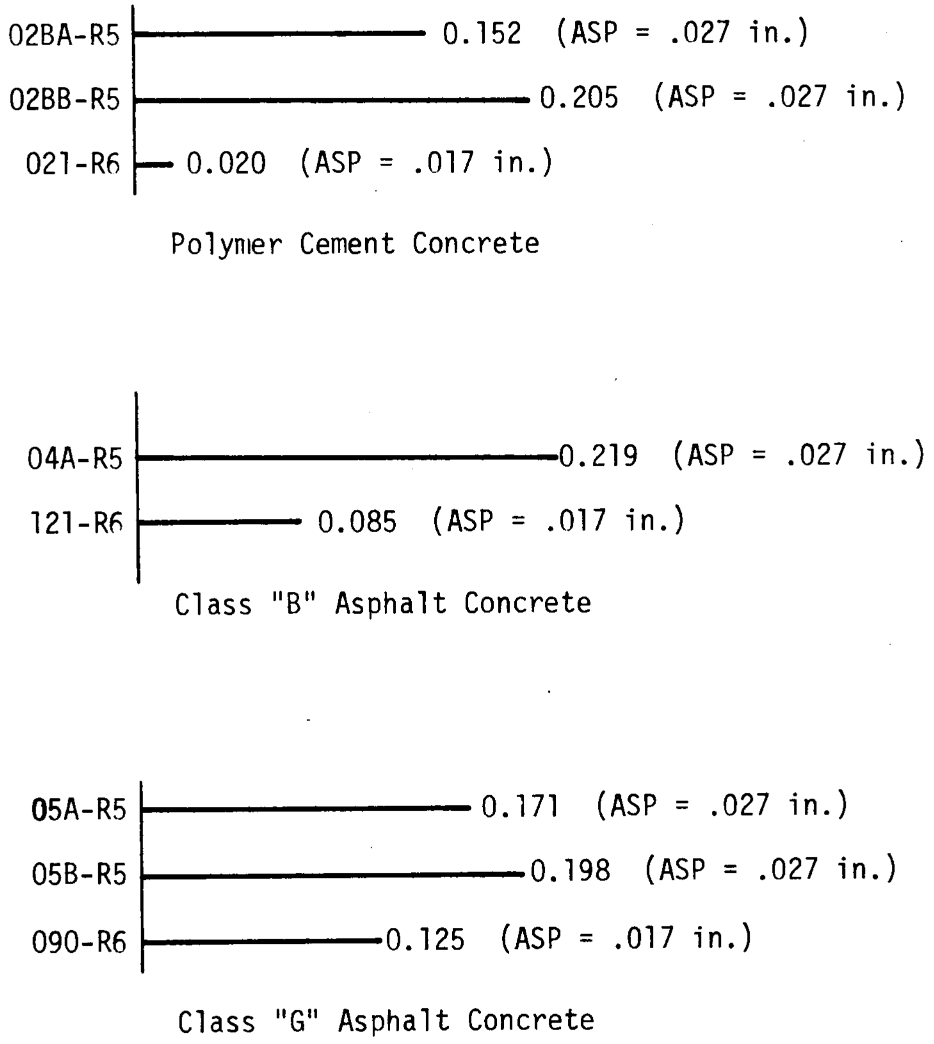
ATS - 18.4 mph

AWR - Average Wear Rate - in/10^6 w.a.

ASP - Average Stud Protrusion - in.

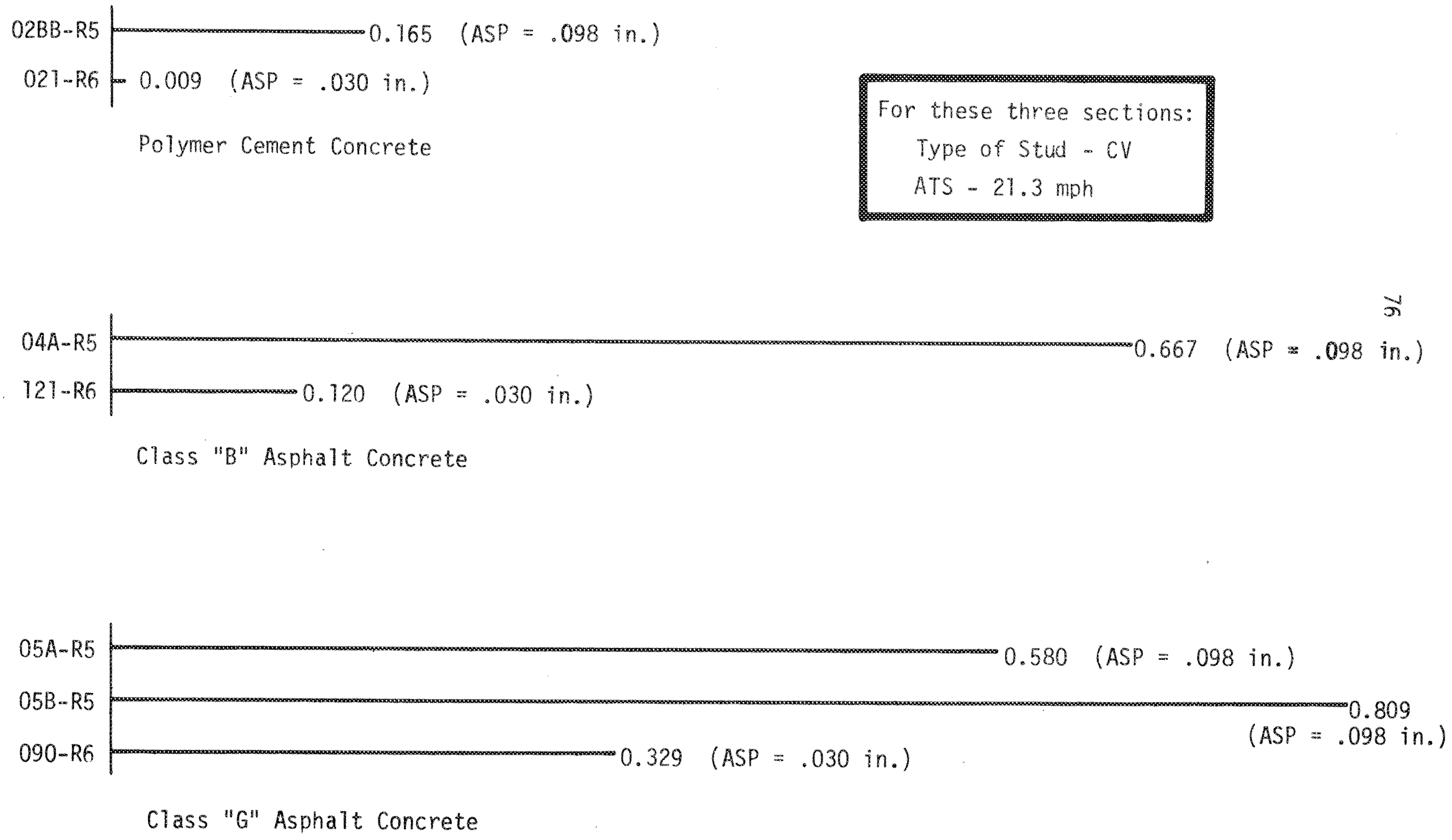
ATS - Average Tire Speed - mph

FIGURE 17: (Cont.)



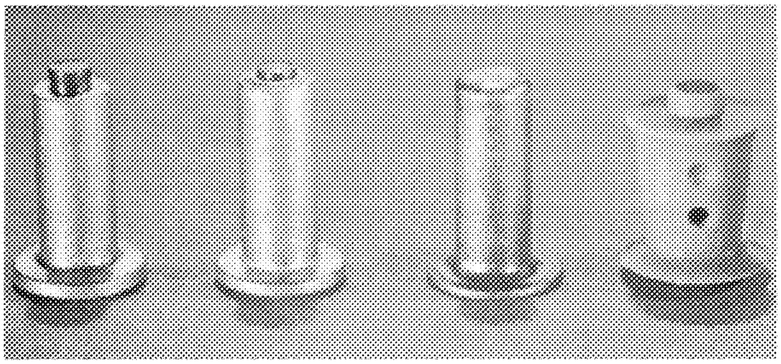
For these three sections:
Type of Stud - PT
ATS - 21.7 mph

FIGURE 17: (Cont.)

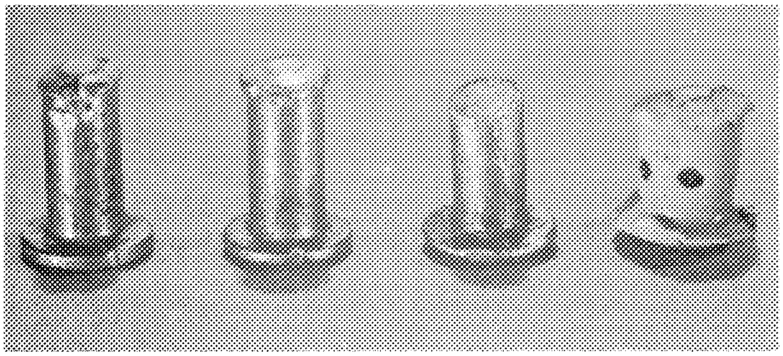


For these three sections:
Type of Stud - CV
ATS - 21.3 mph

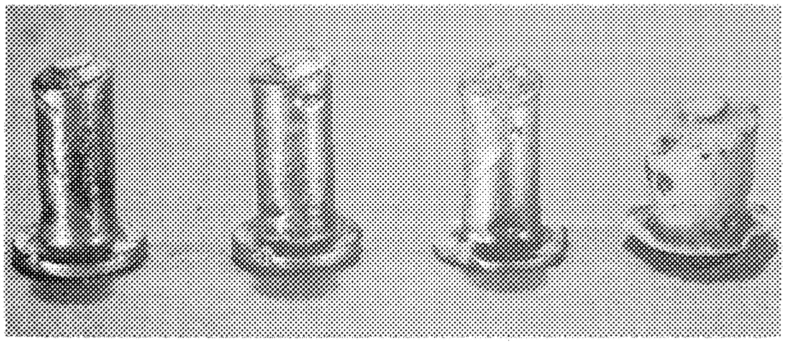
FIGURE 18: Appearance of Studs before, during and after the test.



Tire stud appearance before the test.



Tire stud appearance after 300,000 w.a.



Tire stud appearance after 417,102 w.a.

TABLE 7

SKID RESISTANCE RESULTS DEVELOPED FROM DATA OBTAINED BY THE USE OF THE CALIFORNIA SKID TESTER

Ring No. 5

A) Outside Track

	U N*		C P*		P T*		C V*	
SECTION	ASNR[1]	CSRN[2]	ASNR	CSRN	ASNR	CSRN	ASNR	CSRN
01BA	-35	4	- 9	32	-15	24	-22	18
01BB	-38	- 1	- 3	36	-12	20	-12	24
01BC	-44	- 6	-13	24	-22	13	-26	11
01BD	-43	- 2	-20	18	-17	21	-15	26
02AA	-36	5	-20	22	-28	12	-10	28
02AB	-37	6	-14	27	-19	21	-20	21
02AC	-37	8	-16	22	-25	13	-24	16
02BA	-29	7	-30	0	-19	10	-36	3
02BB	-18	16	-26	0	-30	- 3	-29	0
03A	-34	3	-29	8	-23	9	-18	19
03B	-22	12	- 3	27	-25	9	- 8	26
04A	-27	6	-29	8	-35	0	-22	11
04B	+11	33	+28	50	+ 9	34	+18	45
05A	-13	23	0	35	-13	21	+ 8	42
05B	-13	22	- 2	35	- 7	30	- 6	27
06A	--	--	--	--	--	--	--	--
06B	--	--	--	--	--	--	--	--

[1] ASNR = Average rate of change in the California Skid Resistance value per million wheel applications.

[2] CSRN = California Skid Resistance Number obtained from the regression line evaluated at one million wheel applications.

* See Table 6 for Stud Type.

TABLE 7: (Cont.)

Ring No. 5

B) Center Track

	U N		C V	
SECTION	ASNR	CSRN	ASNR	CSRN
C1A	- 9	37	-17	18
C1B	- 7	33	-15	18
C2A	- 9	35	-18	18
C2B	- 9	27	-15	17
C3A	- 7	29	-13	16
C3B	-11	32	-16	17
C4A	- 4	36	-15	18
C4B	- 2	38	-15	17
C5A	-11	22	-12	16
C5B	+ 1	30	-10	15
C6A	- 6	38	-12	17
C6B	-10	32	-11	17

TABLE 7: (Cont.)

Ring No. 5

C) Inside Track

	C P		U N	
SECTION	ASNR	CSRN	ASNR	CSRN
I1A	-13	24	-11	29
I1B	-10	22	- 8	32
I2AA	- 8	19	- 3	32
I2AB	- 5	16	- 2	22
I2BA	- 4	16	+ 4	29
I2BB	- 5	16	- 3	23
I3A	- 9	22	- 5	29
I3B	-10	25	- 7	29
I4A	- 7	26	- 7	30
I4B	-12	24	-12	29
I5A	- 4	30	- 4	29
I5B	- 6	31	-11	33
I6A	--	--	--	--
I6B	--	--	--	--

TABLE 8: SKID RESISTANCE RESULTS DEVELOPED FROM DATA OBTAINED BY THE USE OF THE CALIFORNIA SKID TESTER

Ring No. 6

	G S T*			F S*			P T*			C V*			C P*			U N*	
SECTION	ASNR[1]	CSRN[2]	AWR[3]	ASNR	CSRN	AWR	ASNR	CSRN	AWR	ASNR	CSRN	AWR	ASNR	CSRN	AWR	ASNR	CSRN	AWR
010	-10	36	.014	-43	0	.129	-43	- 1	.056	-43	- 2	.100	-16	22	.032	- 3	45	.001
021	-29	2	.001	-18	6	.017	-25	2	.020	-19	5	.009	- 5	17	.012	- 7	27	.001
022	-33	3	.007	-27	1	.017	-26	1	.007	-20	5	.004	- 6	16	.022	- 6	27	.001
023	-18	15	.015	-20	8	.027	-20	6	.027	-11	11	.021	- 5	17	.023	- 5	34	.001
031	-14	8	.001	- 6	12	.006	-12	8	.009	-10	9	.001	- 4	16	.008	- 5	22	.002
032	-21	13	.001	-26	2	.030	-22	5	.043	-21	4	.017	- 6	17	.007	- 1	33	.001
033	-21	5	.001	-15	6	.005	-24	1	.012	-20	4	.013	- 8	17	.012	- 7	28	.001
034	-19	14	.011	-16	14	.137	-25	6	.051	-16	13	.045	- 8	20	.024	- 3	27	.001
041	-32	15	.017	-66	-27	.167	-71	-34	.072	-69	-31	.139	-22	13	.063	- 1	42	.001
042	-28	14	.001	-32	- 1	.098	-22	6	.052	-17	10	.055	-20	13	.038	- 4	39	.006
043	-14	-35	.023	-42	- 4	.162	-45	- 7	.100	-36	1	.136	-15	21	.038	- 5	44	.004
050	- 9	40	.042	-47	- 6	.138	-46	- 3	.083	-35	3	.102	-15	22	.046	- 6	44	.008
061	-20	20	.081	-25	17	.298	-32	7	.195	-33	10	.571	-13	28	.299	- 2	32	.001
062	-18	21	.019	-29	13	1.025	-37	3	.121	-35	10	.509	-13	23	.326	- 5	32	.006
070	-21	19	.027	-38	2	.301	-40	- 4	.099	-37	2	.280	-14	24	.122	- 7	36	.008
080	-10	23	.009	-30	3	.212	-28	3	.084	-28	4	.157	-12	22	.158	- 2	33	.001
090	-27	13	.033	-42	2	.478	-35	2	.125	-30	7	.329	-14	24	.198	- 8	32	.002
100	-26	13	.025	-42	0	.462	-51	15	.146	-41	- 2	.368	-12	21	.183	- 6	31	.008
110	-26	12	.001	-37	2	.157	-38	- 2	.046	-39	0	.200	-10	20	.085	- 7	31	.022
121	-12	23	.010	-36	- 3	.132	-37	- 4	.085	-32	1	.120	- 8	19	.088	- 4	28	.008
123	-30	10	.026	-39	- 3	.098	-36	- 4	.053	-32	0	.094	-12	20	.054	- 8	36	.001
122	-39	4	.007	-51	-16	.051	-54	-19	.021	-51	-17	.041	-10	18	.031	- 5	36	.001

[1] ASNR - Average rate of change in the Skid Resistance value per million wheel applications

[2] CSRN - California Skid Resistance Number obtained from the regression line evaluated at one million wheel applications

[3] AWR - Average wear rate

*See Table 6 for Stud Type.

