Research Report
– 570 –

FRICTIONAL PERFORMANCE OF PAVEMENTS AND ESTIMATES OF ACCIDENT PROBABILITY

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ABSTRACT

Objectives of this study were to evaluate standard and experimental surfaces throughout Kentucky in terms of skid resistance and effects of traffic, and to provide criteria for judging suitability of these surfaces to satisfy requirements for skid resistance and economics. The effects of traffic were quantified by regression analysis and scatter of data. Criteria included an estimate of accident risks, effects of speed on skid resistance, and seasonal variations in skid resistance.

Pavements on low volume roads (less than 1,000 vehicles per day) maintained adequate skid resistances. Open-graded friction courses, with the possible exception of sections using phosphate slag aggregate, maintained adequate skid resistance to meet design requirements. The adequacy of other pavements may be judged from the criteria provided herein.

Estimates of accident reduction were made by combining the relationship between skid numbers and accidents with the distribution of skid numbers for each pavement type. Those reductions were used to calculate benefits that, along with costs of overlay, were used to determine benefit-cost ratios. Benefits exceeded costs for roads having AADT's greater than 750, 2,500, and 5,000 and SN's less than 24, 30, and 35, respectively.

KEY WORDS: skid resistance, friction, pavements, wet-pavement accidents, aggregates, surfaces, polishing, wear, traffic.

INTRODUCTION

Reduction in skid resistance of pavements is related to loss of macro-texture and to polishing of aggregates. Loss of macro-texture is caused by wear and, in case of asphaltic concrete, consolidation induced by traffic. Skid resistance varies with cumulative traffic (1). Variances are influenced by and attributed to differences in volume and composition of traffic, aggregate types (polish susceptibility), and weathering (including frequency and duration of rainfall). Variations occur seasonally (2) and are affected by traffic volume. Survey testing of roads in Kentucky since 1974 has generated data to evaluate the performance of several types of pavements. These include Class I bituminous, portland cement concrete, and Kentucky rock asphalt. Other types of pavement with up to about 12 million vehicular passes include sand asphalts and open-graded friction courses.

Degrees of hazard are related to needs for traction and, therefore, to speed and density of traffic, turning and stopping movements, and roadway geometrics. Indeed, there are degrees of risk associated with highway hazards. Nevertheless, expedient judgments are being made in regard to the significance or meaning of skid numbers. Critical SN's have been derived for interstate and toll roads (3) and for principal two-lane roads (US routes) (4). Speed limits were reduced from 26.8 m/s (60 mph) (daytime) to 24.6 m/s (55 mph) in March 1974. The relationship between accidents and pavement friction, therefore, may have been altered. A study of those after-effects is going forward. Preliminary results from two-lane roads (about 8,000 km (5,000 miles)) are presented herein.

Perhaps the surface providing the highest SN's may seem desirable -- to minimize risks. Otherwise, minimizing risks must be balanced with benefits to obtain the greatest safety with monies available. Thus, final criteria for adequacy of surface courses must include a best-good-for-all approach and priority-type programming; and the criteria may be different for various classes of roads.

DATA SOURCES

Skid Test

Beginning in 1974, testing was done from June through November. Skid tests were made with two two-wheel trailers. The equipment, methods, and procedures have been described previously (5, 6). Some pavements were tested at 11 and 25 m/s (25 and 55 mph), and all pavements were tested at the standard test speed of 18 m/s (40 mph).

Accident Information

Accidents reported during calendar years 1976 and 1977 were used in conjunction with SN's obtained in 1975 and 1976, on two-lane roads, to determine a relationship between wet-pavement accidents (as a percentage of total accidents) and SN's. Accidents for the 2-year period totaled 29,783 -- of which 5,930 occurred during wet-pavement conditions -- on 1,209 sections. Accidents reported during 1979 were used in conjunction with SN's obtained during 1977 and 1978, on two-lane roads, to determine wet-pavement accidents per km (mile) per year to ascertain potential benefits from de-slicking. Accidents totaled 16,533 -- of which 3,785 occurred during wet-pavement conditions -- on 1,132 sections.

Precipitation

Precipitation data were obtained from monthly tabulations of "Local Climatological Data" (7) for seven weather stations in and around Kentucky. Yearly averages of precipitation in Kentucky since 1969 are presented in Table 1.

Traffic Volume

Annual average daily traffic (AADT) was determined for each pavement section using traffic flow maps published biennially. The 1975 AADT's were used with accidents occurring during 1976 and 1977 on sections tested in 1975 and 1976. The 1977 AADT's were used with accidents during 1979 on sections tested in 1977 and 1978. The AADT's also were used to calculate cumulative traffic.

TABLE 1. PERCENTAGE OF TIME OF PRECIPITATION IN KENTUCKY (TRACE OR MORE)

YEAR	RAINFALL	SNOW AND ICE	NO PRECIPITATION
1969	11.5	2.6	85.9
1970	11.5	3.1	85.4
1971	10.5	2.4	87.1
1972	14.3	2.3	83.4
1973	13.1	2.3	84.6
1974	13.8	2.4	83.8
1975	13.5	2.4	84.1
1976	9.9	2.1	88.0
1977	10.1	3.9	86.0
1978	11.5	4.2	84.3
1979	13.8	3.9	82.2
All	12.1	2.9	85.0

PROCEDURES

Cumulative Traffic Calculations

For two-lane roads, the cumulative traffic was calculated from the AADT value, divided by two, times the number of days in the time frame. For four and six-lane roads, the values were adjusted according to lane distribution factors reported by Pigman and Mayes (8). All values were as of the date of test. No weighting factors for trucks were applied.

An effective annual average daily traffic was determined for each pavement section by dividing the cumulative traffic by the number of days the pavement was open to traffic. The effective AADT then is the average number of vehicles per day that traversed the pavement.

Regression Analysis

The relationships between skid resistance and cumulative traffic were determined by regression analysis and the method of least squares. Previous research (1) had shown that skid resistance could be related to the logarithms of cumulative traffic; therefore, a logarithmic equation was used here as the model. Cumulative traffic was expressed in terms of millions of vehicle passes. New surfaces subjected to little or no traffic yielded spurious skid numbers. For this reason, data associated with cumulative traffic of less than 0.1 million vehicle passes were omitted from the regression analysis.

Preliminary analysis of Class I bituminous and portland cement concrete pavements indicated the best-fit equations were unduly influenced by sections having low volumes of traffic. Cumulative traffic for these low-volume sections were also low, and SN's were high. This resulted in best-fit equations that predicted unduly low skid numbers at high values of cumulative traffic. For this reason, data were grouped by effective AADT, and the performance equations were determined for each group. Also, scatter of data at low values of cumulative traffic was greater than at high values. Thus, the standard errors of estimate, from regression analyses, were not an appropriate indicator of scatter throughout the range of cumulative traffic. Instead, standard deviations were determined using data stratified by cumulative traffic.

The first part of the procedure to determine standard deviation was to establish a data set representing the differences between measured SN and predicted SN. These differences were then grouped in a five-point moving average beginning with the five highest cumulative traffic values. The standard deviation of the differences in SN and the average cumulative traffic were determined for this group of five points. The data for the highest cumulative traffic was then dropped, and the sixth highest value was added. Again, the standard deviation of the differences in SN and the average cumulative traffic were determined. The procedure continued until the last group consisted of data associated with the five lowest values of cumulative traffic.

A multiple of the calculated standard deviation was subtracted from the SN predicted for the average cumulative traffic. This was done for each five-point group and resulted in a set representing a lower limit of SN's above which a known percentage of measured SN's occur. The percentage depends on the multiple of the standard deviation. Here, a multiple of 2.5 was used to establish SN levels that should be exceeded by 99.4 percent of the measured SN's. Additional analysis was done to determine a multiple, and consequently a percentage, for predetermined levels of SN's. Relationships between the lower limit of SN's and cumulative traffic were determined.

CRITERIA FOR PREQUALIFYING PAVEMENTS

Friction Requirements

The relationship between percentage of accidents on wet pavements and SN's on two-lane roads (about 8,000 km (5,000 miles)) is presented in Figure 1. Here, the points represent averages of groupings by two skid numbers. The data were fitted by regression analysis such that the line would indicate nearly 100 percent at SN of 0. Also, at high values of SN, the percentage of wet-pavement accidents would be at least as high as the percentage of time the pavements were wet. In Kentucky, for the two-year period of accident statistics (1976 and 1977) included in the analysis, this percentage was 10; but it was adjusted to 12. Regression equations were determined for various percentages at which the curve becomes asymtotic. The best-fit line indicated that, even if skid resistance remained equivalent to dry-pavement values, wet-pavement accidents comprised 16 percent of the total. This four-percentage point increase (from 12 percent wet time) resulted because reduced visibility, roadway spray, and hydroplaning contributed to accidents. The data were greatly scattered. Thus, use of this trend line for evaluating specific locations must be in conjunction with other supporting statistics -- such as occurrences of accidents or, perhaps, number of conflicts.

