Use of Skid Performance History as Basis for Aggregate Qualification for Seal Coats and Hot-Mix Asphalt Concrete Surface Courses

PRIYANTHA W. JAYAWICKRAMA AND GARY L. GRAHAM

The polish value (PV) test is a commonly used laboratory test procedure for evaluating the frictional properties of aggregates used in asphalt concrete surface courses. However, the success that has been achieved with this method is limited owing to the poor correlation between laboratory PV values and skid numbers measured in the field. In recognition that some low PV aggregates have provided good skid performance in the field, the Texas Department of Transportation permits aggregates to be qualified on the basis of their historical skid performance on in-service pavements. The current procedure used in developing the skid performance history is based on the guidelines established in the FHWA skid accident reduction program IM 21-2-73. The Texas Department of Transportation's experience with both of these approaches to skid control—aggregate source rating based on polish value and aggregate qualification based on past skid performance data—is documented. The skid performance approach is dealt with in greater detail. A number of shortcomings in the current procedure are identified. The variability in skid measurements and its influence on the reliability of the aggregate qualification procedure are discussed. An extension to the current procedure is proposed so that the reliability of prediction can be appropriately incorporated in the procedure. A research methodology to address the deficiencies in the current aggregate qualification procedure, and hence improve its reliability, is outlined.

The aggregate source rating based on *polish value*, or *RSPV*, is the primary mechanism used by the Texas Department of Transportation (TxDOT) in its skid accident reduction program. The polish value is determined for the coarse aggregates used in the preparation of the asphalt concrete mix. It represents the aggregate friction as recorded by the British pendulum tester (BPT) after it has been subjected to 9 hr of accelerated polishing in the presence of water and abrasive grit. The polish value is believed to represent the ultimate frictional characteristics of the aggregate after it has been in service for a long period. This approach to skid accident reduction is based on the concept that satisfactory pavement skid resistance may be ensured by controlling the polishing characteristics of the mineral aggregates.

Unfortunately, the results obtained from many previous research studies (*1–6*), conducted primarily in Texas, indicate that good correlation between aggregate polish value and measured skid properties on in-service pavements does not exist. Hence, low-aggregate polish value may not necessarily be indicative of poor pavement skid performance. In recognition of this fact, TxDOT permits aggregate sources to be qualified on the basis of satisfactory historical skid performance. The procedure used in establishing the skid performance history is based on the guidelines set forth in the FHWA administrative circular IM 21-2-73 (*7*). Until this time, only a few TxDOT districts, such as Corpus Christi (DS-16) and Pharr (DS-21), have used this alternative procedure consistently. Other districts, such as El Paso (DS-24), Childress (DS-25), and San Antonio (DS-15), have used the procedure occasionally.

The alternative approach, which relies on actual field performance of the aggregates rather than laboratory performance, may have considerable potential of being used effectively in TxDOT's skid accident reduction program. However, during the use of the procedure, the authors have identified a number of shortcomings and limitations. This paper documents the authors' observations and TxDOT's experience with the use of the skid performance history approach for evaluating aggregate frictional properties. The paper begins with an overview of some of the fundamental concepts related to skid performance of pavements and a brief review of both polish value and skid performance history methods. Subsequently, the skid performance history method is reviewed critically in terms of its advantages as well as its shortcomings and limitations. The paper concludes with a brief outline of a research methodology to overcome the deficiencies of the current procedure.

GENERAL BACKGROUND

A brief overview of some of the fundamental concepts related to pavement skid performance is presented. The overview will serve as the foundation for the discussions presented later in this paper.

Factors Controlling Pavement Skid Characteristics

The friction that develops between the tire and the pavement surface is the result of two separate mechanisms: adhesion and hysteresis.