TABLE 9

SKID RESISTANCE RESULTS DEVELOPED FROM DATA OBTAINED BY THE USE OF THE BRITISH PORTABLE SKID TESTER

Ring No. 6

	G S T*		F S*		P T*		C V*		C P*		U N*	
SECTION	ASNR[1]	BSRN[2]	ASNR	BSRN	ASNR	BSRN	ASNR	BSRN	ASNR	BSRN	ASNR	BSRN
010	-34	55	- 7	52	-15	48	-21	42	- 6	47	-13	78
021	-24	28	- 9	36	+ 2	45	-17	30	- 8	40	- 9	54
022	-14	40	- 2	48	-11	38	-19	36	- 6	51	- 9	53
023	-16	42	+16	66	+17	70	-12	49	- 1	57	- 7	57
031	- 6	32	+34	60	+30	57	+ 9	42	- 8	34	-11	40
032	-33	33	+ 2	48	+13	58	-14	33	- 6	44	-10	55
033	-24	13	+14	43	+10	43	- 1	37	- 5	38	- 8	46
034	-21	41	+15	69	+ 3	59	- 3	57	- 9	54	-11	55
041	-54	6	-66	- 2	-74	- 6	-132	-55	-16	47	-12	45
042	-37	37	-27	30	-29	30	-57	11	- 5	46	-12	61
043	-51	40	-21	42	-13	50	-35	35	-14	47	-19	80
050	-65	36	-22	44	-30	39	-19	47	-12	48	-16	76
061	-40	27	-24	52	-36	38	-52	31	-13	61	-11	47
062	-43	23	-31	48	-27	46	-39	42	-15	62	-13	50
070	-38	29	-38	38	-22	45	-30	42	-12	56	-16	54
080	-44	28	-14	53	-18	47	-27	51	-17	58	- 7	56
090	-48	24	-34	44	-27	46	-28	47	-11	59	-10	49
100	-48	21	- 9	59	-28	44	-52	29	-13	60	-10	49
110	-37	26	-39	34	-30	40	-30	43	-12	56	-16	53
121	-40	30	-35	35	-27	42	-35	35	-13	54	-11	51
123	-40	32	-18	48	0	60	-30	40	- 8	54	-14	60
122	-36	37	+ 6	47	-18	43	-24	40	-13	50	-16	64

[1] ASNR = Average rate of change in the British Portable Skid Tester Skid Resistance value per million wheel applications.

[2] BSRN = British Portable Skid Tester Skid Resistance Number obtained from the regression line evaluated at one million wheel applications.

TABLE 10

COMPARISON OF WEAR RATES FROM THE MINNESOTA AND WASHINGTON STATE UNIVERSITY TESTS FOR CV STUDS

PAVEMENT TYPE	AVERAGE WEAR RATES - INCHES/10^6 w.a.		
	WASHINGTON STATE UNIVERSITY		MINNESOTA[1]
	PHASE I	PHASE II	
Asphalt Concrete[2] (High Type)	0.667	0.120	0.408
Asphalt Concrete[3] (Regular)	0.695	0.329	0.790
Portland Cement Conc.	0.118[4]	0.041	0.347
Epoxy Mortar	0.165[5]	0.009[6]	0.159

[1] Reference 20.

[2] This assumed to be equivalent to the class "B" asphalt concrete used in the WSU study.

[3] This is assumed to be equivalent to the class "G" asphalt concrete used in the WSU study. (Average value)

[4] This is the wear rate for the 3" Wirand Concrete Section.

[5] This is the wear rate for the 1/8" Polymer Concrete.

[6] This is the wear rate for the Polymer Cement Concrete.

TABLE 11

COMPARISON OF WEAR RATES FROM THE MINNESOTA AND WASHINGTON STATE UNIVERSITY TESTS FOR CP STUDS

PAVEMENT TYPE	AVERAGE WEAR RATES - INCHES/10^6 w.a.		
	WASHINGTON STATE UNIVERSITY		MINNESOTA[1]
	PHASE I	PHASE II	
Asphalt Concrete[2]	0.419	0.088	0.352
Portland Cement Conc.	0.097[3]	0.031	0.180

[1] Reference 21.

[2] This is assumed to be equivalent to the class "B" asphalt concrete used in the WSU study. (Average value)

[3] Average value.

TABLE 12

COMPARISON OF AVERAGE WEAR RATES FROM DIFFERENT TESTS AND AREAS FOR CV STUD ON PORTLAND CEMENT CONCRETE PAVEMENT

	A.W.R. - INCHES/10^6 w.a.	
STUDY	AVERAGE RIDE	DECELERATION
New Jersey[1]		2.50
Maryland[1]	1.20	---
Quebec[1]	1.00	2.60
Ohio[2]	0.06	---
Chevron Research[3]	2.66	---
Minnesota[4]	0.347	---
WSU: Phase I	0.118	---
Phase II	0.041	---

[1] Reference 22.

[2] Reference 28. Calculated from the rut depth data.

[3] Reference 24. This would indicate a low quality concrete.

[4] Reference 20.

TABLE 13

COMPARISON OF AVERAGE WEAR RATES FROM DIFFERENT TESTS AND AREAS FOR CV STUD ON BITUMINOUS CONCRETE PAVEMENT

STUDY		A.W.R. - INCHES/10^6 w.a. AVERAGE RIDE	DECELERATION
Finland and Norway[1]		0.70	---
Germany[1]		1.10	---
Sweden:	Test Track[2]	1.15	---
	Bromma Track[3]	0.60	---
Ohio[4]		0.06	---
Quebec[1]		1.10	3.60
Chevron Research[5]		0.87	---
Minnesota[6]		0.41	---
WSU:	Phase I	0.66	---
	Phase II	0.12	---

[1] Reference 22.

[2] Reference 27.

[3] Reference 31.

[4] Reference 28. These values have been calculated from their rut depth data.

[5] Reference 24.

[6] Reference 20.