The best-fit line of Figure 1 may be used to determine the increased risk of an accident being a wet-pavement accident at SN's less than the equivalent dry-pavement values. For example, from Figure 1 at SN 60, 18 percent of the accidents occurred on wet pavements; this was a 12.5-percent increase from the 16 percent

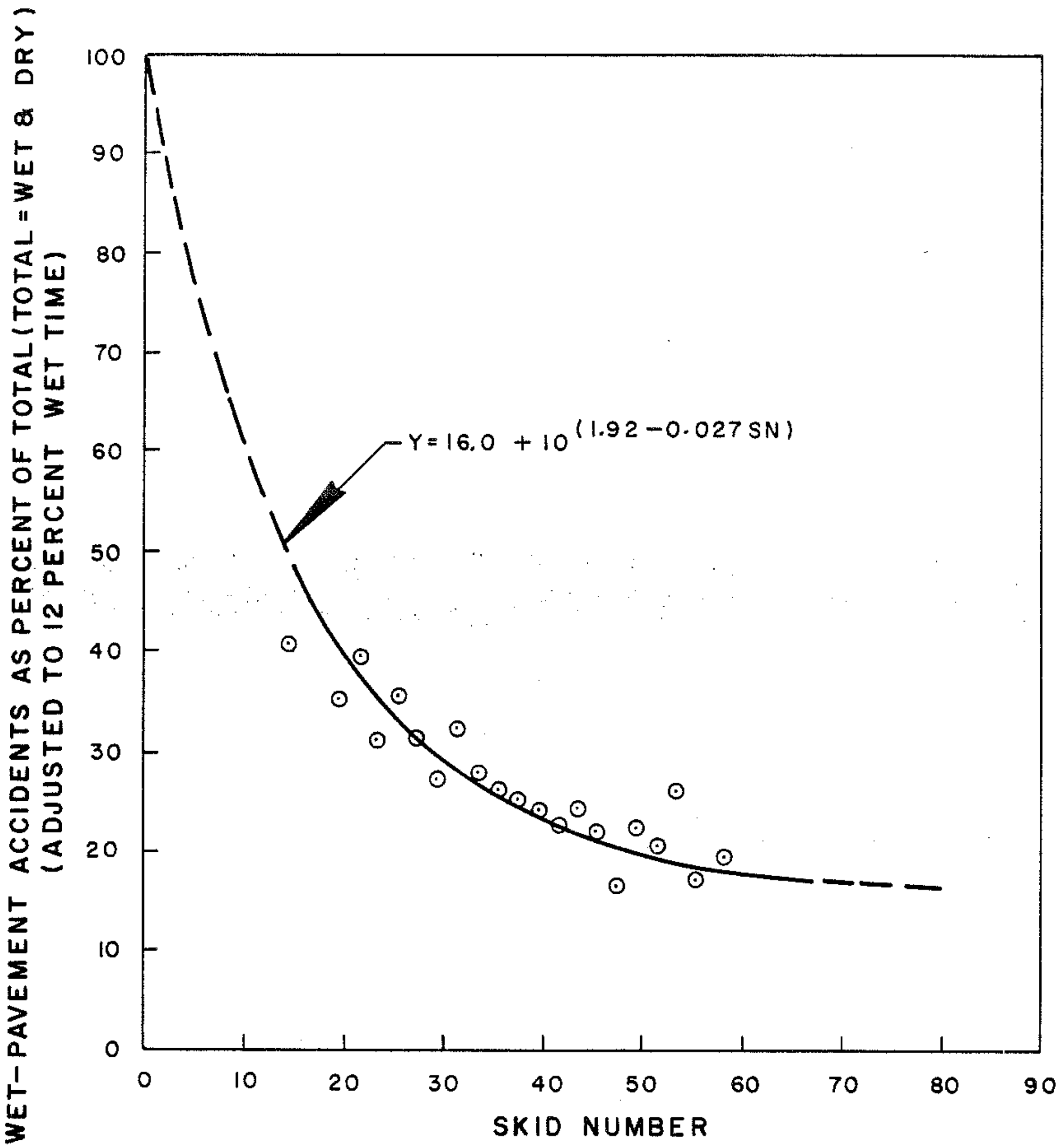

Figure 1. Wet-Pavement Accidents as Percentage of Total (Adjusted to 12 Percent Wet Time) versus Skid Number (1976-1977); 1,200 Sections (about 5,000 miles (8,000 km)) of Two-Lane Roads; Grouped by Two Skid Numbers; AADT's above 750.

that occurred for equivalent, dry-pavement values. Likewise, at SN 27, 32 percent of the accidents occurred on wet pavements; this was a 100-percent increase from the 16 percent.

Of course, pavements cannot be maintained at SN's equivalent to dry-pavement values; and obtainable levels of skid resistance for new pavements must be selected on the basis of other criteria. Moreover, the relationship shown in Figure 1 indicates the desirability of establishing a maximum risk for existing pavements and provides a means of assessing the relative consequences. The selection of maximum risk must be tempered with realism. For example, a maximum increased risk of only 50 percent (SN 38) would mean that over one-half of the road mileage (AADT more than 1,000) would not qualify (almost 8,000 km (5,000 miles)). However, a maximum risk of 91 percent (SN 28) would mean that a more manageable six percent of the road mileage would not qualify (almost 1,000 km (600 miles)).

Present criteria for identifying pavements in need of de-slicking (9) specifies that any highway section with an AADT greater than 1,000 should be de-slicked if the SN of the pavement is 28 or less. A total of 1,011 km (632 miles) of state roads met this criterion. In addition, highway sections with SN's between 29 and 32 were selected if accident experience indicated a wet- to dry-pavement accident ratio of at least 0.30. These sections totaled an additional 48 km (30 miles). As efforts to de-slick candidate roads are successful, increasing the minimum SN allowed on existing pavements may be feasible.

Based on these present criteria for identifying existing pavements in need of de-slicking, the criterion for new pavements, for this category of road, was set to prevent future occurrences. The criterion specifies that the mature SN of a surface, at minus 2.5 standard deviations (99.4 percent assurance), must exceed 32.

Pavement Life

Judgments of the suitability of surfaces must include a consideration of service life and traffic volumes to determine when a SN is a mature value. A surface, during its life, may provide suitable SN's for a road with low traffic volume but may not be adequate for a road with high traffic volume. For example, if a pavement provides adequate SN through 10 million vehicle passes and its service life is estimated as 12 years, the pavement is suitable for use on roads with traffic volumes as high as 4,600 vehicles per day (average volume for the 12 years). At lower traffic volumes, the pavement would age 12 years prior to accumulating 10 million vehicle passes. At higher traffic volumes, the surface may exhibit SN's of 32 or less before reaching the 12 years of life and, thus, may require a premature (or planned) surface renewal.

The useful life of an overlay depends on such variables as type and thickness of the overlay, traffic volume, numbers and types of trucks, and weather conditions (10). The useful life of an overlay ends when it becomes unusually slick, rough, cracked, or rutted. Predicting the number of years when any of these failing conditions will occur is quite difficult. The actual term of service ends when the pavement is resurfaced again or when the road is abandoned.

Effects of Speed

Another characteristic to be considered in judging the suitability of surfaces is the relationship between skid resistance and speed. Skid resistance decreases with increasing speed. Many of the pavements were tested at 11 m/s (25 mph) and 25 m/s (55 mph). A representative curve for each pavement type is shown in Figure 2. The decrease in skid resistance, from 18 m/s (40 mph) to 25 m/s (55 mph), ranged from a high of 10 SN's on portland cement concrete (burlap drag texturing) to 3 SN's on open-graded friction courses.