Adhesion

Adhesion represents the frictional component due to tangential shearing forces that develop at the actual contact surface between

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P. W. Jayawickrama, Department of Civil Engineering, Texas Tech University, Lubbock, Tex. 79409-1023. G. L. Graham, Division of Highway Design, Pavements Section, Texas Department of Transportation, 125 East 11th Street, Austin, Tex. 78701-2483.

the tire and the aggregate. Its magnitude is determined by the *microtexture*, or the fine-scale grittiness present on the aggregate surface. As the aggregate polishes under the effects of traffic, microtexture is lost, resulting in lower adhesion. Laboratory polish value is a measure of how fast and how easily an aggregate loses its microtexture under traffic action.

Hysteresis

As the tire moves on and around the aggregate particles on the pavement surface, the rubber material of the tire deforms. These deformations cause additional loss of energy. This frictional component between the tire and the pavement is called hysteresis. Its magnitude is controlled by the *macrotexture*, or the large-scale asperities present on the pavement surface. Macrotexture represents the overall topography of the pavement surface, which is a function of the size, shape, and gradation of the coarse aggregates.

Relationship Between Skid Number and Test Speed

The skid number (SN) and the speed at which it is measured (V) are inversely related; in other words, skid number decreases as the speed increases. Figure 1 depicts the relationship between SN and V.

The inverse relationship between the skid number and the test speed is explained as follows. The skid numbers are measured under wet pavement conditions, and hence they depend on the thickness of the water film between the tire and the pavement surface. As the tire moves over the wet pavement surface, water is displaced from underneath the tire. At low speeds, the rate of expulsion of the water is low and the flow rate could be easily accommodated by the grooves in the tire and the macrotexture in the pavement. At these speeds the measured skid number depends primarily on the microtexture of the pavement and is independent of the macrotexture. However, as the speed increases, the rate of water expulsion from underneath the tire increases as well. If the pavement has a smooth macrotexture, the channels on the pavement surface will now be unable to handle the larger flow rate. As a result, the thickness of the water film underneath the tire increases and the measured skid number decreases rapidly. A heavily textured pavement, however, will have better drainage capability and therefore will be able to maintain the skid number at a higher level. Therefore, in a pavement with good macrotexture, the skid number does not decrease with speed as much as it does on a pavement with poor macrotexture. This hypothesis for explaining the SN-V relationship has been confirmed by observed behavior. Typical SN-V relations for different combinations of micro- and macrotextures are shown in Figure 1 (*left*).

The relationship between SN and V can be described by the following equation (*9*) and is graphically presented in Figure 1 (*right*).

$$SN = SN_0\, e^{-(PNG/100)\cdot V} \tag{1}$$

where SN_0 is the intercept of the curve with the *y*-axis representing the fictitious SN at speed zero. The magnitude of SN_0 is a function of the microtexture of the pavement. PNG stands for percentage normalized gradient and represents the slope of the curve. PNG is a measure of macrotexture of pavement; they are inversely related: the greater the macrotexture in the pavement, the smaller the magnitude of the slope (PNG).

As a result, good correlation should not be expected between the skid number measured at the standard test speed of 64 km/hr (40 mph), denoted by SN_{40}, and laboratory polish value. Instead, statistical regression should be performed between SN_0 and the labora-