Class "G" Asphalt Concrete
Section 090
CP Stud

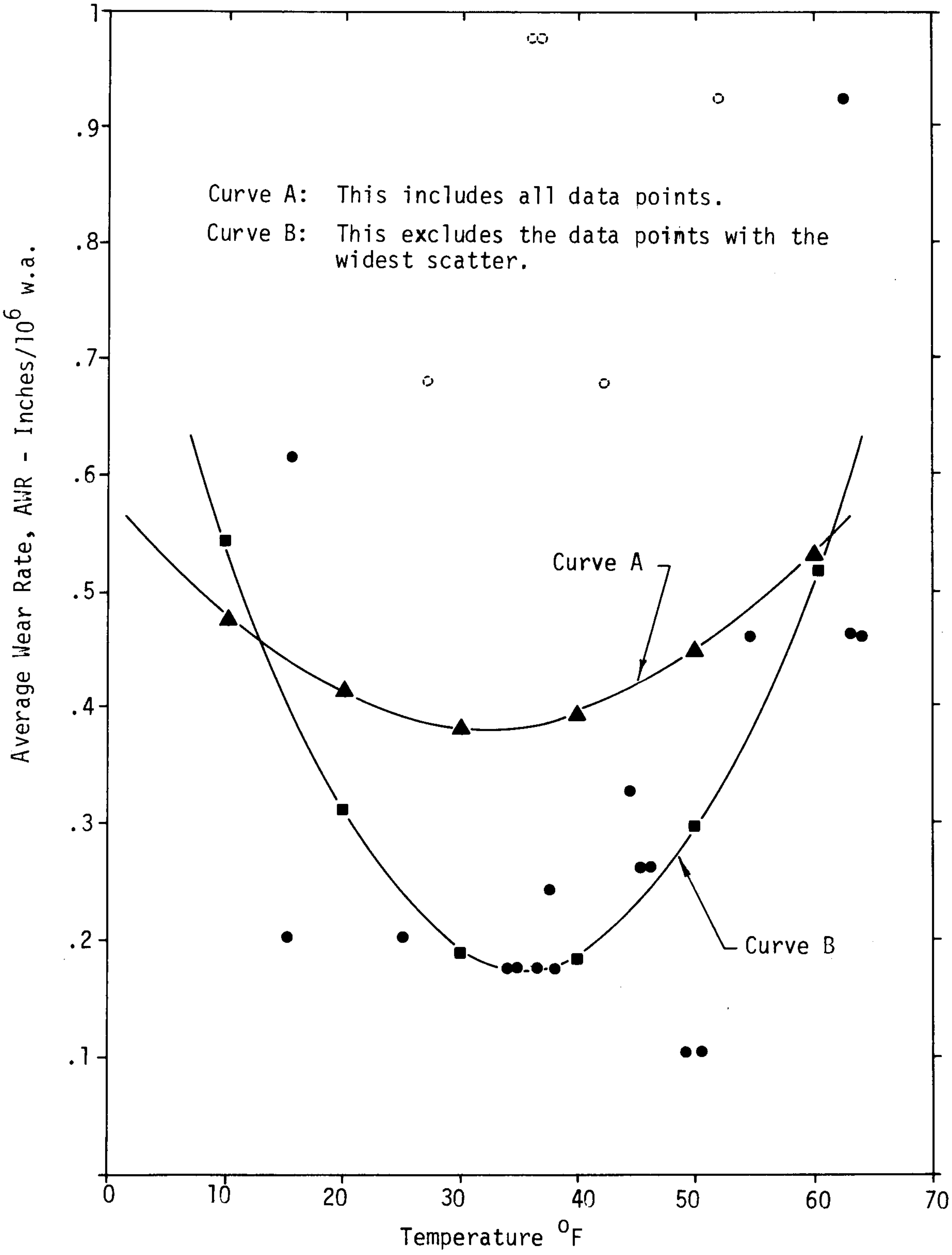


FIGURE 19: Wear Rate versus Pavement Surface Temperature

Portland Cement Concrete
Section 122
CP Stud

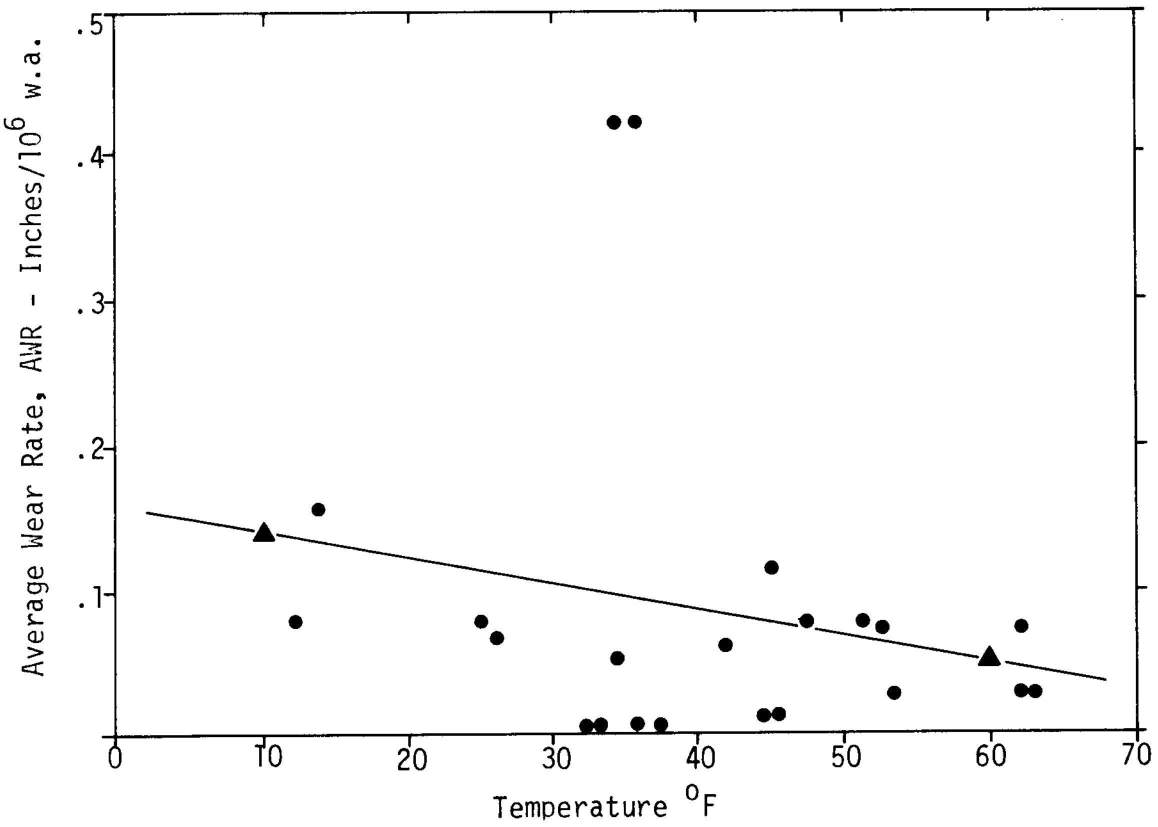


FIGURE 20: Wear Rate versus Pavement Surface Temperature

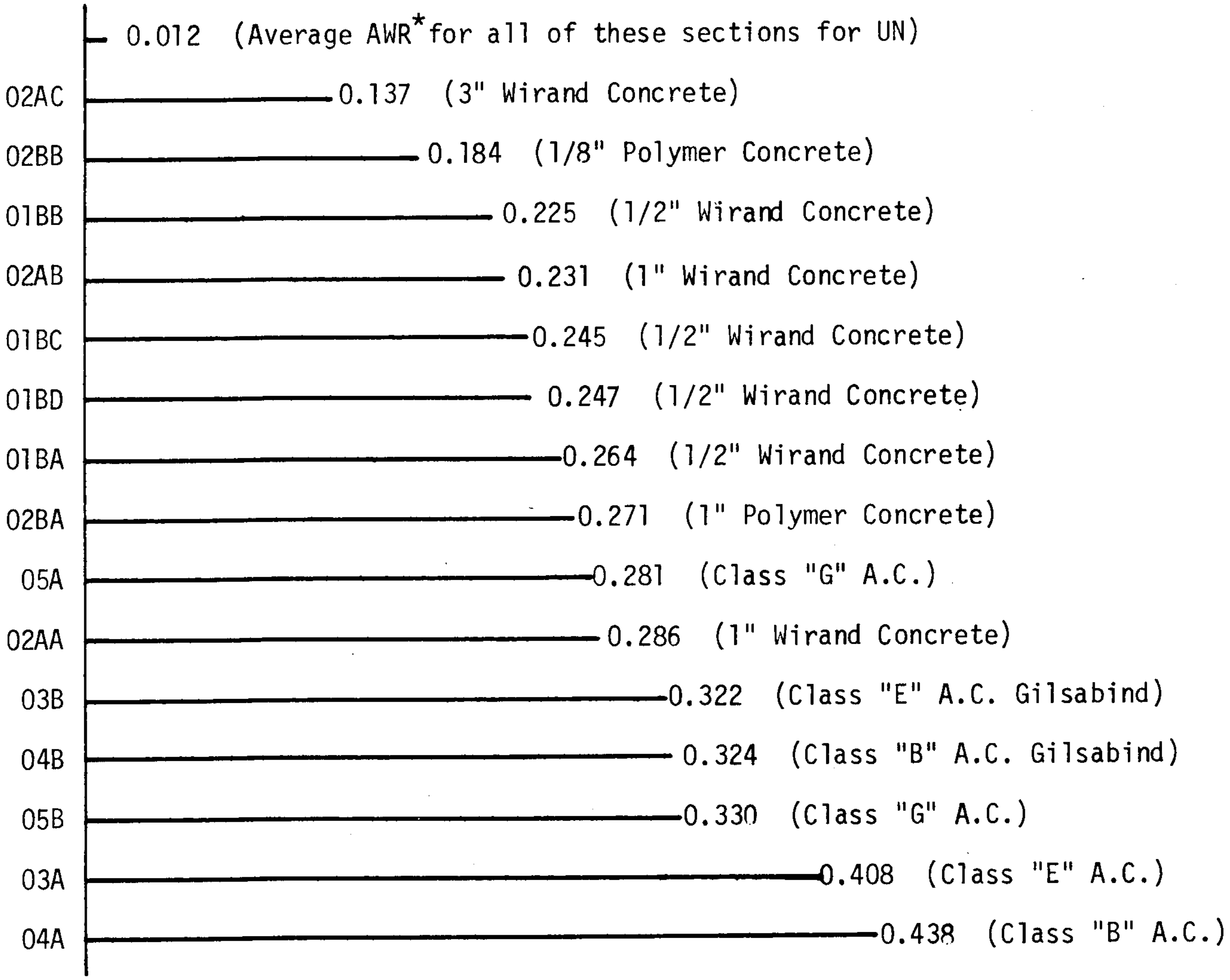
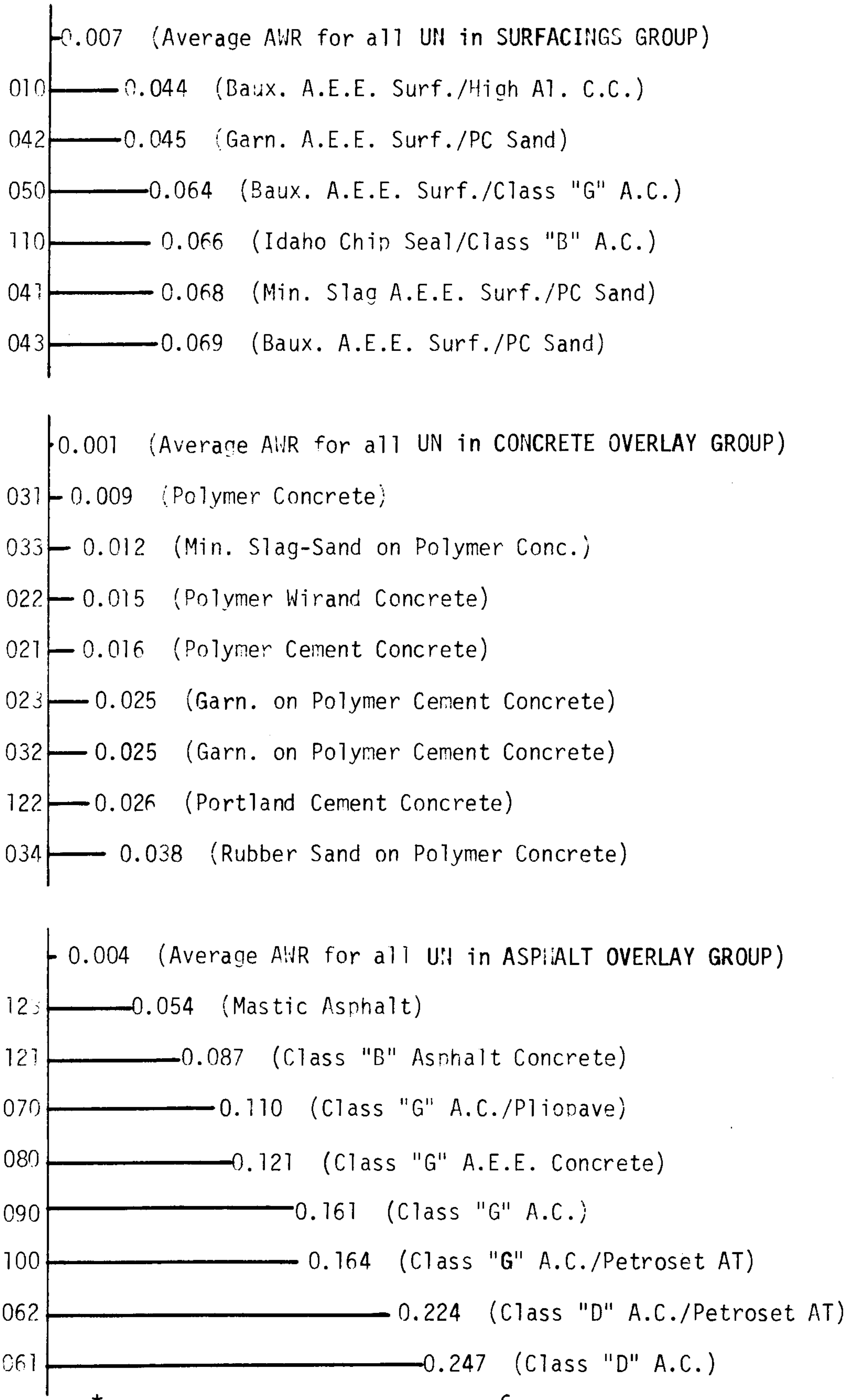


FIGURE **21:** Average AWR* Values Determined for the Combined Action of CP and PT Tire Studs from Ring No. 5 Data.

*AWR - Average Wear Rate - in/10^6 w.a.

FIGURE 22: Average AWR* Values Determined for the Combined Action of CP and PT Tire Studs from Ring No. 6 Data.



*AWR - Average Wear Rate - in/10^6 w.a.

TABLE 14: TYPES OF TRAFFIC STRIPING PAINTS

BRAND OF PAINT	CODE NO.
Prismo Universal[1]	#1
Merkin Mastercraft Heavy Duty Traffic Paint-350 White[2]	#2
Gleem Zone Marking Paint - Instant Dry White[3]	#3
Thermoplastic Striping Tape - Prismo[1]	#4

[1] Manufactured by Prismo Corporation

[2] Merkin Paint Company,
A Division of Baltimore Paint & Chemical Corporation
2325 Hollins Ferry Road
Baltimore, Maryland

[3] Gleem Division
Baltimore Paint and Chemical Corporation

TABLE 15: RANKING OF STRIPES ACCORDING TO WEAR - SECTION 021 - 10,000 w.a.

STRIPE NO.	WHEEL PATHS							
	1	2	3	4	5	6	7	8
	TYPE OF STUDS AND TIRES							
	UN	CP	UST[1]	UST[1]	CV	PT.	FS	GST
1	2	2	2	2	2	2	3	3
2	3	3	3	3	*	4	4	2
3	4	4	4	4	*	3	2	4
4	1	1	1	1	1	1	1	1

*Stripe completely worn off

[1] UST - Unstudded Truck Tire

TABLE 16: RANKING OF STRIPES ACCORDING TO WEAR - SECTION 100 - 10,000 w.a.

STRIPE NO.	WHEEL PATHS							
	1	2	3	4	5	6	7	8
	TYPE OF STUDS AND TIRES							
	UN	CP	UST	UST	CV	PT	FS	GST
1	2	2	4	4	4	4	4	4
2	3	3	3	3	3	3	3	3
3	4	4	2	2	2	2	2	2
4	1	1	1	1	1	1	1	1

TABLE 17: RANKING OF **STRIPES** ACCORDING TO WEAR - SECTION 021 - 25,000 w.a.

STRIPE NO.	WHEEL PATHS							
	1	2	3	4	5	6	7	8
	TYPE OF STUDS AND TIRES							
	UN	CP	UST	UST	CV	PT	FS	GST
1	2	2	2	2	2	2	3	3
2	3	4	3	3	*	4	4	2
3	4	3	4	4	*	3	2	4
4	1	1	1	1	1	1	1	1

*Stripe completely worn off

TABLE 18: RANKING OF STRIPES ACCORDING TO WEAR - SECTION 100 - 25,000 w.a.

STRIPE NO.	WHEEL PATHS							
	1	2	3	4	5	6	7	8
	TYPE OF STUDS AND TIRES							
	UN	CP	UST	UST	CV	PT	FS	GST
1	4	4	4	4	2	2	3	3
2	3	3	2	2	3	4	2	4
3	2	2	3	3	4	3	4	2
4	1	1	1	1	1	1	1	1

TABLE 19: RANKING OF STRIPES ACCORDING TO WEAR - SECTION 021 - 50,000 w.a.

STRIPE NO.	WHEEL PATHS							
	1	2	3	4	5	6	7	8
	TYPES OF STUDS AND TIRES							
	UN	CP	UST	UST	CV	PT	FS	GST
1	2	2	2	2	*	*	*	*
2	3	3	3	3	*	*	*	*
3	4	3	4	4	*	2	2	2
4	1	1	1	1	1	1	1	1

*Stripe completely worn off

TABLE 20: RANKING OF STRIPES ACCORDING TO WEAR - SECTION 100 - 50,000 w.a.

STRIPE NO.	WHEEL PATHS							
	1	2	3	4	5	6	7	8
	TYPES OF STUDS AND TIRES							
	UN	CP	UST	UST	CV	PT	FS	GST
1	4	*	4	4	4	3	3	3
2	3	*	2	2	3	4	4	4
3	2	2	3	3	2	2	2	2
4	1	1	1	1	1	1	1	1

*Stripe completely worn off

TABLE 21: RANKING OF STRIPES ACCORDING TO WEAR - SECTION 021 - 150,000+ w.a.

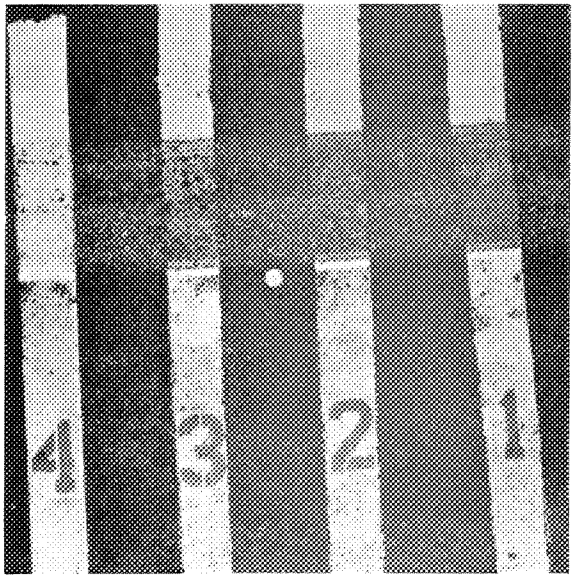
STRIPE NO.	WHEEL PATHS							
	1	2	3	4	5	6	7	8
	TYPE OF STUDS AND TIRES							
	UN	CP	UST	UST	CV	PT	FS	GST
1	3	*	2	2	*	*	*	*
2	2	*	3	3	*	*	*	*
3	4	2	4	4	*	2	*	*
4	1	1	1	1	1	1	1	1

*Stripe completely worn off

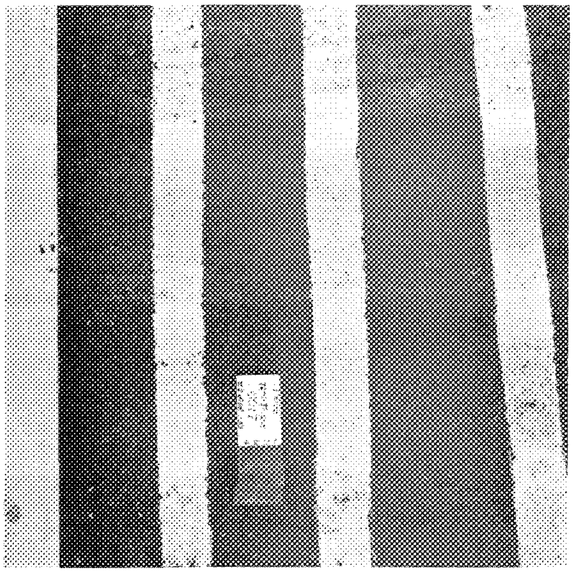
TABLE 22: RANKING OF STRIPES ACCORDING TO WEAR - SECTION 100 - 150,000+ w.a.