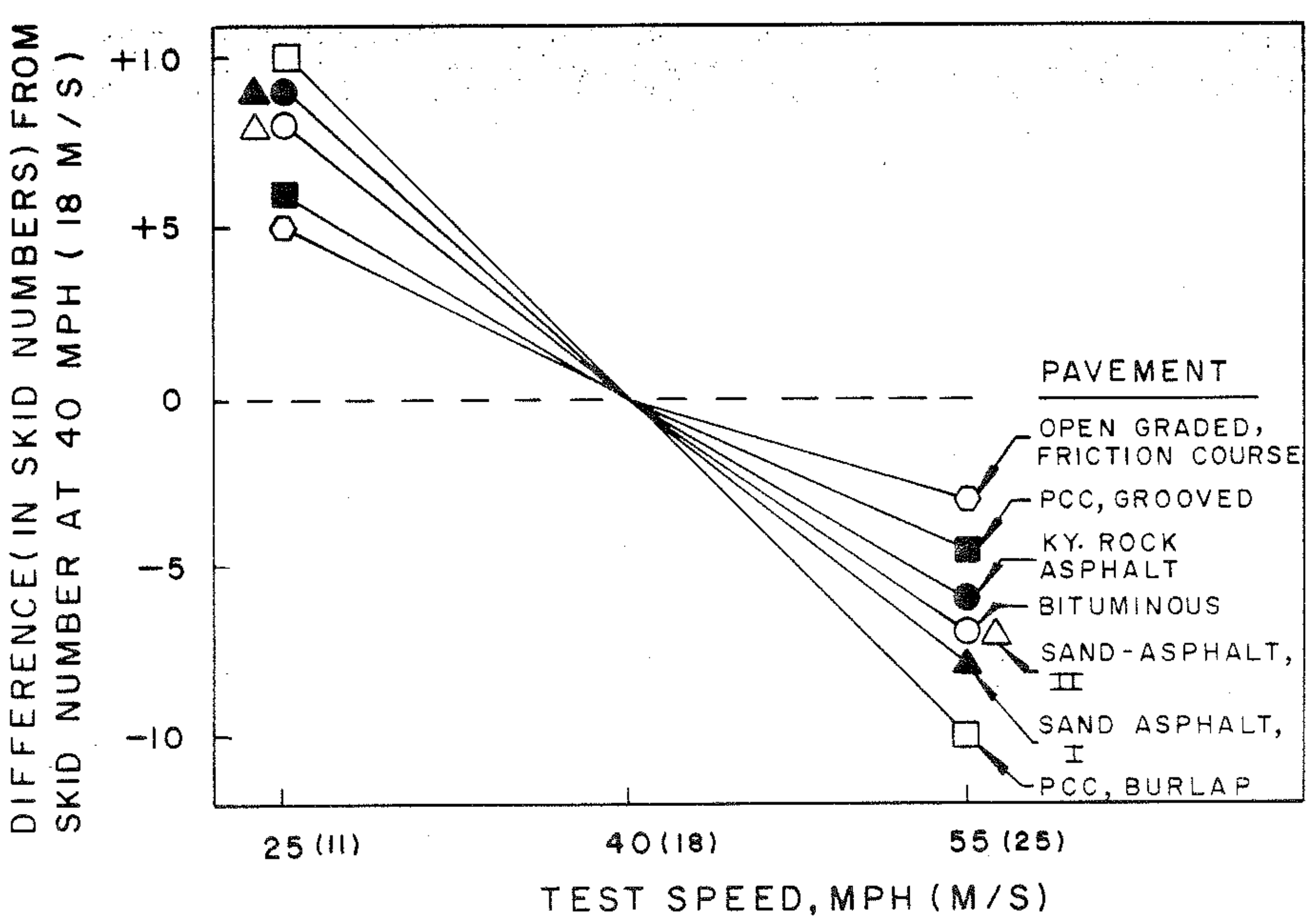

Figure 2. Effect of Speed on Skid Resistance of Several Pavement Types.

A vast majority of pavements involved in the study to relate accidents with pavement friction on two-lane roads (see Figure 1) were Class I bituminous. Therefore, surfaces for high-speed roads, and with decrease in skid resistance lower than for Class I, may be viewed more positively; and surfaces with higher decreases in skid resistance may be viewed more negatively. On the other hand, surfaces for low-speed roads may be viewed more positively if increases in skid resistance, from 18 m/s (40 mph) to 11 m/s (25 mph), are higher.

Seasonal Variations

Evaluations, herein, were based on tests conducted during the summer and fall. Research has shown that skid resistance varies seasonally and is lowest during the late summer and early fall (2). Class I bituminous surfaces, on higher volume roads, were as much as 14 SN's higher during the winter than that during the late summer. Sand asphalt exhibited as much as 11 SN's higher, and PCC pavements were 5 SN's higher. Data on one section of an open-graded friction course indicated the skid resistance of that surface varied little. A higher SN during the winter and spring is a positive attribute of a pavement and should be considered in the selection of surfaces.

PAVEMENT PERFORMANCE

Class I Bituminous

Class I bituminous is a densely graded, high-type asphaltic concrete. Limestone was the predominant coarse aggregate in these surfaces. Unfortunately, most, if not all, limestones are susceptible to polishing. The surfaces also contained natural or conglomerate sand in the proportion of not less than 40 percent of the combined aggregate. Mineral composition, gradation, and particle-shape requirements for sand, however, were not specified.

Best-fit equations for the two effective AADT groups of interstate and toll roads are plotted in Figure 3. Also plotted, for pavement sections with more than 2,500 vehicles per day, is the best-fit line representing a lower limit of minus 2.5 standard deviations. Equations for this and other pavements are presented

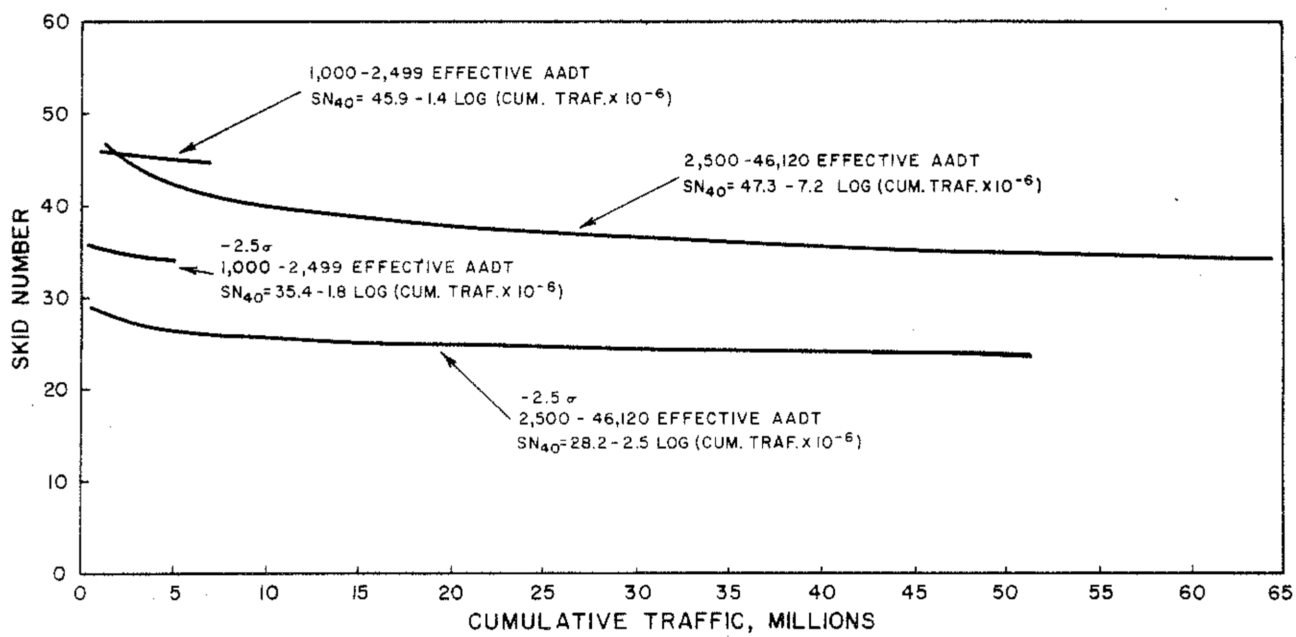

Figure 3. Effect of Traffic on Skid Resistance of Bituminous Concrete Surfaces (Interstate and Toll Roads).

in Table 2. The estimated SN's, representing medians for each pavement, at 0.1, 1, 5, 10, and 60 million vehicle passes, and the lower limit at 10 million vehicle passes are presented in Table 3.

As mentioned previously, tests on new bituminous surfaces that had experienced little or no traffic yielded spurious skid numbers. Valid tests were conducted only after asphalt coating on the surface of the aggregates, and other contaminates, had worn away. Surfaces having low cumulative traffic had initial SN's in the order of 50 for interstate and toll roads and 45 for US and KY routes. Subsequent loss of skid resistance occurred as the sections accumulated more traffic. Both the cumulative traffic and

TABLE 2. BEST-FIT EQUATIONS RELATING SKID NUMBER AND CUMULATIVE TRAFFIC FOR VARIOUS TYPES OF PAVEMENTS

PAVEMENT	EFFECTIVE AADT RANGE	EFFECTIVE AADT AVERAGE	NO. OF SECTIONS	NO. OF DATA POINTS	BEST-FIT EQUATIONS SN = A + BxLOG(CT*) MEDIAN A	MEDIAN B	LOWER LIMIT** A	LOWER LIMIT** B
Class I, Bituminous:								
Interstate & Toll Roads	1,000- 2,499	1,560	43	83	45.9	-1.4	35.4	-1.8
	2,499-46,120	8,380	41	95	47.3	-7.2	28.2	-2.5
US & KY Roads	1,000- 2,499	1,770	100	99	42.3	-4.3	28.2	+1.0
	2,499-34,000	5,080	130	132	40.2	-2.0	25.8	-3.1
Portland Cement Concrete	1,000- 2,499	2,070	46	68	48.9	-0.6	36.0	-1.5
	2,499-38,200	9,490	167	499	49.3	-7.9	22.7	+3.9
Kentucky Rock Asphalt	1,180- 7,590	2,950	20	20	57.2	-7.9	51.2	-15.3
Sand-Asphalt, Type I	690-20,130	8,680	17	58	39.9	-1.2	28.1	-4.2
Sand-Asphalt, S.P. 59B	4,000-14,550	8,900	3	58	47.3	-1.7	35.1	0.0
Sand-Asphalt, Type II:								
(Rural)	300-10,560	4,070	16	49	49.3	-3.8	35.8	-2.8
(Urban)	1,040-18,650	8,040	9	39	36.6	-7.0	8.5	+4.6
Open-Graded, Friction Course, Type 1:								
Green River Gravel	2,220-19,400	6,610	10	63	48.2	+4.5	38.9	+0.7
Slag	400-43,610	12,030	12	48	49.0	-3.7	39.3	-6.2
Gravel	1,100-10,400	6,680	6	21	52.8	-4.4	32.2	-4.7
Granite	5,300-11,500	6,520	7	6	48.6	+5.4	38.3	+4.3
Type 2: All Aggregate	2,400- 6,900	3,360	6	16	47.1	+1.2	...	...