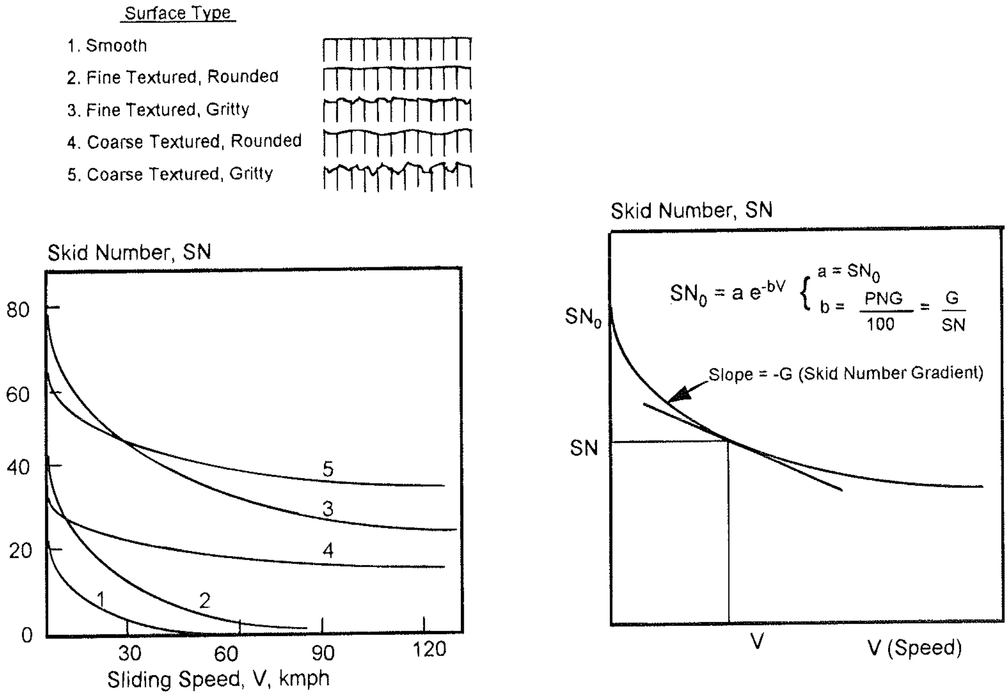

FIGURE 1 Variation in skid number with test speed: ***left*****, Kummer and Meyer (*****8*****);** ***right*****, Meyer (*****9*****).**

tory tests data concerning aggregate polishing characteristics. A correlation developed in a recent study using this approach yielded $R^2 = .948$ (*9*). Similarly, regression equations can be developed to relate PNG and parameters that control macrotexture such as aggregate gradation. The same study (*9*) used mean texture depth as determined by the sand patch method and obtained $R^2 = 0.96$.

This approach, which allows separation of the micro- and macrotexture components in the skid numbers, shows considerable promise. However, it must be noted that the method requires that the SN-V relation be established for each pavement section under investigation. For this purpose it will be necessary to perform skid tests at several speeds.

Existing Approach Based on Rated Source Polish Value

As mentioned earlier, rated source polish value (*RSPV*) is the primary mechanism used in Texas for evaluating the frictional characteristics of aggregate sources. An *RSPV* is required only for those sources that produce material for pavement *surface* courses. As a first step, the candidate source must be included in the department's quality monitoring (*QM*) program. All aggregate sources included in the *QM* program are sampled by a department representative on a regular basis. The samples are then tested in the TxDOT Materials and Tests Division laboratories to determine their polish value. All polish value samples are prepared and tested in accordance with Test Method Tex-438-A, Accelerated Polish Test for Coarse Aggregates. The *RSPV* for the aggregate source will be calculated on the basis of the five most recent *QM* polish value (PV) test results. The *RSPV* for a given aggregate source represents the lower statistical limit of the PV values above which 90 percent of the aggregate sample population from that source should fall. The equation used in this calculation is as follows (*10*):

$$RSPV = \bar{x} - 1.533\left(\sqrt{\frac{MS}{5}}\right) \qquad (2)$$

where $\bar{x}$ is the average of the five most recent *QM* polish values and *MS* is the variance of the five most recent *QM* polish values.

The sampling frequency for a given aggregate source will depend on two factors: (*a*) volume of material supplied to the department annually, and (*b*) variability in the polish values measured in previous tests. If the variance of the five samples used to calculate RSPV does not exceed 3.5 *and* the volume of material supplied is less than 100,000 tons per year, then the sampling frequency for aggregate source will be once every 6 months. But if the volume of material supplied annually is more than 100,000 tons, the sampling frequency is increased to once every 3 months. However, if the variance of the five samples used to calculate the *RSPV* is 3.5 or greater, a suitable sampling frequency for that specific source will be determined after the PV data are evaluated.