STRIPE NO.	WHEEL PATHS							
	1	2	3	4	5	6	7	8
	TYPE OF STUDS AND TIRES							
	UN	CP	UST	UST	CV	PT	FS	GST
1	2	*	4	4	2	2	2	2
2	3	*	3	3	4	4	4	4
3	4	*	2	2	3	3	3	3
4	1	1	1	1	1	1	1	1

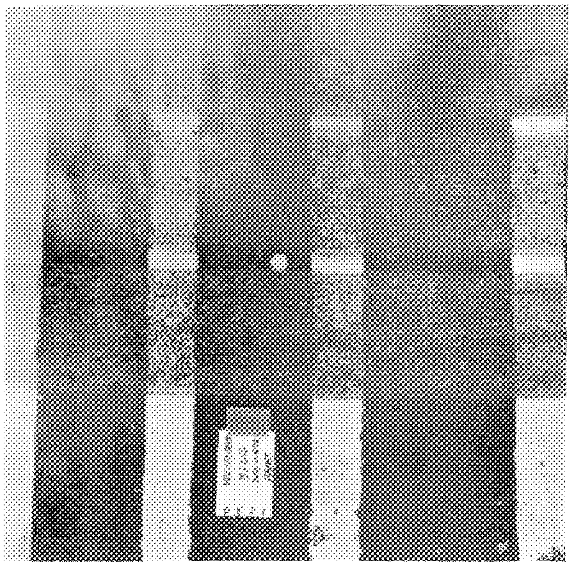
*Stripe completely worn off



(a) 1100 - wheel paths 1 and 2

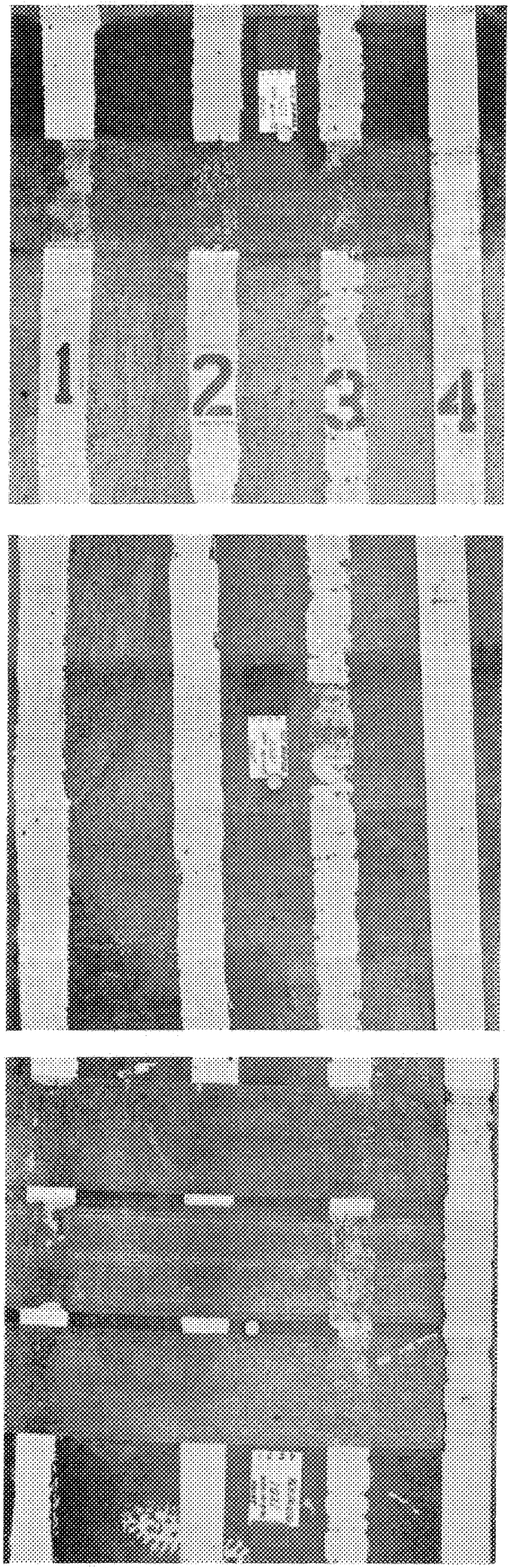


(b) 2100 - wheel paths 3 and 4



(c) 3100 - wheel paths 5 - 8

FIGURE 23: The appearance of the traffic stripesin Section 100 after 50,000 wheel applications.



(a) 1021 - wheel paths 1 and 2

(b) 2021 - wheel paths 3 and 4

(c) 3021 - wheel paths 5 to 8

FIGURE 24: The appearance of the Traffic paints in Section 021 after 50,000 wheel applications.

FIGURE 25: Pavement Wear Displayed by the Use of Plaster Castings of the Wheel Paths. (Typical)

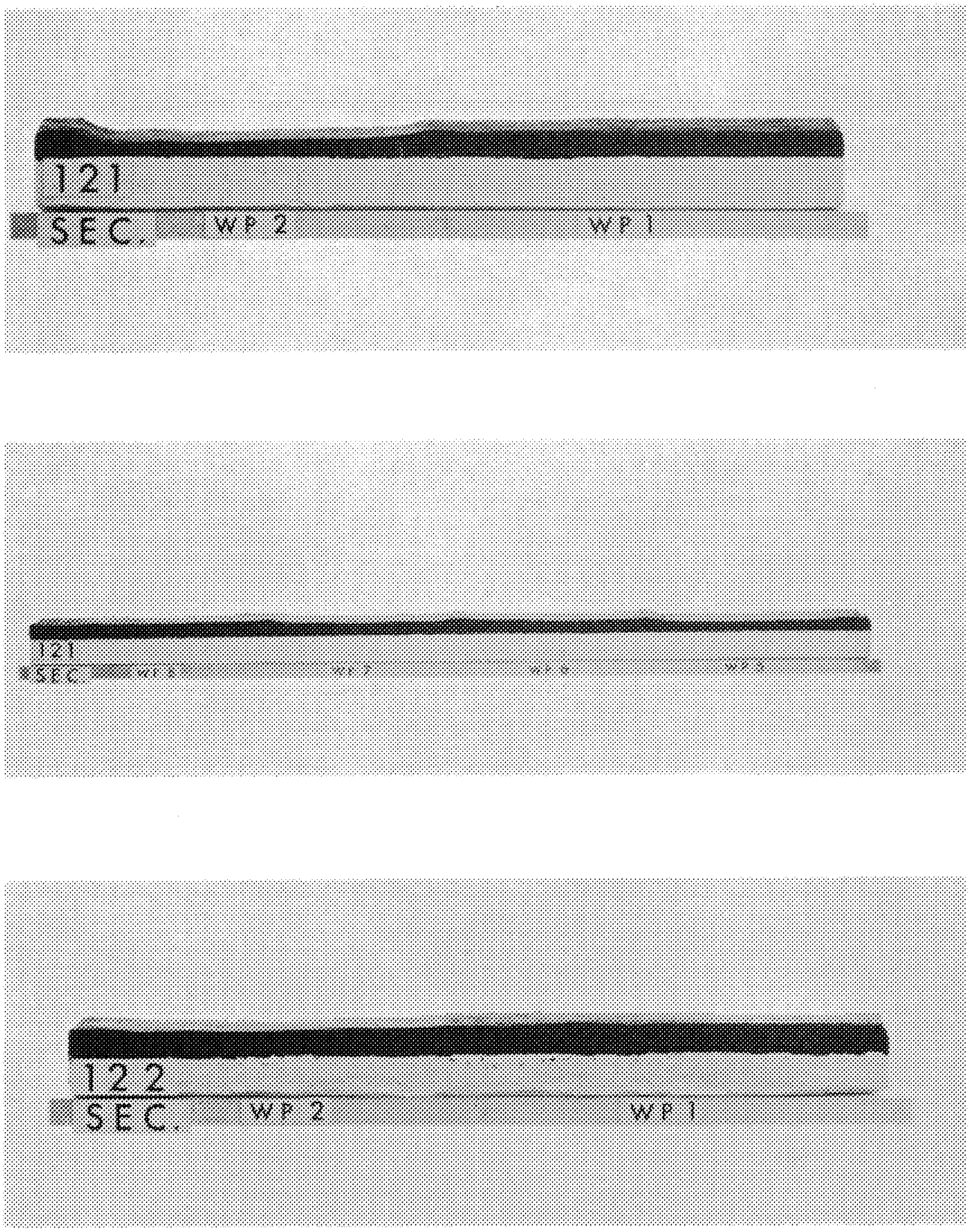
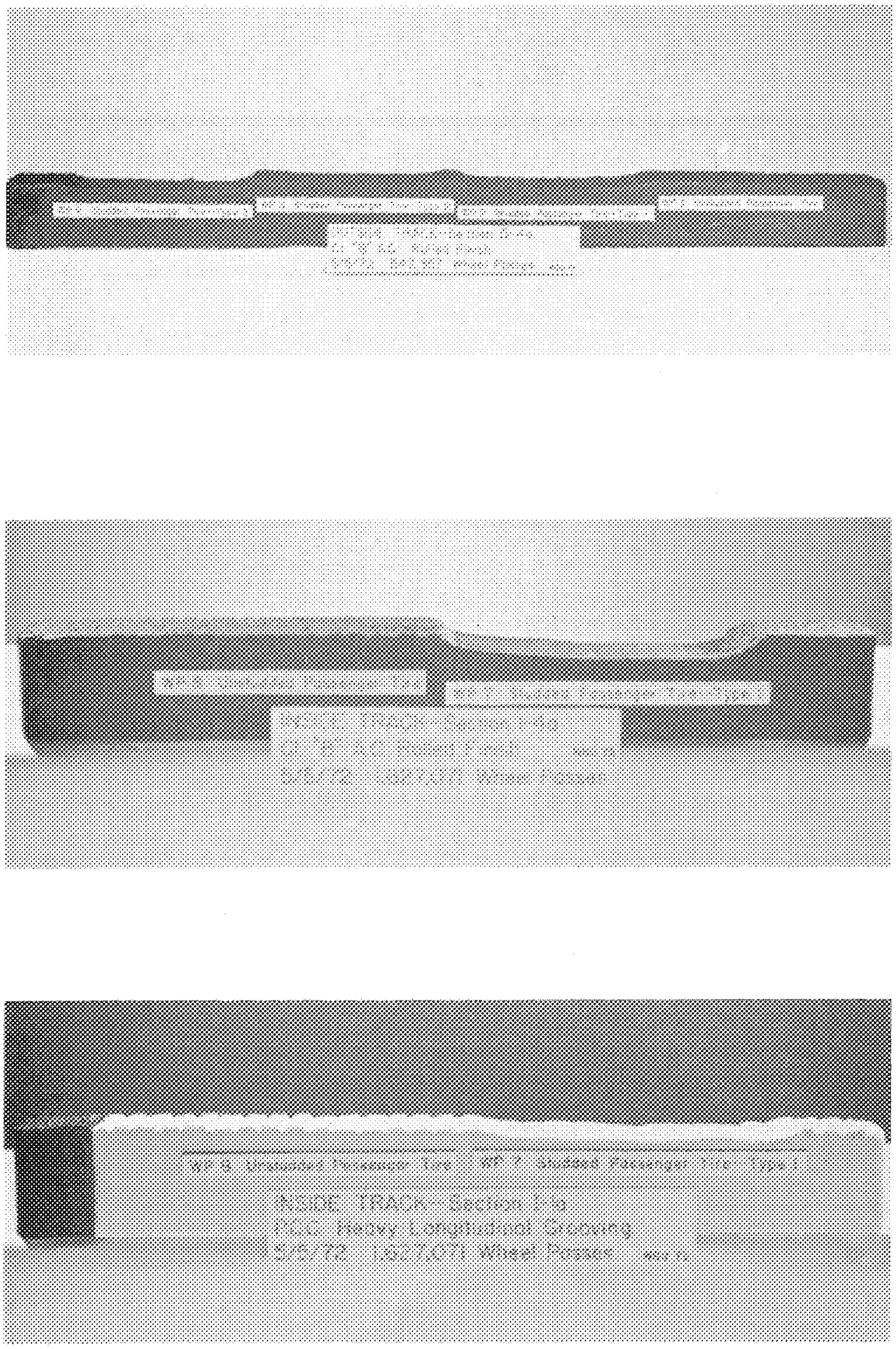


FIGURE 26: Pavement Wear Displayed by the Use of Plaster Castings of the Wheel Paths. (Typical)



APPENDIX A

GENERAL INFORMATION

APPENDIX A

General Information

						Driving Tire		
	$\boxed{1}$*	$\boxed{1}$	$\boxed{1}$	$\boxed{1}$	$\boxed{3}$	$\boxed{3}$	$\boxed{3}$	$\boxed{3}$
Tire Speed:	1.125v	1.110v	1.084v	1.063v	1.026v	1.000v	0.920v	0.900v
	Outside Track Passenger Tires				Center Track Truck Tires		Inside Track Passenger Tires	
Ring No. 5:								
Wheel Path No.	1	2	3	4	5	6	7	8
Type of Stud	UN	CP	PT	CV	UN	CV	CP	UN
Ring No. 6:								
Wheel Path No.	8	7	6	5	4	3	2	1
Type of Stud	GST	FS	PT	CV	UN	UN	CP	UN

Ring No. 5: Outside Track - 20 different pavement sections and 4 wheel paths with one tire running in each wheel path

Center Track - 12 sections and 2 wheel paths with three tires running in each wheel path

Inside Track - 14 sections and 2 wheel paths with three tires running in each wheel path

Ring No. 6: Twenty-two sections in each track with the same number of wheel paths and tires as indicated for Ring No. 5

*The number in the boxes indicates the number of tires running in the wheel path.

NOTE: The base reference speed, v, is the speed of the driving tire. This base speed for most of the testing period was 20 mph.

APPENDIX B

TYPICAL COMPUTER DATA OUTPUT SHEETS

```
CLASS G A.C.
 30901
 30902
 30903

  3  SITE AVERAGE OF  SECTION   30900
                                                      WHEEL  PATH

         PASS NO.              5                   6                   7                   8
             129.          0.0                 0.0                 0.0                 0.0
           50000.          0.599781E-01        0.464707E-01        0.916445E-01        0.117078E-01
          100000.          0.978166E-01        0.585290E-01        0.131422E 00        0.174784E-01
          150000.          0.100497E 00        0.647086E-01        0.140770E 00        0.112984E-01
          250000.          0.113574E 00        0.682486E-01        0.162615E 00        0.140597E-01
          300000.          0.113310E 00        0.715633E-01        0.170676E 00        0.892755E-02
          350000.          0.154187E 00        0.797096E-01        0.239214E 00        0.170127E-01
          400000.          0.182395E 00        0.819892E-01        0.295558E 00        0.224531E-01
          500000.          0.211722E 00        0.871264E-01        0.320917E 00        0.196483E-01
          556838.          0.203812E 00        0.883698E-01        0.308386E 00        0.184583E-01
          717102.          0.270054E 00        0.126722E 00        0.365082E 00        0.363638E-01
WHEEL PATH    8

      X              X2              X3              X4              X2Y             XY              Y              Y2
 0.337407E 07   0.154430E 13   0.820417E 18   0.476305E 24   0.371520E 11   0.713359E 05   0.177408E 00   0.369026E-02

   LEAST SQUARES LINE           Y =   0.593960E-02 +  0.332158E-07 X ±  0.108945E-01

   LEAST SQUARES PARABOLA       Y =   0.806249E-02 +  0.120904E-07 X +  0.310346E-13 X2 ±  0.110553E-01
WHEEL PATH    7

      X              X2              X3              X4              X2Y             XY              Y              Y2
 0.337407E 07   0.154430E 13   0.820417E 18   0.476305E 24   0.470293E 12   0.926275E 06   0.222528E 01   0.576535E 00

   LEAST SQUARES LINE           Y =   0.555407E-01 +  0.478453E-06 X ±  0.658705E-01

   LEAST SQUARES PARABOLA       Y =   0.322068E-01 +  0.710655E-06 X + -0.341120E-12 X2 ±  0.592890E-01
WHEEL PATH    6

      X              X2              X3              X4              X2Y             XY              Y              Y2
 0.337407E 07   0.154430E 13   0.820417E 18   0.476305E 24   0.150093E 12   0.300751E 06   0.773437E 00   0.640860E-01

   LEAST SQUARES LINE           Y =   0.320660E-01 +  0.124689E-06 X ±  0.281633E-01

   LEAST SQUARES PARABOLA       Y =   0.270454E-01 +  0.174653E-06 X + -0.734012E-13 X2 ±  0.287925E-01
WHEEL PATH    5

      X              X2              X3              X4              X2Y             XY              Y              Y2
 0.337407E 07   0.154430E 13   0.820417E 18   0.476305E 24   0.323754E 12   0.630173E 06   0.150735E 01   0.265340E 00

   LEAST SQUARES LINE           Y =   0.359720E-01 +  0.329469E-06 X ±  0.394126E-01
   LEAST SQUARES PARABOLA       Y =   0.298553E-01 +  0.390342E-06 X + -0.894268E-13 X2 ±  0.406639E-01
```