* Cumulative traffic in millions of vehicle passes.
** At -2.5 standard deviations.

TABLE 3. SKID NUMBER AT SEVERAL VALUES OF CUMULATIVE TRAFFIC FOR VARIOUS TYPES OF PAVEMENTS

	SKID NUMBER					
	CUMULATIVE TRAFFIC-MILLIONS					MINUS 2.5
PAVEMENT	0.1	1	5	10	60	σ **
Class I, Bituminous, Interstate & Toll Roads:						
AADT 1,000 - 2,499	50	46	45	44*	..	34*
AADT 2,500 - 46,120	50	47	42	40	35	26
Class I, Bituminous, US & KY Roads:						
AADT 1,000 - 2,499	45	42	39	38*	..	29*
AADT 2,500 - 34,000	45	40	39	38	37*	23
Portland Cement Concrete	55	49	48	48*	..	34*
	55	49	44	41	35	26
Kentucky Rock Asphalt	..	57	52	49	..	36
Sand-Asphalt, Type I	42	40	39	39	..	24
Sand-Asphalt, S.P. 59B	..	47	46	46	..	35
Sand-Asphalt, Type II:						
(Rural)	54	49	47	45*	..	33*
(Urban)	44	37	32	30	..	13
Open-Graded, Friction Course, Type 1:						
Green River Gravel	42	48	51	53	..	40
Slag	53	49	46	45	..	33
Gravel	57	53	50*	48*	..	28*
Granite	45	49	52*	..	..	43*
Type 2: All Aggregate	45	47	48*	..	..	..

* Extropolated using best-fit equation.
** At 10 million vehicle passes.

traffic volume (effective AADT) were significant variables.

For interstate and toll roads with 1,000 to 2,500 vehicles per day, the SN decreased to 46 after only one million vehicle passes and decreased less rapidly to a SN of 45 at seven million vehicle passes. The lower limit indicated that 99.4 percent of these sections maintained SN's greater than 34 at five million vehicle passes. For surfaces with more than 2,500 vehicles per day, the SN was 47 at one million vehicle passes and decreased to 40 at ten million vehicle passes and to 35 after sixty million vehicle passes. The lower limit indicated that 99.4 percent of these sections maintained SN's greater than 24 at 50 million vehicle passes.

For US and KY routes with 1,000 to 2,500 vehicles per day, the SN decreased to 42 after one million vehicle passes and continued decreasing to 39 at five million vehicle passes. The lower limit indicated that 99.4 percent of these sections maintained SN's greater than 28 at five million vehicle passes. For surfaces with more than 2,500 vehicles per day, the SN was 40 at one million vehicle passes and continued decreasing gradually to a SN of 37 at 27 million vehicle passes. The lower limit indicated that 99.4 percent of these sections maintained SN's greater than 21 at 20 million passes.

Portland Cement Concrete

Limestone has been used as the coarse aggregate in most portland cement concrete pavements. Projects on I 75 in Northern Kentucky and projects on I 71, however, contained crushed calcareous glacial gravel. Fine aggregates were natural sand, comprising 34 to 40 percent of the combined solid volume of the fine and coarse aggregate. Sections of road containing crushed calcareous glacial gravel aggregate exhibited the same performance histories as sections with limestone aggregate. There was, however, a slight difference in the minus 2.5 standard deviation. The lower limit for sections of road with glacial gravel aggregate was about one skid number less than that obtained for all sections; the values for sections of road with limestone coarse aggregate was the same as for all sections.

Tests of portland cement concrete surfaces (burlap drag texturing) with low values of cumulative traffic indicated initial SN's on the order of 55. Subsequent loss of skid resistance occurred as the roadway sections accumulated traffic. SN's, for surfaces with less than 2,500 vehicles per day, dropped to about 49 after only one million vehicle passes and continued decreasing less rapidly to a SN of 48 after seven million vehicle passes. For these sections, the lower limit indicated that 99.4 percent maintained SN's greater than 34 at seven million vehicle passes. For surfaces with more than 2,500 vehicles per day, the SN was 49 at one million vehicle passes, dropped to 41 at ten million vehicle passes, and continued decreasing to SN 35 at sixty million vehicle passes. Also, for sections with more than 2,500 vehicles per day, the lower limit indicated that 99.4 percent maintained SN's greater than 29 at 60 million vehicle passes.

Kentucky Rock Asphalt

Although Kentucky rock asphalt is not currently being applied in Kentucky, the skid resistance performance is useful for comparison. Twenty projects were tested during 1975. Data were insufficient to determine initial skid resistance. Skid numbers decreased to about 56 after one million vehicle passes and continued decreasing to about 49 at ten million vehicles passes. The lower limit indicated that 99.4 percent of these sections maintained SN's greater than 36 at nine million vehicle passes.

Sand Asphalt

Limestone sand obviously reduced the frictional levels of sand-asphalt surfaces constructed prior to 1970 (1, 11). Continued study demonstrated that better sands could be selected on the basis of mineral composition, gradation, and partical shape (12). Sand-Asphalt (Skid Resistant), Special Provision 59B, resulted. With continued refinement of mineral composition and gradation, the mixture evolved into Sand-Asphalt Surface, Type I, and Sand-Asphalt Surface (Skid Resistant), Type II.

Sand-Asphalt, Type I -- Sand-Asphalt, Type I, is intended to provide a thin, fine-textured wearing surface from aggregates generally available from commercial sources. This mixture has been used since 1974. Aggregates included natural sand, natural sand with slag sand, natural sand with limestone sand, pit sand with limestone sand, and slag sand with natural sand. Initial SN's were about 42. The best-fit line indicated a decrease in SN to 39 at ten million vehicle passes. Scatter caused the minus 2.5 standard deviations to drop to a SN of 24 at ten million vehicle passes. However much of the scatter resulted from combining data for different aggregate types.

Sand-Asphalt (Skid Resistant), Special Provision 59B -- Three adjacent sections of road were surfaced in 1972 and 1973. The aggregate was crushed quartz gravel. Performance was expected to depend on the degree of crushing and sharpness achieved. SN's were about 47 after one million vehicle passes and decreased slowly to about 45 at ten million vehicle passes. The lower limit, determined by regression analysis, indicated that 99.4 percent of the SN's were greater than 35 up to ten million vehicle passes.

Sand-Asphalt (Skid-Resistant), Type II -- Sand-Asphalt (Skid Resistant), Type II, is fine-textured and has been used since 1974.

Aggregates included slag sand, slag sand with natural sand, quartz sand, quartz sand with mortar sand, and crushed gravel sand with crushed limestone sand. Several projects yielded low SN's. The data were divided into two groups -- urban and rural. Almost all of the low SN's were in urban areas. The reasons remain a point of conjecture and require further study. Sections in rural areas had initial SN's near 54 and maintained SN's near 46. The lower limit indicated that 99.4 percent of the sections had SN's greater than 34 at four million vehicle passes. Sections in urban areas had initial SN's near 44 and maintained SN's near 30. The lower limit for these sections was less than 14 at ten million vehicle passes.

Open-Graded Friction Courses

Open-graded friction courses (OGFC) were first used in Kentucky in 1973. Since then, over 50 sections have been paved. Most of these sections were Type 1 -- allowing aggregate sizes up to 13 mm (1/2 inch). Six of the sections were Type 2 -- allowing aggregate sizes up to 10 mm (3/8 inch). Aggregate included crushed quartz gravel, crushed quartz gravel with limestone aggregate, crushed slag, crushed granite, crushed conglomerate gravel, crushed conglomerate gravel with limestone aggregate, limestone with crushed gravel, and limestone aggregate with crushed granite.