This procedure for establishing an *RSPV* is applicable only to aggregate sources that have maintained *active status* within the department's *QM* program. Such aggregate sources may supply materials to pavement construction projects provided that their *RSPV* satisfies the minimum PV requirement for the given project. The minimum PV requirement depends on the traffic volume expected on the roadway, as indicated in Table 1. Other sources that do not have an *RSPV*—called *informational sources*—are required to qualify their material on a project-by-project basis.

TABLE 1 TxDOT PV Requirements

ADT	Minimum PV
Greater than 30,000	35
5,000 to 30,000	32
2,000 to 5,000	30
750 to 2,000	28
Less than 750	No requirement

The method for evaluating aggregate frictional characteristics relies on the results of the aggregate polish value as determined by Test Method Tex-438-A. There have been a number of criticisms of the use of a laboratory PV criterion to evaluate aggregate performance in the field, many of which stem from the poor correlations that have been observed between the laboratory PVs and the field skid measurements as determined using the locked-wheel skid trailer.

It is now recognized that one of the major reasons for observed discrepancy is the difference in test speed. The speed at which the rubber shoe of the BPT contacts the surface of the specimen is approximately 7 mph. At such low speeds the adhesion component of the friction is dominant. As described previously, this component is primarily a function of the microtexture of the contacted surface. Although BPT measurements are made with the surface wetted, the hydrodynamic effects that are controlled by the macrotexture of the surface are practically absent.

The skid numbers measured by the locked-wheel trailer, on the other hand, typically report frictional resistance at 64 km/hr (40 mph). Hence, such measurements represent not only the effects of microtexture but also the effects of macrotexture. It is now agreed that the poor correlations that have been obtained between the laboratory polish value and the field skid numbers (SN_{40}) are largely due to the failure to recognize the significance of the macrotexture. Studies conducted more recently (*11,12*) show that much better correlations can be obtained when the effects of micro- and macrotexture in skid measurements are separated from each other.

It can then be concluded that aggregate polishing characteristics as measured by the PV test are only one of the many factors that control field skid resistance. Therefore, satisfactory skid performance may not be achieved by controlling polish behavior of aggregates. Other factors, especially those that influence the macrotexture of the pavement surface, must be considered in the design.

USE OF SKID PERFORMANCE HISTORY FOR AGGREGATE EVALUATION

In recognition of the fact that some low-PV material has provided satisfactory in-service performance, TxDOT permits the qualification of the aggregate source based on historical friction data. The procedure for developing skid performance history using skid data was based on the findings of the FHWA Skid Accident Reduction Program and is outlined in the following.

The skid performance history for a given aggregate source is developed from skid numbers (SN_{40}) measured on pavements that have been constructed using aggregates of that type and from that source. A single data point typically would represent the average of a number of measurements made on a given test section of the roadway. For each of these data points, the cumulative number of vehicle passes corresponding to the lane on which the skid measurements were made is estimated and recorded. From these data, plots of SN_{40} versus cumulative vehicle passes per lane (VPPL) can be prepared. The top halves of Figures 2 and 3 are examples of such plots that have been obtained for two separate aggregate sources in Texas. These plots use linear scale and show the deterioration of skid performance with accumulation of traffic. For the analysis, however, the data must be plotted on logarithmic scale. The logarithmic plots for the same aggregate sources are shown in the bottom halves of Figures 2 and 3. The bold lines represent the best-fit linear regression models. This linear relationship between $\log_{10}$ (SN_{40}) and $\log_{10}$ (VPPL) now represents the skid performance history of the aggregate source. This model will provide the basis for aggregate qualification based on past skid performance, which must be performed on a project-by-project basis.