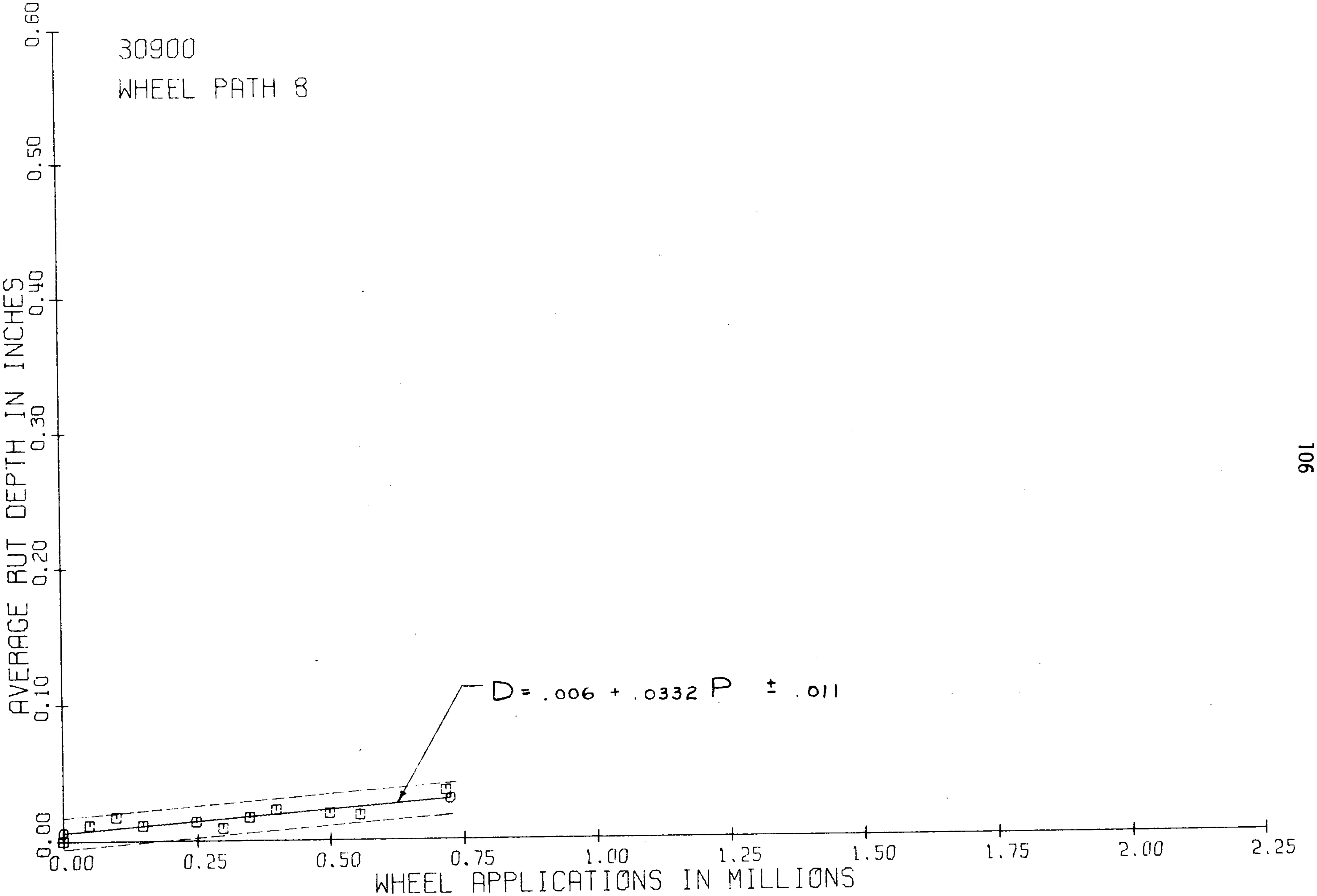
```
CLASS G A.C.
 10901
 10902
 10903

  3  SITE AVERAGE OF  SECTION  1090
                                                         WHEEL PATH

         PASS NO.               1                    2
             387.             0.0                  0.0
           75000.             0.821161E-03         0.725971E-01
          150000.             0.287194E-02         0.103253E 00
          300000.             0.550091E-02         0.213756E 00
          450000.             0.356199E-02         0.251312E 00
          750000.            -0.934135E-03         0.300145E 00
          900000.            -0.543768E-02         0.324187E 00
         1050000.            -0.100792E-02         0.359034E 00
         1200000.             0.318758E-02         0.413375E 00
         1500000.            -0.732903E-03         0.442766E 00
         2151306.             0.115748E-01         0.409056E 00
WHEEL  PATH    2

       X              X2             X3             X4             X2Y            XY             Y              Y2
  0.852669E 07   0.111137E 14   0.174899E 20   0.307932E 26   0.438476E 13   0.313221E 07   0.288948E 01   0.983117E 00

   LEAST SQUARES LINE          Y =   0.109099E 00 +  0.198130E-06 X ±  0.144982E 00

   LEAST SQUARES PARABOLA      Y =   0.361734E-01 +  0.476056E-06 X + -0.141052E-12 X2 ±  0.546120E-01
WHEEL  PATH    1

       X              X2             X3             X4             X2Y            XY             Y              Y2
  0.852669E 07   0.111137E 14   0.174899E 20   0.307932E 26   0.517550E 11   0.247194E 05   0.194057E-01   0.228001E-03

   LEAST SQUARES LINE          Y =   0.988106E-04 +  0.214841E-08 X ±  0.876801E-02

   LEAST SQUARES PARABOLA      Y =   0.335453E-02 + -0.102595E-07 X +  0.629724E-14 X2 ±  0.673050E-02
```

```
P.C.C.
 31221

  1  SITE AVERAGE OF SECTION  31220
                                                     WHEEL PATH

          PASS NO.            5                   6                   7                   8
             129.         0.0                 0.0                 0.0                 0.0
           25000.         0.363505E-01        0.173373E-01        0.125490E-01        0.172536E-01
           50000.         0.175725E-01        0.423477E-02        0.207108E-01        0.106166E-01
          100000.         0.287025E-01        0.215255E-01        0.342121E-01        0.104735E-01
          150000.         0.273762E-01        0.233061E-01        0.310422E-01        0.903328E-02
          250000.         0.358007E-01        0.187588E-01        0.208097E-01        0.101666E-01
          300000.         0.349284E-01        0.245932E-01        0.340950E-01        0.140146E-01
          350000.         0.337260E-01        0.258833E-01        0.400716E-01        0.141443E-01
          400000.         0.313240E-01        0.107656E-01        0.381127E-01        0.134997E-01
          500000.         0.419879E-01        0.254009E-01        0.494485E-01        0.103839E-01
          556838.         0.341858E-01        0.107269E-01        0.348677E-01        0.128045E-01
          717102.         0.513250E-01        0.308581E-01        0.483573E-01        0.134359E-01
WHEEL PATH   8

      X              X2             X3             X4             X2Y            XY             Y              Y2
 0.339907E 07   0.154493E 13   0.820432E 18   0.476306E 24   0.195876E 11   0.422678E 05   0.134826E 00   0.171900E-02

   LEAST SQUARES LINE         Y =  0.925148E-02 +  0.700452E-08 X ±  0.838077E-02

   LEAST SQUARES PARABOLA     Y =  0.823768E-02 +  0.185924E-07 X + -0.176207E-13 X2 ±  0.863151E-02
WHEEL PATH   7

      X              X2             X3             X4             X2Y            XY             Y              Y2
 0.339907E 07   0.154493E 13   0.820432E 18   0.476306E 24   0.645167E 11   0.132945E 06   0.364276E 00   0.133737E-01

   LEAST SQUARES LINE         Y =  0.158747E-01 +  0.511258E-07 X ±  0.178209E-01

   LEAST SQUARES PARABOLA     Y =  0.114919E-01 +  0.101223E-06 X + -0.761776E-13 X2 ±  0.169330E-01
WHEEL PATH   6

      X              X2             X3             X4             X2Y            XY             Y              Y2
 0.339907E 07   0.154493E 13   0.820432E 18   0.476306E 24   0.345847E 11   0.725286E 05   0.213390E 00   0.478009E-02

   LEAST SQUARES LINE         Y =  0.119023E-01 +  0.207596E-07 X ±  0.171417E-01

   LEAST SQUARES PARABOLA     Y =  0.100285E-01 +  0.421767E-07 X + -0.325669E-13 X2 ±  0.177313E-01
WHEEL PATH   5

      X              X2             X3             X4             X2Y            XY             Y              Y2
 0.339907E 07   0.154493E 13   0.820432E 18   0.476306E 24   0.629840E 11   0.129361E 06   0.373279E 00   0.133897E-01

   LEAST SQUARES LINE         Y =  0.196095E-01 +  0.405893E-07 X ±  0.181014E-01

   LEAST SQUARES PARABOLA     Y =  0.182367E-01 +  0.562803E-07 X + -0.238597E-13 X2 ±  0.189098E-01
```

```
P.C.C.
 11221

  1  SITE AVERAGE OF  SECTION   11220
                                                        WHEEL  PATH

           PASS NO.                   1                     2
              387.              0.0                   0.0
            75000.              0.299332E-02          0.268095E-01
           150000.             -0.159078E-01          0.803427E-02
           300000.             -0.361864E-02          0.590580E-01
           450000.             -0.260389E-01          0.433801E-01
           750000.              0.111766E-01          0.699129E-01
           900000.              0.892412E-03          0.731704E-01
          1050000.             -0.417037E-02          0.708857E-01
          1200000.             -0.190334E-01          0.504537E-01
          1500000.             -0.622497E-02          0.798275E-01
          1670514.             -0.176092E-01          0.628719E-01
          2151306.             -0.210433E-01          0.804243E-01

WHEEL  PATH   2

        X              X2             X3             X4             X2Y            XY             Y              Y2
  0.101972E 08   0.139044E 14   0.221517E 20   0.385807E 26   0.991106E 12   0.691504E 06   0.624828E 00   0.407584E-01


   LEAST SQUARES LINE          Y =  0.260291E-01 +  0.306436E-07 X ±  0.363570E-01


   LEAST SQUARES PARABOLA      Y =  0.136623E-01 +  0.777621E-07 X + -0.238829E-13 X2 ±  0.306926E-01
WHEEL  PATH   1

        X              X2             X3             X4             X2Y            XY             Y              Y2
  0.101972E 08   0.139044E 14   0.221517E 20   0.385807E 26  -0.191473E 12  -0.117023E 06  -0.985841E-01   0.225016E-02


   LEAST SQUARES LINE          Y = -0.282245E-02 + -0.634630E-08 X ±  0.221744E-01


   LEAST SQUARES PARABOLA      Y = -0.572545E-02 +  0.471446E-08 X + -0.560637E-14 X2 ±  0.227445E-01
```