For Type 1 OGFC using crushed quartz gravel (Green River) aggregate, with and without limestone aggregate (Figure 4) initial SN's were less than 43. SN's increased to 48 at one million vehicle passes and to 53 at ten million vehicle passes. The lower limit was initially lower but improved to 40 after ten million passes.

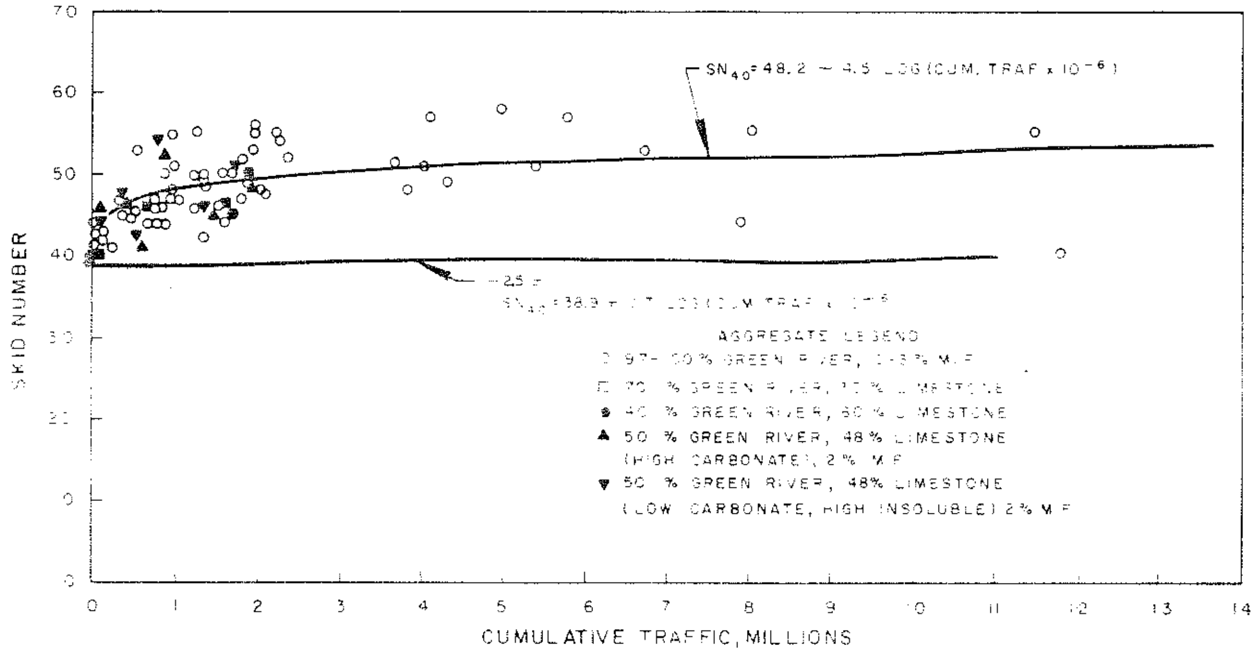

Figure 4. Effect of Traffic on Skid Resistance of Open-Graded Friction Courses, Type 1 -- Crushed Quartz Gravel (Green River).

For Type 1 OGFC using crushed slag with and without limestone aggregate initial SN's were about 53. After one million passes, the SN had decreased to 49. Mature values were about 44. There was sufficient scatter of data to result in a lower limit SN of 32 at 15 million passes.

For Type 1 OGFC using crushed gravel aggregate with and without limestone, initial SN's varied considerably -- from 37 to 68 -- with an average of about 54. They maintained an average SN near 50. The lower limit was a SN of 29 at five million passes.

Data for Type 1 OGFC using crushed granite were limited, but indicated mature SN's greater than 50 and a lower limit of about 40.

The limited data for Type 2 OGFC for all aggregate types indicated mature SN's near 47. Data were insufficient to determine a lower limit.

At three locations, sections of the Type 1 OGFC were placed without limestone aggregate, and adjacent sections included limestone aggregate. The SN's at two million vehicle passes for each of the nine sections are plotted in Figure 5. Limestone

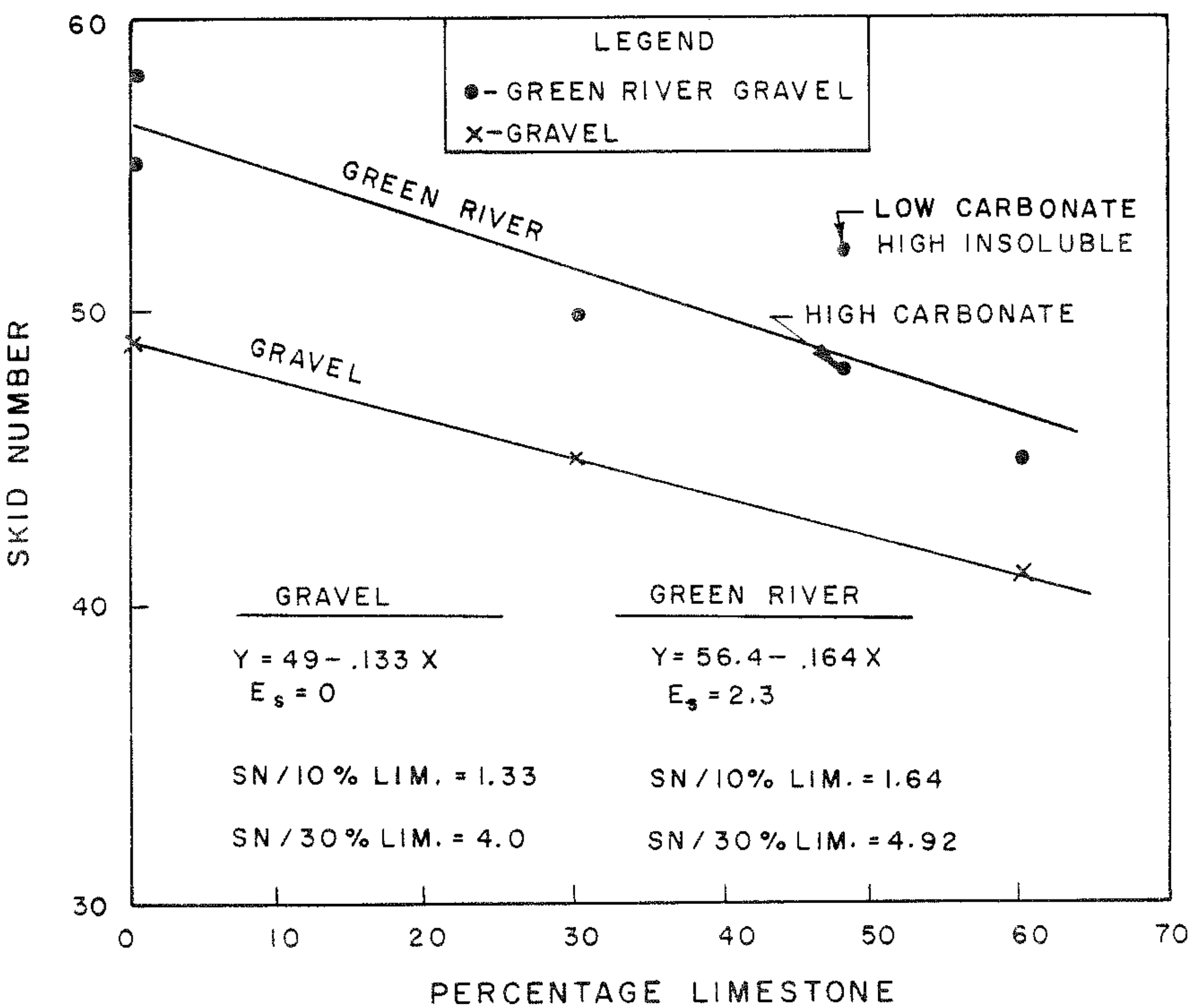

Figure 5. Effect of Limestone Sand on Skid Resistance of Open-Graded Friction Courses, Type 1, at Two Million Vehicle Passes.

aggregate reduced the skid resistance of the Type 1 OGFC using crushed quartz gravel (Green River) by 1.64 SN for each ten percent of limestone aggregate in the mixture. The low-carbonate, high-insoluble limestone performed slightly better than average -- reducing the skid resistance by 1.25 SN for each ten percent of limestone aggregate in the blend. The high-carbonate limestone aggregate performed sightly worse than average -- reducing the skid resistance by 2.0 SN for each ten percent of limestone aggregate in the blend. Limestone aggregate reduced the skid resistance of the Type 1 OGFC using crushed bank gravel by 1.33 SN for each ten percent of limestone used.