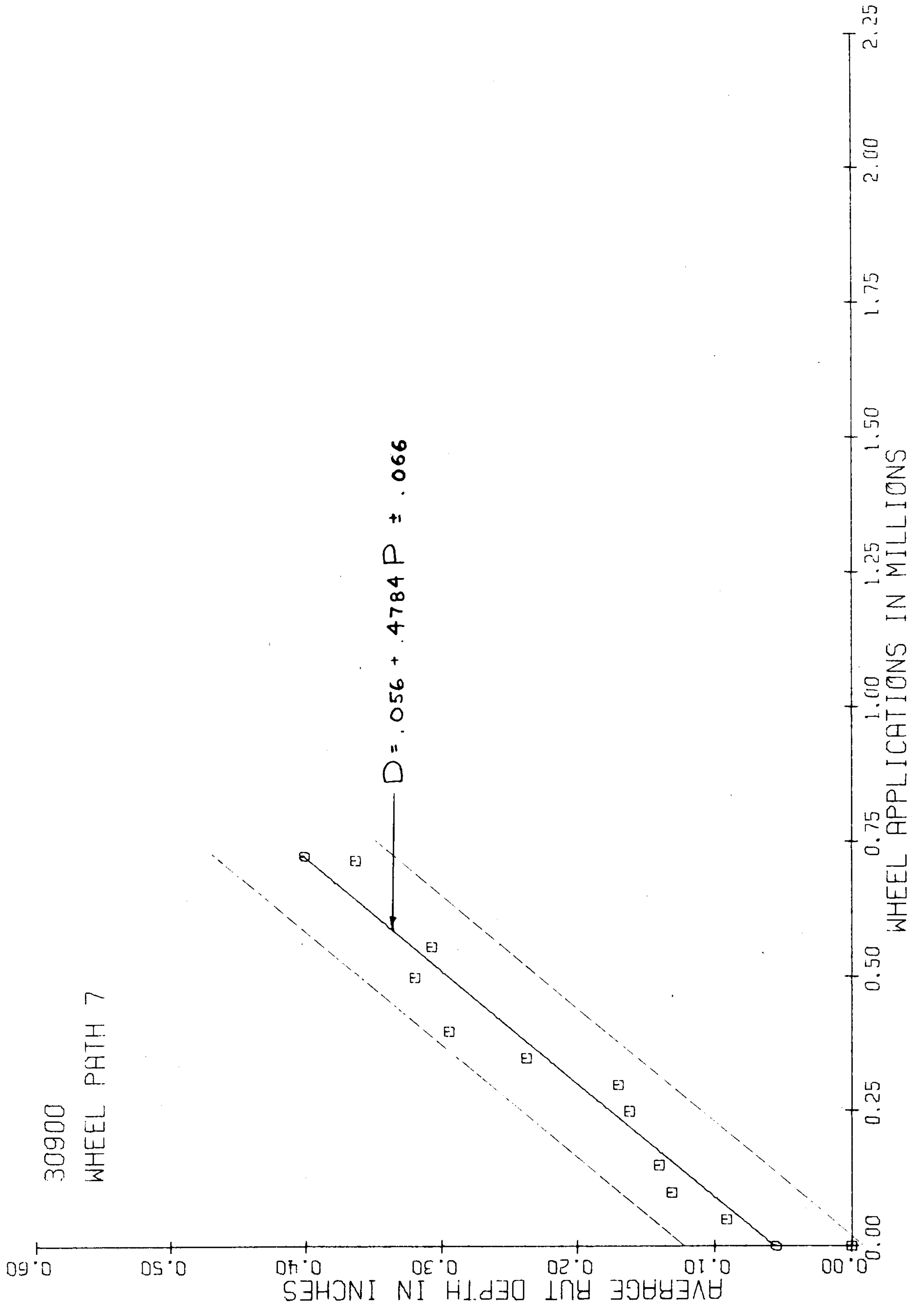
APPENDIX C

ILLUSTRATIVE SAMPLING OF THE PLOTS OF THE REGRESSION LINES OBTAINED FROM THE ANALYSIS OF THE DATA



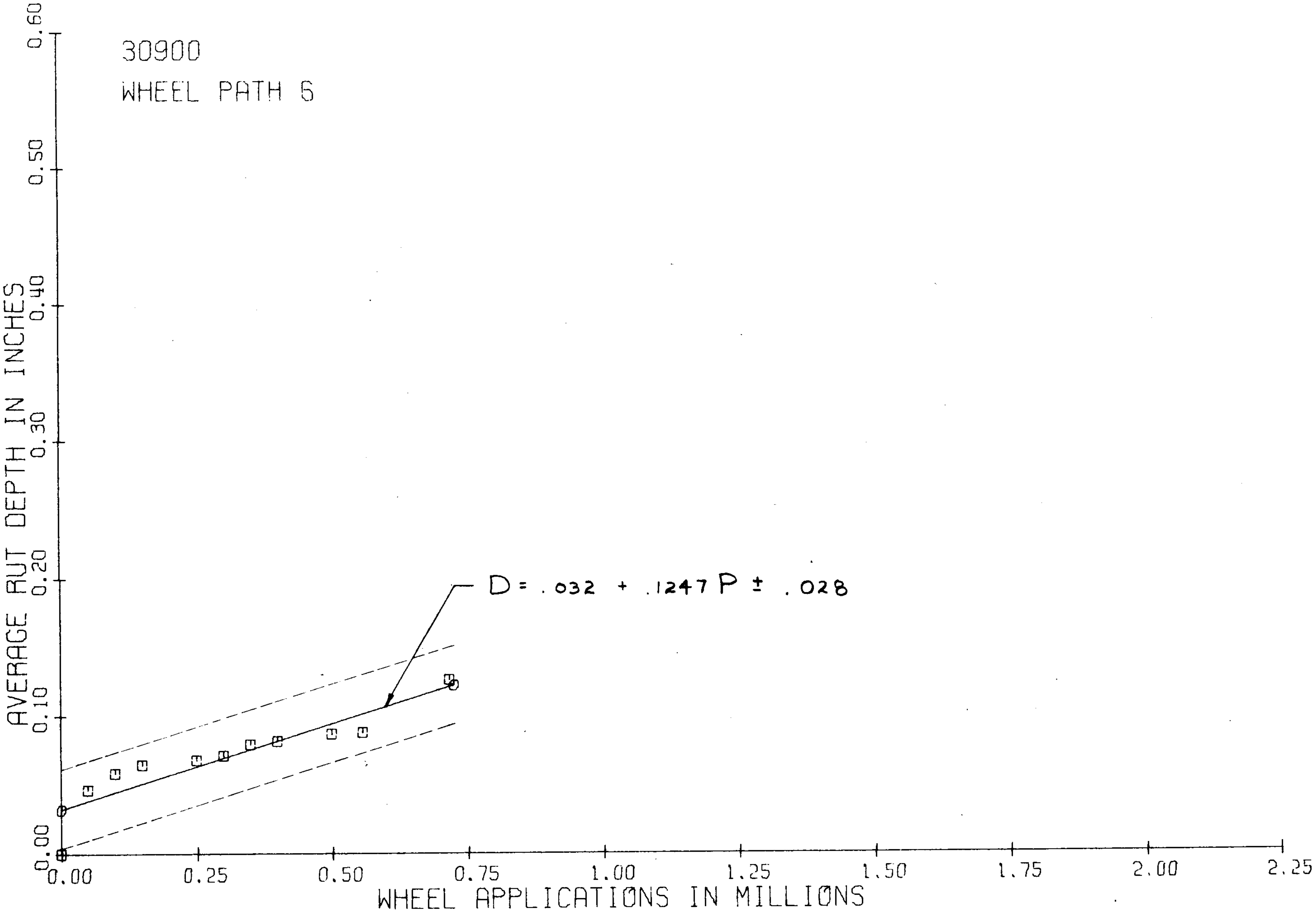
D = .006 + .0332 P ± .011

CLASS G A C

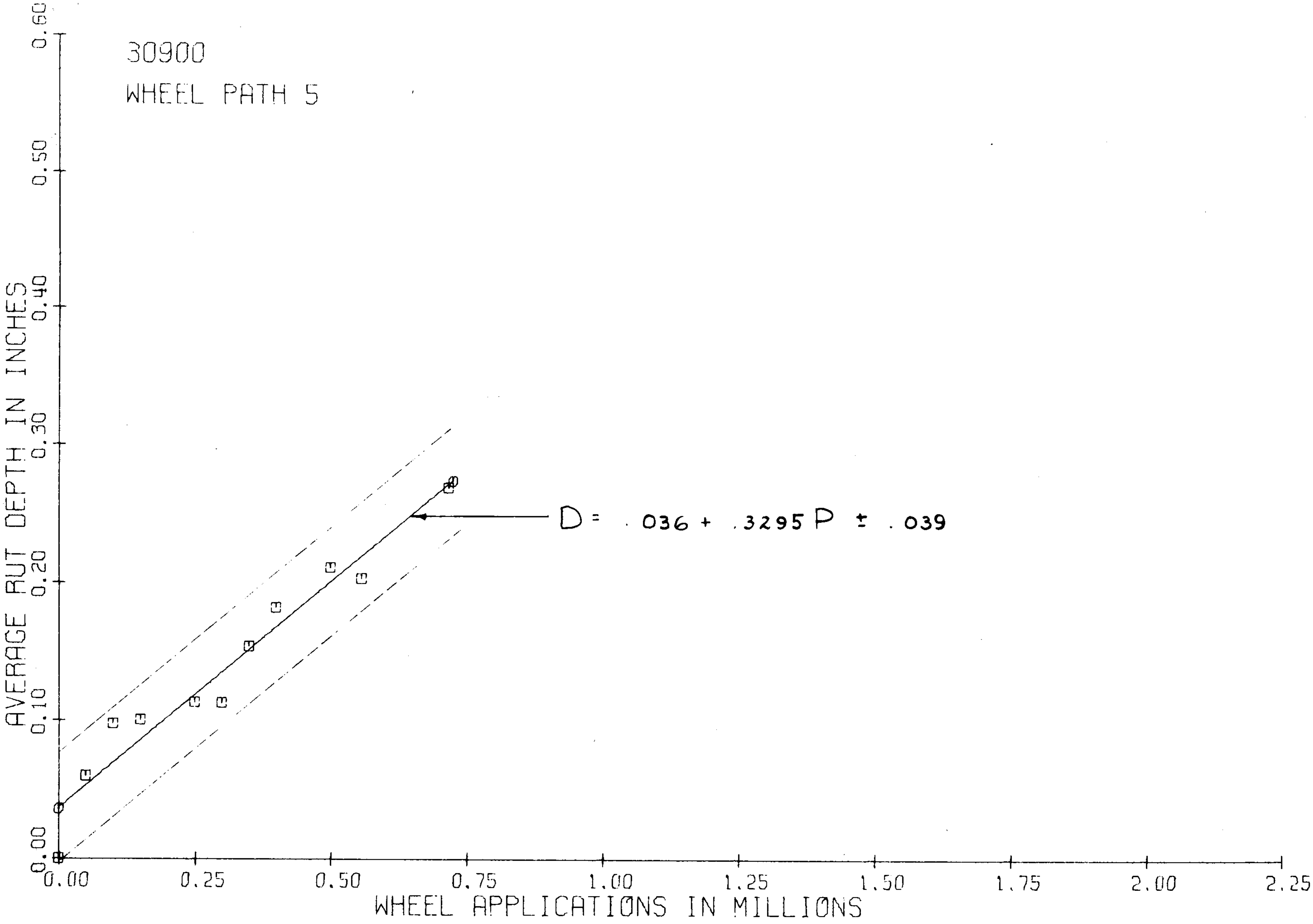


$D = .056 + .4784\,P \pm .066$

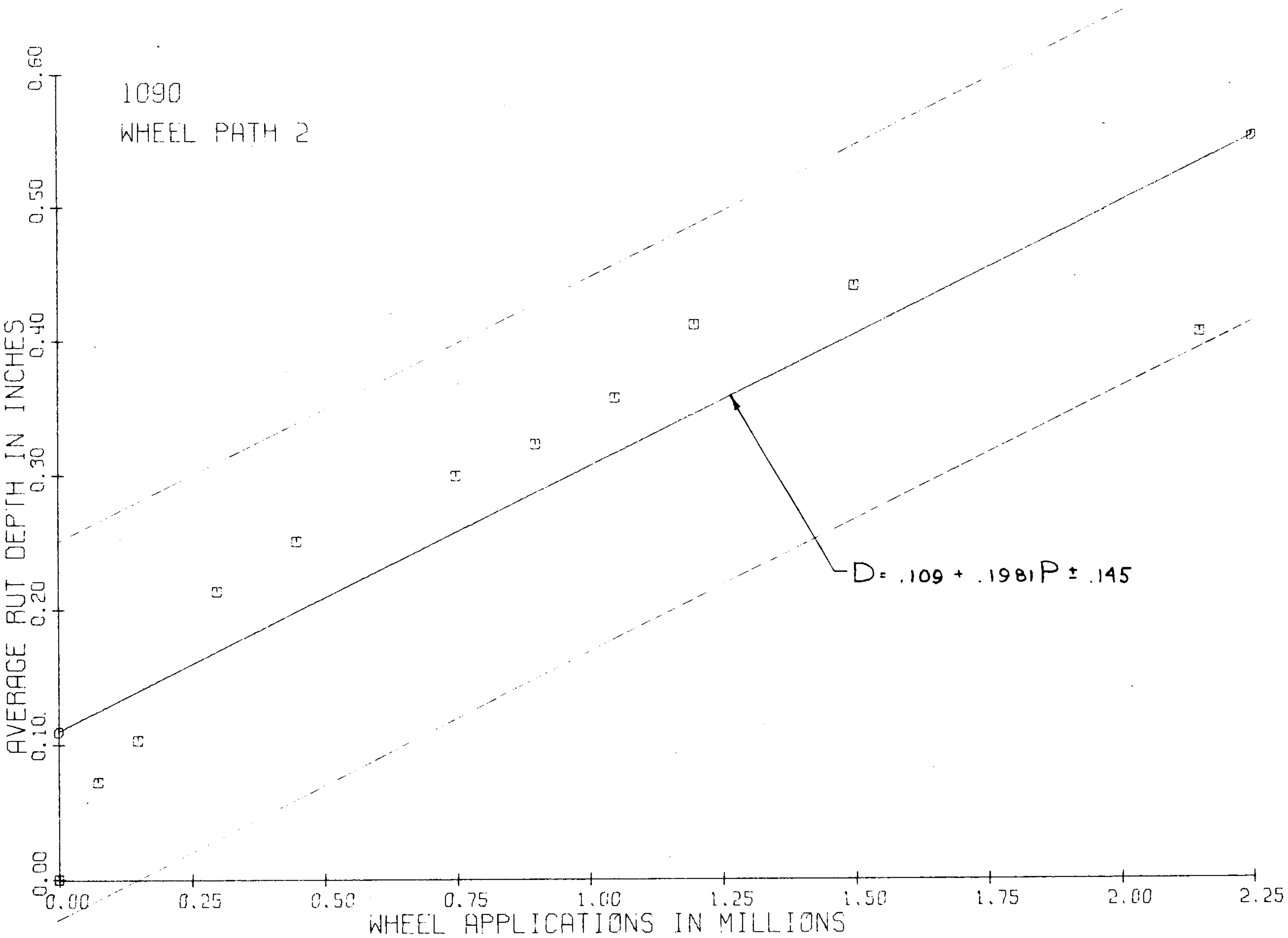
CLASS G A.C.


30900
WHEEL PATH 6
D = .032 + .1247 P ± .028
AVERAGE RUT DEPTH IN INCHES
0.00
0.10
0.20
0.30
0.40
0.50
0.60
WHEEL APPLICATIONS IN MILLIONS
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25

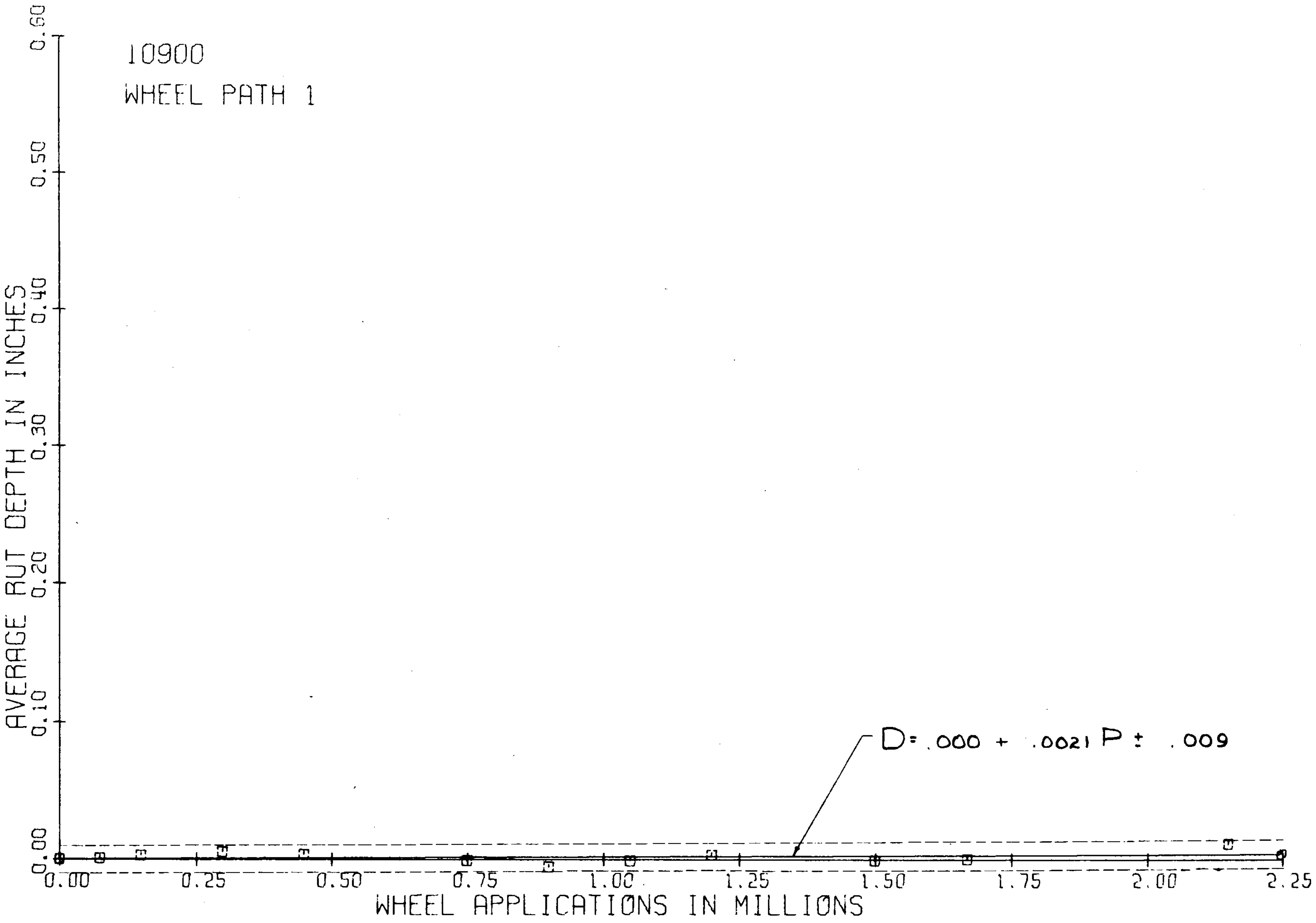
CLASS G A.C.