BENEFITS AND COSTS

Benefits

Benefits herein were derived from calculations of the reduction in the number of wet-pavement accidents. The reduction depends on the previous SN of the road, the SN after de-slicking and the traffic volume. To quantify these relationships, wet-pavement accidents per km (mile) during 1979, on roads skid tested in 1977 and 1978, were analyzed. The data were stratified by AADT and each AADT group was subdivided, by equal number of wet-pavement accidents, into six groups. The resulting values and best-fit lines are shown in Figure 6. Here, SN was the independent

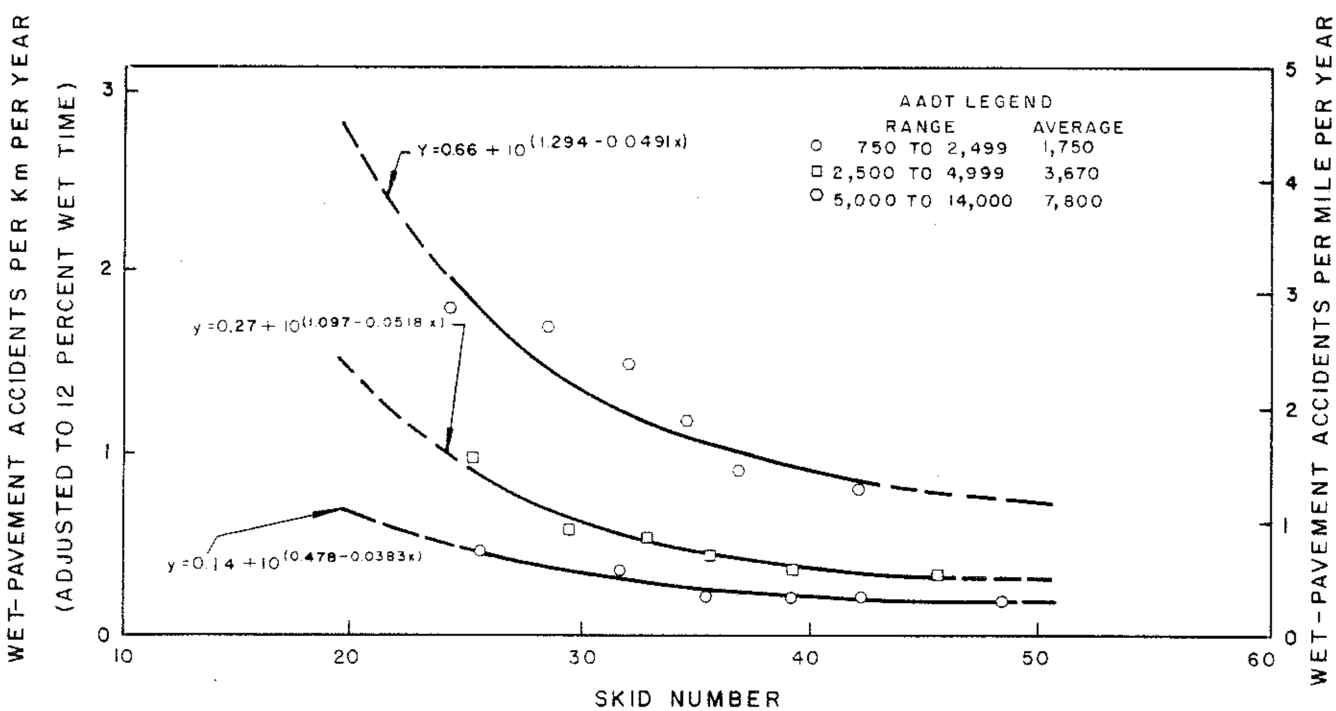

Figure 6. Wet-Pavement Accidents per Mile (km) per Year (Adjusted to 12 Percent Wet Time) versus Skid Number (1979); 1,132 Sections (about 4,400 miles (7,100 km)) of Rural, Two-Lane Roads; Stratified by AADT; Grouped by Equal Number of Wet-Pavement Accidents.

variable. The three curves were also converted so that traffic volume was the independent variable, and the resulting family of curves is shown in Figure 7. These relationships show, for example, that, if a road with a SN of 20 and AADT of 8,000 were deslicked and improved to a SN of 40, wet-pavement accidents would be reduced from 2.8 to 1.0 per km (4.4 to 1.5 per mile) per year and result in a benefit of $11,700 per km ($18,850 per mile) per year. The average cost of a wet-pavement accident was calculated based on accidents on rural, two-lane roads in Kentucky and cost of fatal, injury, and property-damage-only accidents cited by the National Safety Council (13).

Performance evaluation of pavements has shown that SN's obtained vary considerably for each type of surface. Thus, to

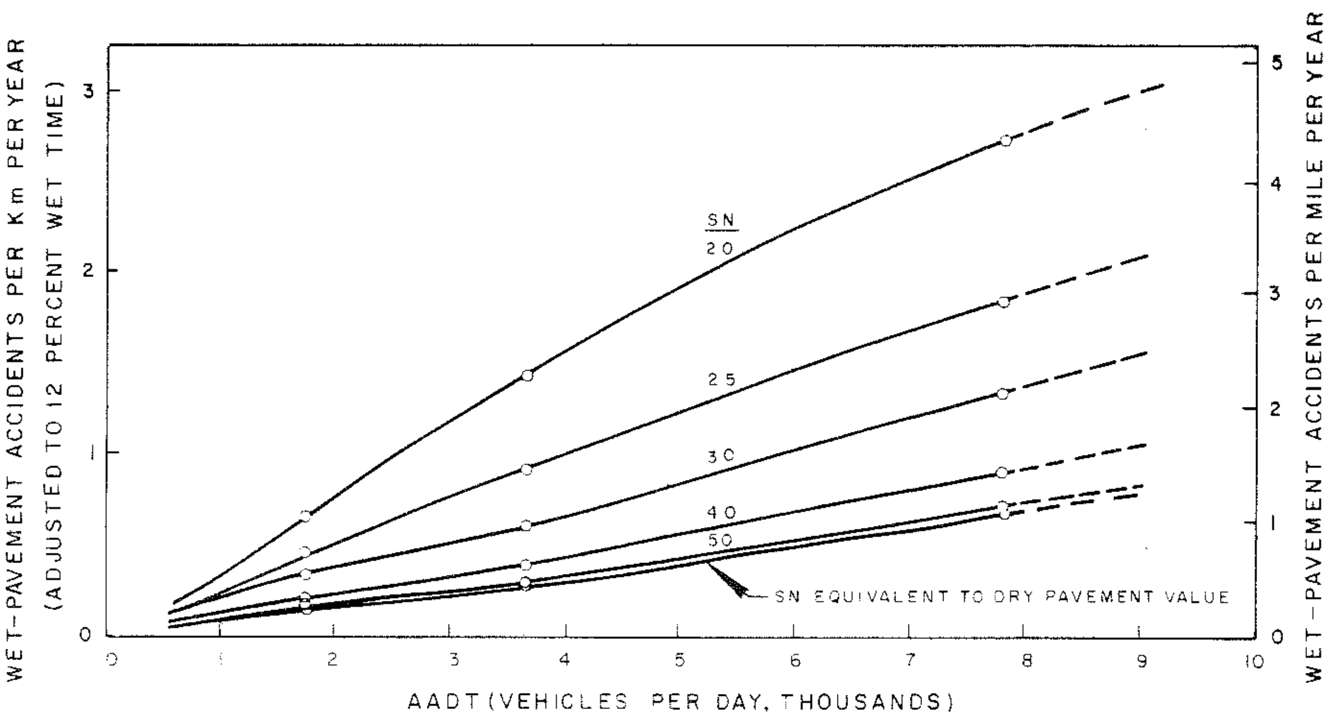

Figure 7. Wet-Pavement Accidents per Mile (Km) per Year (Adjusted to 12 Percent Wet Time) (1979), from Best-Fit Curves of Figure 6, versus Traffic Volume.

ascertain benefits expected, the deviations of SN's expected must be included. The analysis used the mean SN and three standard deviations for each surface at the cumulative traffic corresponding to the half-life of the pavement (see Table 4) and at the three levels of AADT cited in Figure 6. These distributions were combined with the curves of Figure 6 to yield the number of wet-pavement accidents per km (mile) per year expected after surface renewal. This value was subtracted from the number of wet-pavement accidents before surface renewal, indicated in Figure 6, for several SN's. The differences times the average cost of a wet-pavement accident in Kentucky in 1979 ($6,500) yielded the benefits per km (mile) per year.

TABLE 4. MEAN SKID NUMBER OF PAVEMENTS AND STANDARD DEVIATION AT INDICATED CUMULATIVE TRAFFIC

AADT RANGE	750 - 2,499		2,500 - 4,999		5,000 - 14,000	
AADT AVERAGE	1,750		3,670		7,800	
HALF-LIFE (YEARS)	7.1		6.1		4.1	
CUMULATIVE TRAFFIC (MILLIONS)	2.3		4.1		5.8	
PAVEMENT	MEAN SN	STANDARD DEVIATION	MEAN SN	STANDARD DEVIATION	MEAN SN	STANDARD DEVIATION
Class I, Bituminous, Interstate & Toll Roads:						
AADT 1,000 - 2,499	45.4	4.3	...	...	...	...
AADT 2,500 - 46,120	...	...	42.9	6.5	41.8	6.2
Class I, Bituminous, US & KY Roads:						
AADT 1,000 - 2,499	40.7	4.9	...	...	...	...
AADT 2,500 - 34,000	...	...	39.0	6.1	38.7	6.1
Sand-Asphalt, Type I	39.5	5.2	39.2	5.5	39.0	5.6
Sand-Asphalt, Type II:						
(Rural)	47.9	5.2	47.0	5.2	46.4	5.1
(Urban)	34.1	9.6	32.3	8.4	31.3	7.7
Open-Graded, Friction Course, Type 1:						
Green River Gravel	49.8	4.2	51.0	4.6	51.6	4.8
Slag	47.7	4.3	46.7	4.5	46.2	4.7
Gravel	51.2	8.3	50.1	8.3	49.4	8.3
Granite	50.6	4.3	51.9	4.4	52.7	4.4

Cost

Initial costs (1979 dollars) of the various surface courses for the minimum thicknesses required for surface renewal are cited in Table 5. Those costs are for a 7.3-meter (24-foot) wide two-lane road and do not include leveling or other incidental work.

The other input for determining cost is the estimated service life. The service life, for the ranges of AADT cited in Figure 6, were estimated as 14, 12, and 8 years; for low, medium, and high values of AADT, respectively. Dividing the cost by the estimated life and allowing a ten-percent cost per year of money gave the estimated costs per km (mile) per year as cited in Table 5.

Benefit-Cost Analysis

The benefit-cost ratios (Table 6) indicated that use of any surface is cost effective for surface renewal if the AADT is more than 2,500 and the existing SH's are low. In fact\ if an existing pavement with an AADT of 5,000 or more has a SN as high as 34, application of an overlay using Open-Graded Friction Course, Type 1, yields a ratio of 1.0. Thus, from a cost-effectiveness

TABLE 5. COST OF VARIOUS SURFACE COURSES

SURFACE MIX	COARSE AGGREGATE	THICKNESS (MM)(INCHES)	TONS PER KM(MILE)	DOLLAR COST (1979) PER TON(TON)	DOLLAR COST (1979) PER KM(MILE)*	COSTS PER KM(MILE) PER YEAR (THOUSANDS) LOW AADT	MED AADT	HIGH AADT
Class I, Bituminous	Limestone	25 (1)	436 (774)	22.12 (24.38)	11,725 (18,866)	3.20 (5.14)	3.08 (4.95)	3.12 (5.02)
Class I, Bituminous	Crushed Gravel	25 (1)	432 (767)	21.34 (23.52)	11,214 (18,043)	3.06 (4.92)	2.94 (4.74)	2.98 (4.80)
Class I, Bituminous	Slag	25 (1)	405 (719)	20.75 (22.87)	10,206 (16,422)	2.78 (4.48)	2.68 (4.31)	2.71 (4.37)
Class AA, Bituminous	Crushed Gravel	25 (1)	436 (774)	26.67 (29.40)	14,143 (22,756)	3.85 (6.20)	3.71 (5.98)	3.76 (6.05)
Open-Graded, Friction Course	Various	19 (3/4)	258 (458)	26.76 (29.50)	8,397 (13,511)	2.29 (3.68)	2.21 (3.55)	2.23 (3.59)
Sand-Asphalt, Type I	Various	16 (5/8)	258 (458)	29.20 (32.19)	9,162 (14,741)	2.50 (4.02)	2.41 (3.87)	2.44 ([illegible])
Sand-Asphalt, Type II	Various	16 (5/8)	258 (458)	27.08 (29.85)	8,497 (13,671)	2.32 (3.73)	2.23 (3.59)	2.26 ([illegible])

* Cost for a 7.3 meter (24-foot) wide, two-lane road; does not include leveling or other incidental work.

perspective, efforts should continue, as in the past, to use available monies to de-slick pavements with the lowest SN's to reduce wet-pavement accidents the most and achieve the greatest benefits.

In most cases, surfaces yielding the highest benefit-cost ratios should be selected for the overlay. Open-graded friction course provides the best ratio. However, if future costs change or vary for certain locations, another surface may be selected. Additionally, other considerations may warrant selection of other surfaces. Ultimately, benefit and cost information should be an input to priority programming of a pavement management system.

TABLE 6. BENEFIT-COST RATIOS FROM OVERLAYING

PAVEMENT	AADT*	WET/KM (MILE) EXPECTED**	SKID NUMBER BEFORE OVERLAYING 20	22	24	26	28	30	32	34	36	38	40
Class I, Bituminous, Interstate & Toll Roads:	LOW	0.20 (0.32)	0.9	0.8	0.6	0.5	0.4	0.3	0.3	0.2	0.1	0.1	0.1
	MED	0.40 (0.64)	2.2	1.7	1.3	1.0	0.7	0.5	0.4	0.3	0.2	0.1	0.0
	HIGH	0.92 (1.48)	3.8	3.0	2.3	1.7	1.3	0.9	0.6	0.4	0.2	0.1	0.0
Class I, Bituminous, US & KY Roads:	LOW	0.25 (0.40)	0.9	0.7	0.6	0.4	0.3	0.3	0.2	0.1	0.1	0.0	...
	MED	0.44 (0.70)	2.1	1.6	1.2	0.9	0.6	0.4	0.3	0.1	0.0	0.0	...
	HIGH	1.00 (1.60)	3.6	2.8	2.1	1.5	1.1	0.7	0.4	0.2	0.0	...	...
Sand-Asphalt, Type I	LOW	0.25 (0.40)	1.1	0.9	0.7	0.5	0.4	0.3	0.2	0.1	0.1	0.0	0.0
	MED	0.42 (0.68)	2.7	2.1	1.6	1.1	0.8	0.6	0.4	0.2	0.1	0.0	...
	HIGH	0.98 (1.56)	4.0	3.6	2.7	2.0	1.4	1.0	0.6	0.4	0.1	0.0	...
Sand-Asphalt, Type II (Rural)	LOW	0.20 (0.32)	1.3	1.1	0.9	0.7	0.6	0.5	0.4	0.3	0.2	0.2	0.1
	MED	0.33 (0.53)	3.2	2.5	1.9	1.5	1.1	0.9	0.6	0.5	0.3	0.2	0.1
	HIGH	0.80 (1.28)	5.6	4.4	3.4	2.6	2.0	1.6	1.2	0.9	0.6	0.4	0.3
(Urban)	LOW	0.39 (0.63)	0.9	0.6	0.4	0.3	0.1	0.0	...	...	...	...	...
	MED	0.77 (1.21)	2.1	1.4	0.8	0.4	0.0	...	...	...	...	...	...
	HIGH	1.56 (2.50)	3.5	2.3	1.4	0.6	0.0	...	...	...	...	...	...
Open-Graded, Friction Course, Type I: Green River Gravel	LOW	0.17 (0.27)	1.4	1.1	0.9	0.8	0.6	0.5	0.4	0.3	0.3	0.2	[illegible]
	MED	0.30 (0.48)	3.3	2.6	2.0	1.6	1.2	0.9	0.7	0.5	0.4	0.3	0.2
	HIGH	0.73 (1.17)	5.8	4.6	3.6	2.8	2.2	1.7	1.4	1.0	0.3	0.6	0.4
Slag	LOW	0.20 (0.32)	1.3	1.1	0.9	0.7	0.6	0.5	0.4	0.3	0.2	0.2	0.1
	MED	0.34 (0.54)	3.2	2.5	2.0	1.5	1.2	0.9	0.6	0.5	0.3	0.2	0.1
	HIGH	0.81 (1.29)	5.6	4.4	3.4	2.7	2.1	1.6	1.2	0.9	0.6	0.4	0.3
Gravel	LOW	0.18 (0.29)	1.4	1.1	0.9	0.7	0.6	0.5	0.4	0.3	0.2	0.2	0.1
	MED	0.32 (0.51)	3.3	2.5	2.0	1.5	1.2	0.9	0.7	0.5	0.4	0.3	0.2
	HIGH	0.78 (1.25)	5.6	4.4	3.5	2.7	2.1	1.6	1.2	0.9	0.7	0.5	0.3
Granite	LOW	0.17 (0.27)	1.4	1.1	0.9	0.7	0.6	0.5	0.4	0.3	0.3	0.2	[illegible]
	MED	0.29 (0.47)	3.3	[illegible]	2.0	1.6	1.2	0.9	0.7	0.6	0.4	0.3	[illegible]
	HIGH	0.72 (1.15)	5.8	[illegible]	3.6	2.9	2.2	1.8	1.4	1.1	0.8	0.6	0.4

* Refer to legend of Figure 6.
** Wet-pavement accidents per km (mile) per year after overlaying.
NOTE: Benefits from reduction of wet-pavement accidents only.