30900
WHEEL PATH 5
AVERAGE RUT DEPTH IN INCHES
0.00
0.10
0.20
0.30
0.40
0.50
0.60
WHEEL APPLICATIONS IN MILLIONS
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
D = .036 + .3295 P ± .039

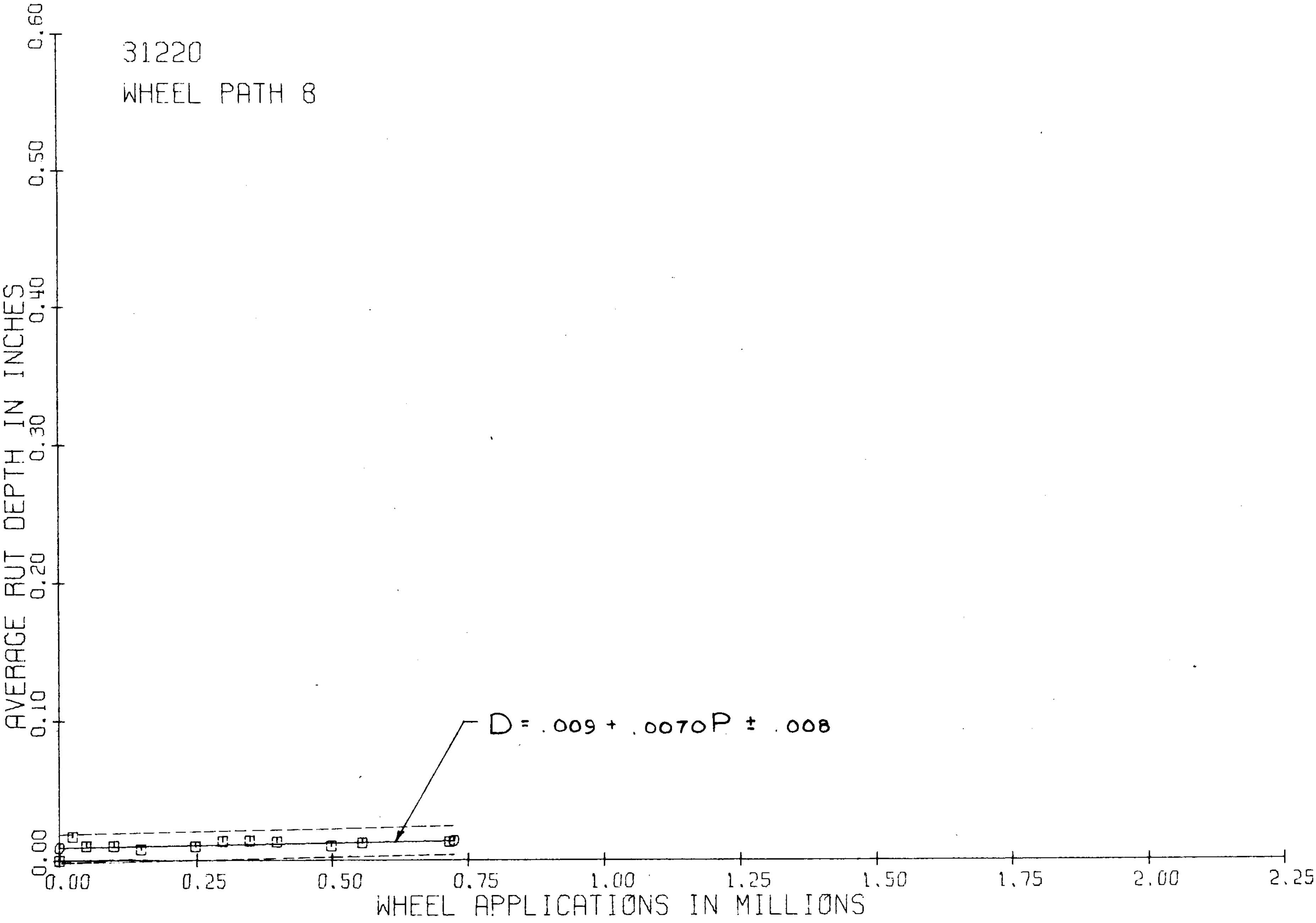
CLASS G A.C.


1090
WHEEL PATH 2
AVERAGE RUT DEPTH IN INCHES
0.00
0.10
0.20
0.30
0.40
0.50
0.60
WHEEL APPLICATIONS IN MILLIONS
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
D = .109 + .1981P ± .145

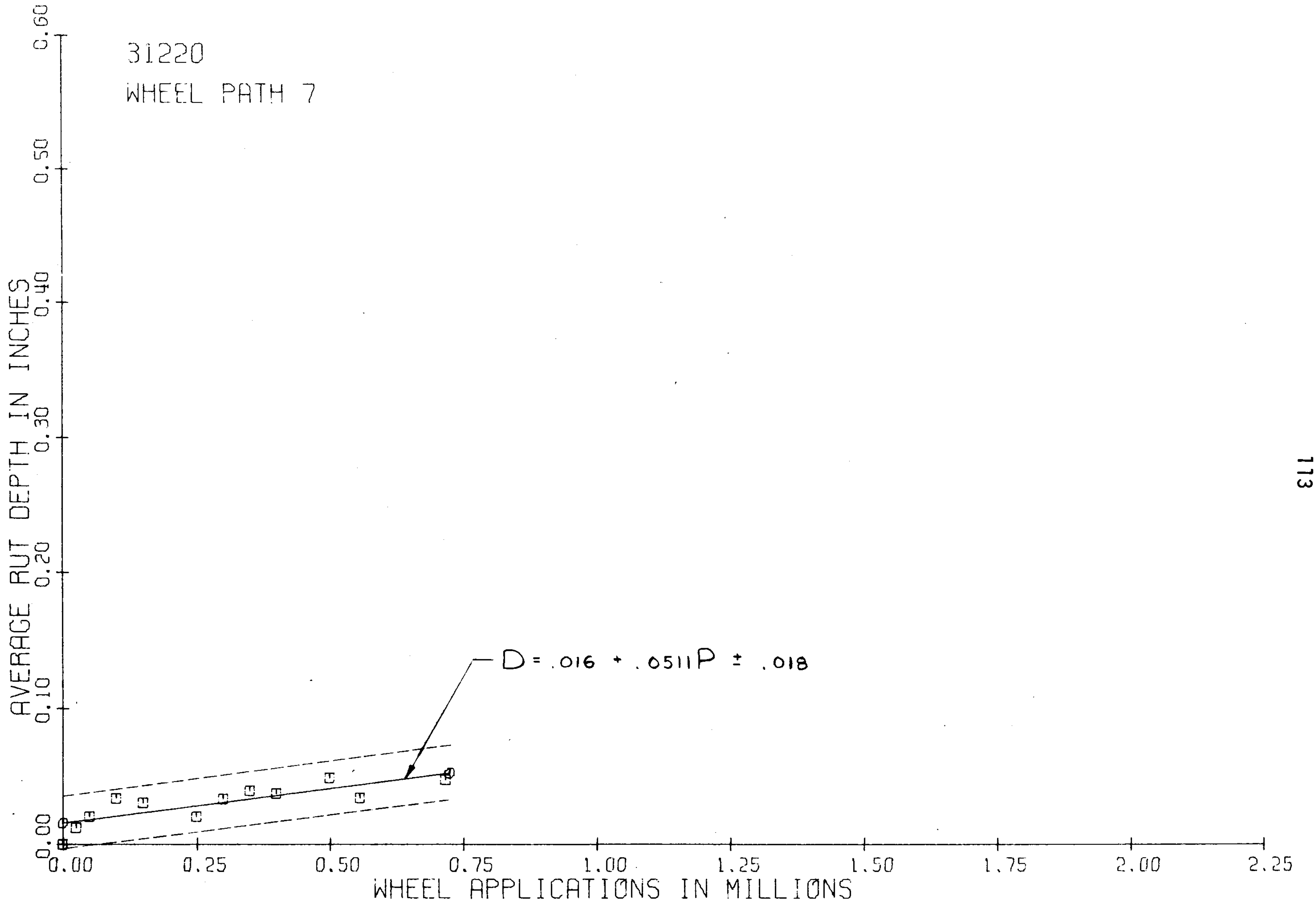
CLASS G A.C.


10900
WHEEL PATH 1
AVERAGE RUT DEPTH IN INCHES
0.00
0.10
0.20
0.30
0.40
0.50
0.60
WHEEL APPLICATIONS IN MILLIONS
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
D= .000 + .0021 P ± .009

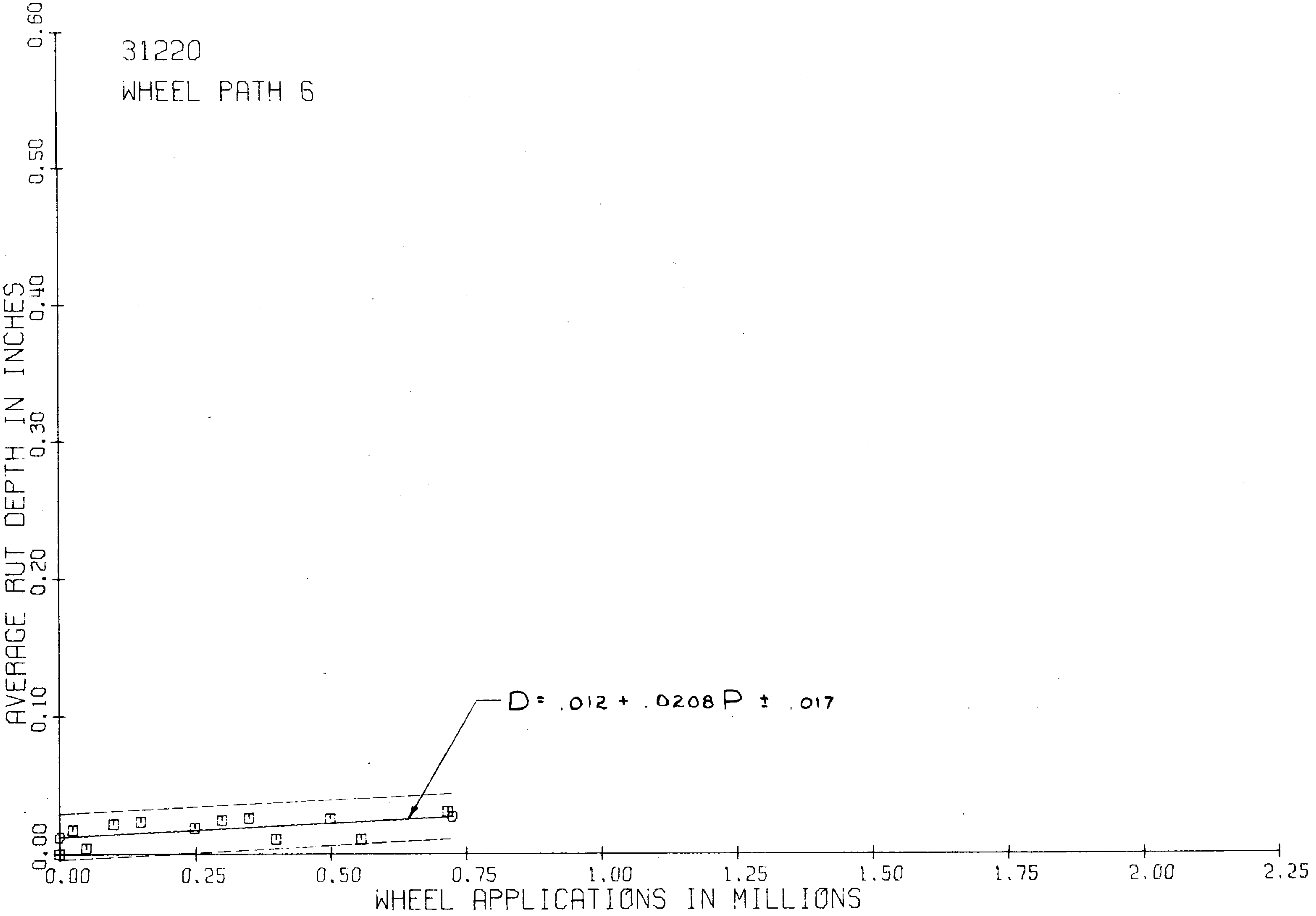
CLASS G A.C.

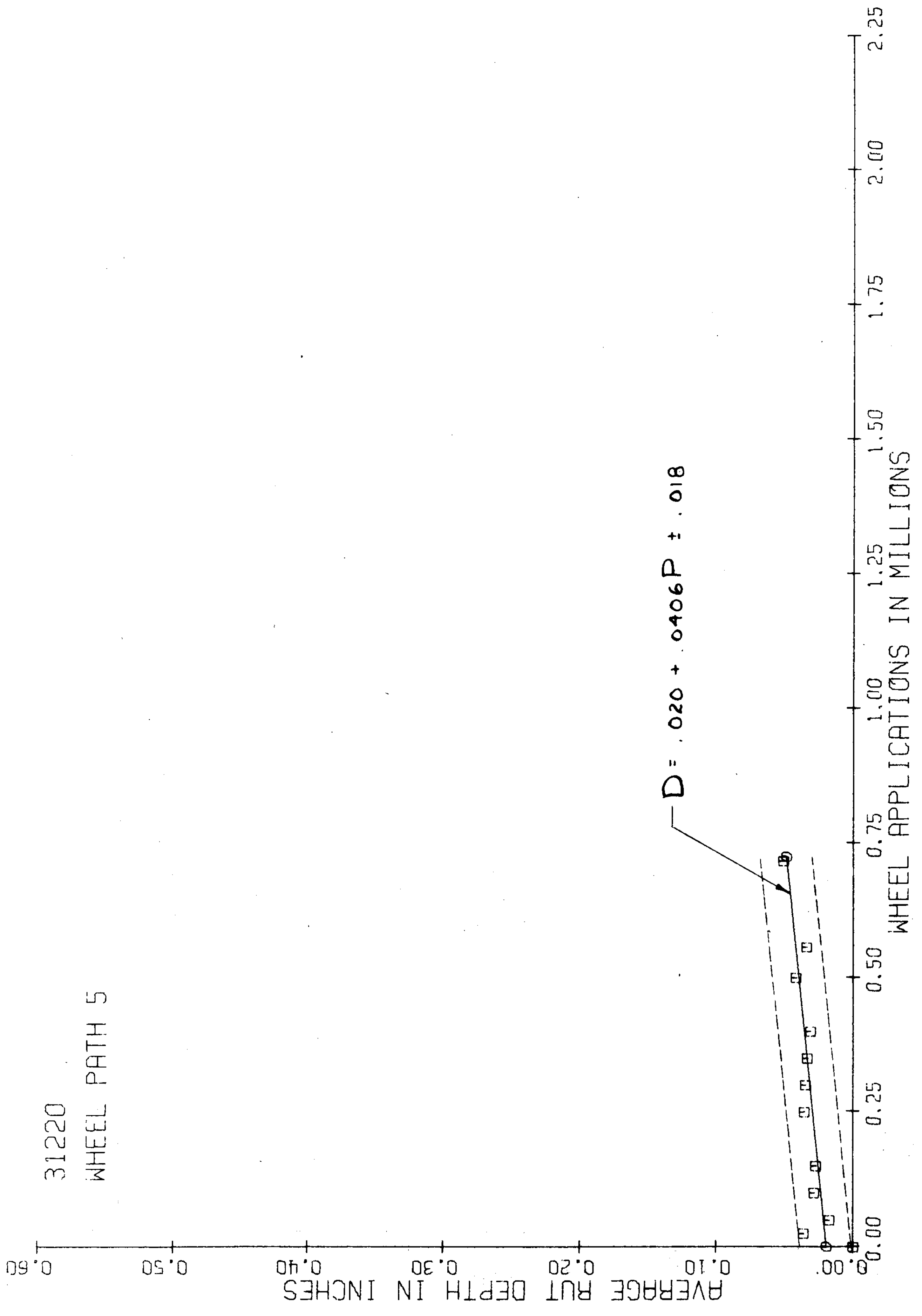

31220
WHEEL PATH 8
AVERAGE RUT DEPTH IN INCHES
0.00
0.10
0.20
0.30
0.40
0.50
0.60
WHEEL APPLICATIONS IN MILLIONS
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
D = .009 + .0070P ± .008

P.C.C.

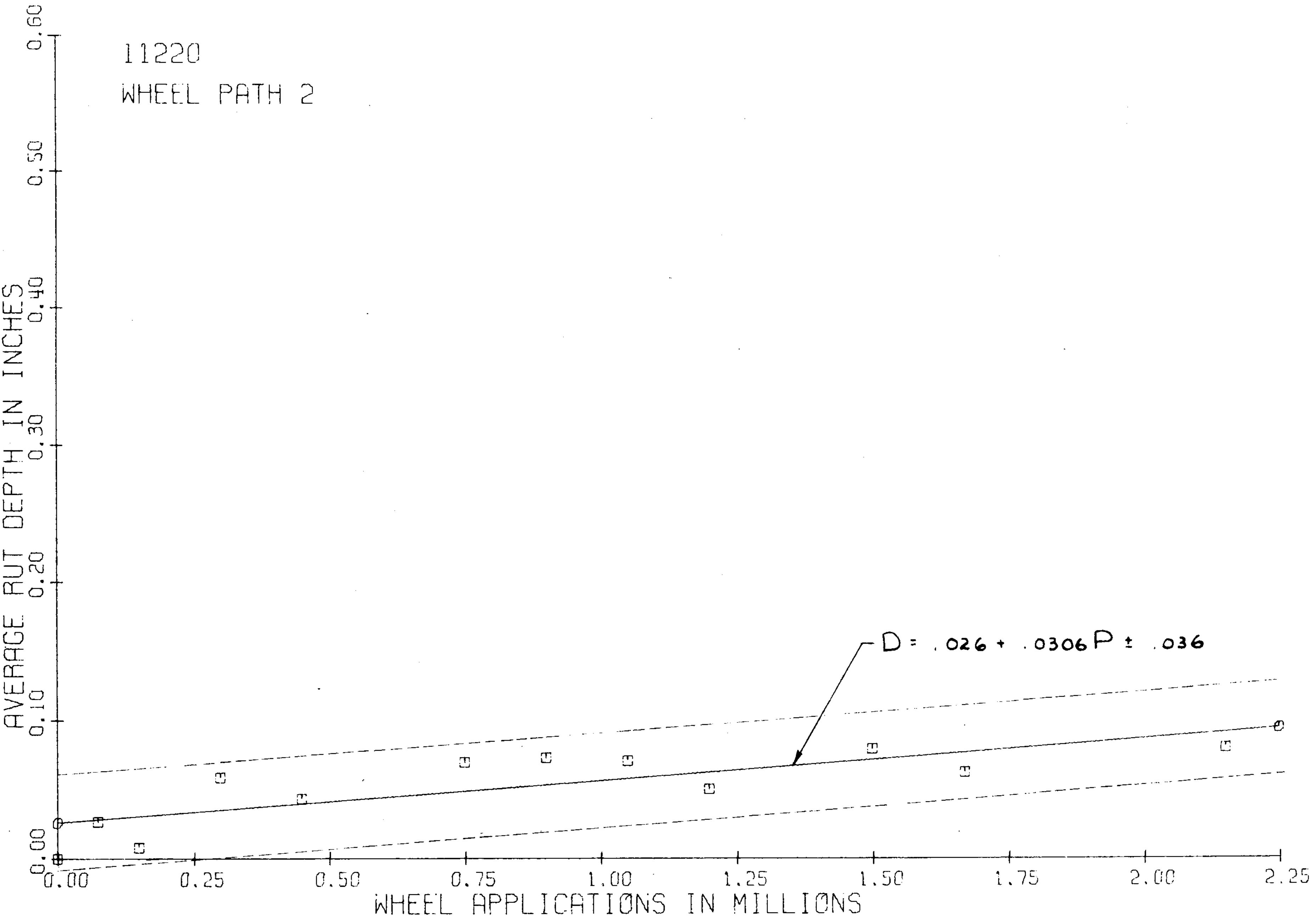

31220
WHEEL PATH 7
AVERAGE RUT DEPTH IN INCHES
0.00
0.10
0.20
0.30
0.40
0.50
0.60
WHEEL APPLICATIONS IN MILLIONS
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
D = .016 + .0511P ± .018

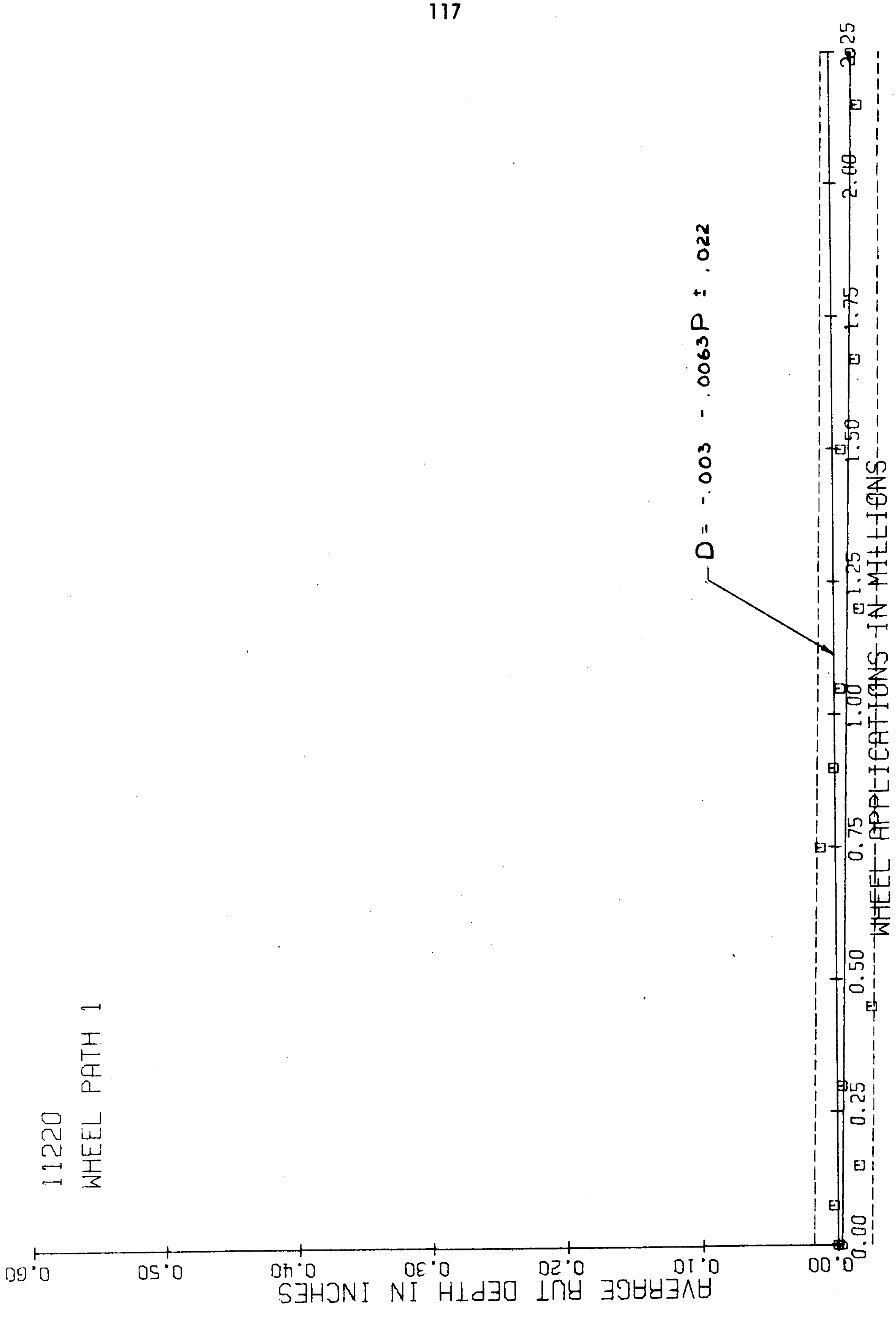
P.C.C.


31220
WHEEL PATH 6
AVERAGE RUT DEPTH IN INCHES
0.00
0.10
0.20
0.30
0.40
0.50
0.60
WHEEL APPLICATIONS IN MILLIONS
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
D = .012 + .0208 P ± .017


31220
WHEEL PATH 5
D = .020 + .0406P ± .018
AVERAGE RUT DEPTH IN INCHES
0.00
0.10
0.20
0.30
0.40
0.50
0.60
WHEEL APPLICATIONS IN MILLIONS
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25

P.C.C.


11220
WHEEL PATH 2
D = .026 + .0306P ± .036
AVERAGE RUT DEPTH IN INCHES
0.00
0.10
0.20
0.30
0.40
0.50
0.60
WHEEL APPLICATIONS IN MILLIONS
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25



$D = -.003 - .0063P \pm .022$

P.C.C.

APPENDIX D

SAMPLE CALCULATIONS SHOWING THE DETERMINATION OF THE AVERAGE STUD PROTRUSION LENGTHS (ASP)

APPENDIX D

Sample Calculations Showing the Determination of the Average Stud Protrusion Lengths (ASP).

The ASP for any particular stud was determined on a weighted basis by the following procedure.

Step 1: Prior to placing the tire on the traffic simulator, all 112 studs in the tire were measured with a dial gauge. The expected value or the mean value for the 112 measurements was determined by $\frac{\Sigma d}{n}$. Subsequently, at various numbers of revolutions during the operation of the traffic simulator, stud measurements were made on a representative number of studs in the tire (normally 30 studs were measured). For each set of measurements, the mean value was obtained from the use of $\frac{\Sigma d}{n}$. A typical set of average values is given in Table a. In some wheel paths there were three tires that were being driven by the apparatus. For these wheel paths the mean value for the stud protrusion length was obtained by using the measurements from all three tires.

Step 2: The average stud protrusion length for each interval of tire revolutions was obtained by simply averaging the value at the beginning of the interval with the value at the end of the interval. The ratio of the number of revolutions in each interval compared to the total number of revolutions in the test was also obtained.

Step 3: The product of the interval ratio and the average stud protrusion value was obtained for each interval. This product provided the effect associated with the particular average stud length acting on the material for a specified portion of the total time of the test.

Step 4: The weighted average stud protrusion length (ASP) was obtained by adding the products obtained for each interval.

The ASP for each tire was obtained by this procedure.

Table a.[1]

No. of Rev.	Rev. Increment	Interval Ratio	Mean Stud[2] Protrusion Length	Stud Protrusion	Weighted Values
0			.0418		
	5,000	.0069725		.0381	.0003
5,000			.0344		
	5,000	.0069725		.0364	.0003
10,000			.0385		
	15,000	.0209175		.0342	.0007
25,000			.0300		
	25,146	.0350661		.0308	.0011
50,146			.0315		
	49,854	.0695214		.0223	.0015
100,000			.0131		
	50,000	.0697250		.0146	.0010
150,000			.0162		
	50,000	.0697250		.0156	.0011
200,000			.0151		
	50,000	.0697250		.0155	.0011
250,000			.0159		
	50,000	.0697250		.0138	.0010
300,000			.0118		
	Tire Change	---		---	---
300,000			.0283		
	14,317	.0199650		.0242	.0005
314,317			.0200		
	35,683	.0497600		.0216	.0011
350,000			.0223		
	50,000	.0697250		.0220	.0015
400,000			.0217		
	100,000	.1394500		.0186	.0026
500,000			.0154		
	155,458	.2167864		.0187	.0041
655,458			.0220		
	61,644	.0859627		.0216	.0019
717,102			.0213		
		Σ = 1.0000000		ASP = Σ =	.0198

The average stud protrusion length (ASP) for the entire test period is taken to be 0.020 ± 0.001 inch.

[1] The numbers in this table pertain to the tire with the CP (controlled protrusion) stud used in Experimental Ring No. 6.

[2] Determined from the actual data measurements.

The ASP values obtained for the remaining tires with studs used in the project are as follows:

	ASP (inch)	
Type of Stud	Exp. Ring 5	Exp. Ring 6
CP	.092 & .063*	.020*
PT	.027	.017
CV	.098	.030
FS	---	.029

*Based on measurements of the stud protrusion lengths obtained from three tires.

APPENDIX E

ACTUAL PRECIPITATION VS W. A.

APPENDIX E

ACTUAL PRECIPITATION[1] vs w.a.

RING NO. 5			RING NO. 6		
MONTH	PRECIPITATION INCHES	w.a.	MONTH	PRECIPITATION INCHES	w.a.
1972			1972		
February	1.78	108,570	November	0.37	17,334
March	2.83	207,872	December	3.20	82,667
April	0.67	201,696	1973		
May	0.00	24,219	January	1.15	119,159
			February	0.68	89,761
			March	1.25	181,366
			April	0.19	226,815
1304.2 Hr.	5.20	542,357	1896.7 Hr.	6.84	717,102
Rate	.0040"/Hr.	9.59×10^{-6} in./w.a.	Rate	.0036"/Hr.	9.54×10^{-6} in./w.a.

---

[1] This is the amount of precipitation that fell during actual testing. Data is taken from references 1 and 2 and from Palouse Field Conservation Station - Pullman 2 NW.

RING NO. 5:

Rate:	0.0040 inches/hour 9.59×10^{-6} inches/w.a.

RING NO. 6:

Rate:	0.0036 inches/hour 9.54×10^{-6} inches/w.a.

CONCLUSION: No appreciable difference in precipitation amounts during the testing period.