SUMMARY

The estimated SN's at 0.1, 1, 5, 10, and 60 million vehicle passes (Table 3) represent median values for each type of pavement -- half of the sections had higher SN's and half lower SN's. The highest median SN's were for Open-Graded Friction Course, Type 1, with crushed Green River gravel. The other pavements had SN's of 38 or higher, except for Sand-Asphalt, Type II, constructed in urban areas. The SN's at minus 2.5 standard deviations represent values that are exceeded by 99.4 percent of the paving projects. These values are presented in Figure 8 and provide an indication of worst-case performance.

The criterion for new pavements specifies that the mature SN of a surface, at minus 2.5 standard deviations (99.4 percent

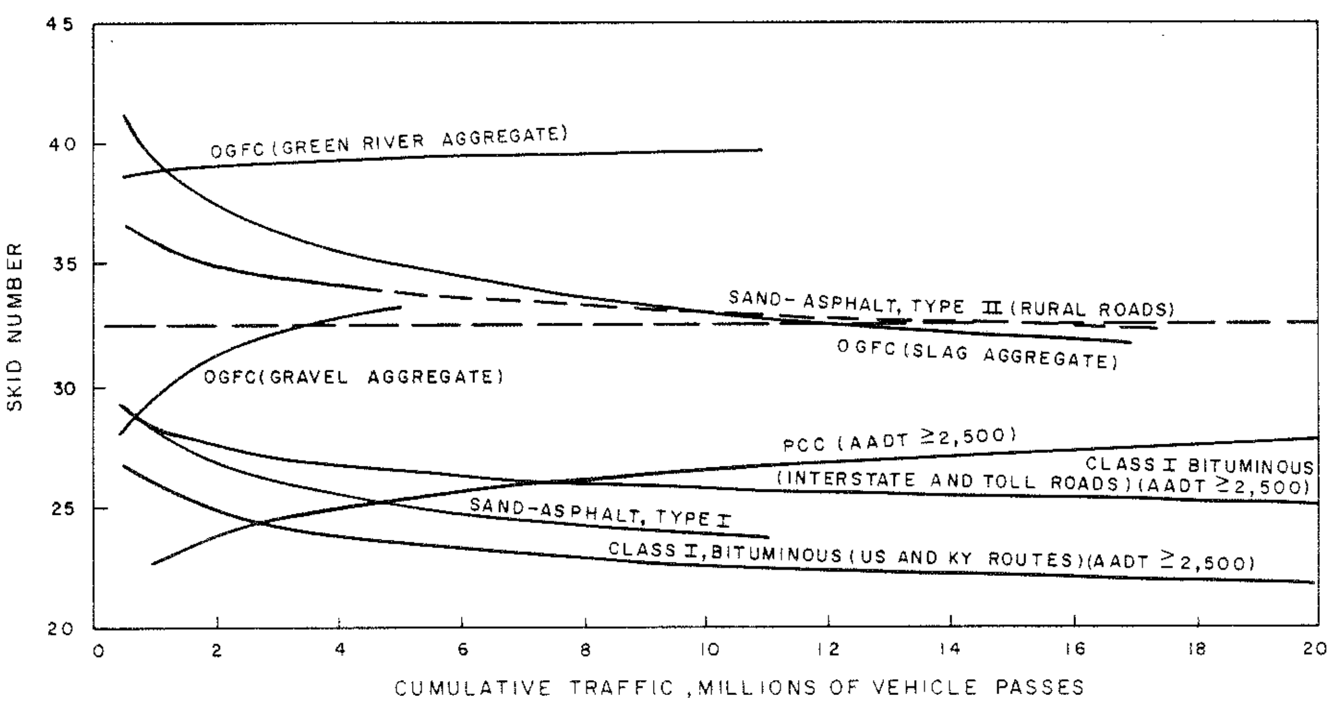

Figure 8. Minus 2.5 Standard Deviations (99.4-Percent Assurance) for Several Pavement Types.

assurance), must exceed 32. Class I bituminous and portland cement concrete pavements (burlap drag texturing) with AADT's more than 2,500 and Sand-Asphalt (Type I) pavements did not provide the necessary assurance of SN's greater than 32. Class I bituminous (interstate and toll-road quality) and portland cement concrete, with AADT's less than 2,500 (not shown in Figure 8), provided suitable SN's throughout their lives. Open-graded friction courses with Green River aggregate provided suitable SN's through the number of vehicle passes accumulated to date and, by interpolation, through the life of the pavement. Open-graded friction courses with slag aggregate provided adequate SN's through 12 million vehicle passes. For 8-year service life, this surface is suitable for roads with AADT less than 8,200. Conversely, if applied to a road with AADT of 11,000 vehicles per day, the surface may exhibit SN's of 32 or less after only 6 years and may require surface renewal at that time. Open-graded friction courses, with other gravel aggregate, provided necessary assurance against low SN's to one million vehicle passes; however, data were too limited to allow final assessment. Sand-Asphalt, Type II, on rural roads, provided adequate SN's through 15 million vehicle passes. For an 8-year service life, this corresponds to an AADT of 10,300.

Service life has been estimated based on AADT (see Table 4). Using current costs of overlay (see Table 5), benefit-cost analyses indicated that overlaying an existing pavement having an SN less than 35 and AADT greater than 5,000 yields benefits from reduction of wet-pavement accidents to equal or exceed the cost of overlay. Benefits also exceeded costs for roads with SN's less than 30 and AADT greater than 2,500 and for roads with SN's less than 24 and

AADT greater than 750. Additional benefits (10), which may be included in an expanded analysis, include increased comfort, time savings, fuel savings, maintenance savings, and reduction of other types of accidents.

A minimum SN of 28, for roads with more than 1,000 vehicles per day, has been recommended to safeguard the public from undue hazards associated with slippery pavements regardless of the accident history of the road. Also, as indicated from the relationship between skid resistance and cumulative traffic, the best surface does not assure mature SN's above 45. Thus, criteria for the design of surface courses concern primarily the range of SN's between 28 and 45. The percentages of pavement sections estimated to equal or exceed, at 10 million vehicle passes, these values were determined (see Table 7). At least 95 percent of all

TABLE 7. PERCENTAGE OF PAVEMENT SECTIONS HAVING SKID NUMBERS EQUAL TO OR EXCEEDING SELECTED MINIMUM AT 10 MILLION VEHICLE PASSES

	MINIMUM SKID NUMBER AT 10 MILLION VEHICLE PASSES																	
PAVEMENT	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
Class I, Bituminous, Interstate & Toll Roads:																		
AADT 1,000- 2,499	100	100	100	100	100	99	99	98	97	96	93	90	85	79	72	64	55	<50
AADT 2,500- 46,120	98	98	96	95	93	90	86	82	77	71	65	58	50	<50				
Class I, Bituminous, US & KY Roads:																		
AADT 1,000- 2,499	99	99	98	97	95	92	87	80	72	62	52	<50						
AADT 2,500- 34,000	95	93	90	87	84	80	75	70	64	58	51	<50						
Portland Cement Concrete:																		
AADT 1,000- 2,499	100	100	100	100	100	99	99	98	98	97	95	93	91	88	85	81	76	70
AADT 2,500- 38,200	99	98	97	96	95	93	90	86	83	78	72	66	60	53	<50			
Kentucky Rock Asphalt	100	100	100	100	100	100	100	100	99	99	98	97	96	94	91	88	84	79
Sand-Asphalt, Type I	97	95	93	90	87	85	79	75	68	61	54	<50						
Sand-Asphalt, SP 59B	100	100	100	100	100	100	99	99	99	98	96	94	91	86	80	73	65	56
Sand-Asphalt, Type II:																		
(Rural)	100	100	100	100	100	99	99	98	97	95	93	90	86	82	76	67	62	54
(Urban)	61	54	<50															
Open-Graded, Friction Course, Type 1:																		
Green River Gravel	100	100	100	100	100	100	100	100	100	100	100	99	99	99	98	97	95	93
Slag	100	100	100	100	100	100	99	98	97	95	93	90	86	81	75	68	41	52
Gravel	99	99	98	98	97	97	96	95	93	91	89	87	84	81	78	74	70	66
Granite	100	100	100	100	100	100	100	100	100	100	100	100	100	99	99	99	98	97

pavement sections -- except Sand-Asphalt, Type II (urban) -- provided SN's greater than or equal to a SN of 28. However, if the level of skid resistance required is SN of 32 and the desired percentage level is again 95 percent, then Class I bituminous (high AADT roads) and Sand-Asphalt, Type I -- in addition to Sand-Asphalt, Type II (urban) -- are not suitable. The percentages are useful for selecting pavement types to meet different requirements and to assure due margin of safety. Other criteria for selecting surface courses include speed effects (see Figure 2) and seasonal variations in skid resistance.

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