The procedure used in aggregate qualification can be best explained using the following example. Consider a six-lane roadway (three lanes in each direction) with average daily traffic (ADT) of 8,000, design life of hot-mix asphalt concrete (HMAC) surface course of 8 years, and traffic speed of 60 mph. Based on the information provided in Table 2 (*7*), a minimum skid number of 35 should be maintained on this pavement during its service life. Assuming that Aggregate Source 1 is to be used in the construction of this pavement, enter the graph shown in Figure 2 (*bottom*) with logarithm of the desired SN_{40} (i.e., $\log_{10} 35 \simeq 1.55$) and read off $\log_{10}$ (VPPL) = 7 from the x-axis. Taking the antilogarithm, VPPL = 10 million.

Accordingly, the pavement surface can sustain 10 million vehicle passes on the most heavily traveled lane before the skid number falls below the desired value of 35. Now, using a directional distribution factor of 0.5 and a lane distribution factor of 0.7, the corresponding useful service life for a roadway with ADT = 8,000 will be 9.78 years. Since this number is larger than the design life of the pavement surface course (i.e., 8 years), the aggregate qualifies for use in this project.

This approach has been used with good success in several Texas districts. The method has been used to qualify many aggregate sources that do not meet the desired PV requirement but have provided satisfactory performance in the past. These aggregates con-

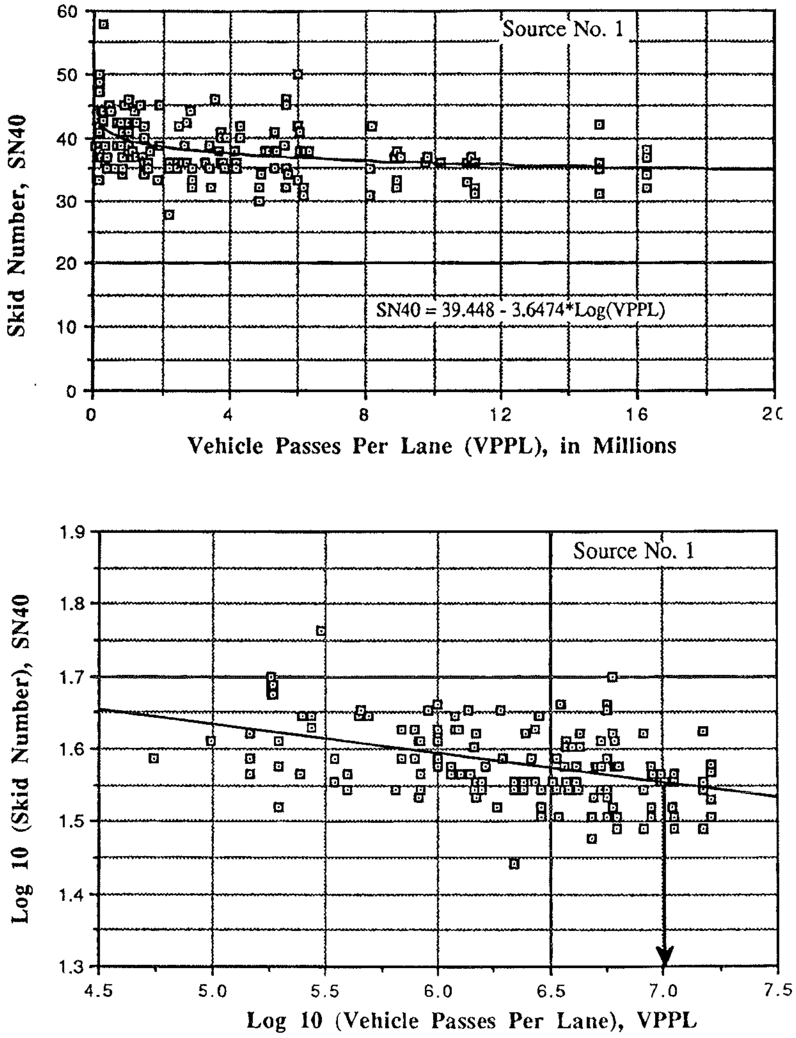

FIGURE 2 Skid performance history for Texas Aggregate Source 1: *top*, linear scale; *bottom*, logarithmic scale.

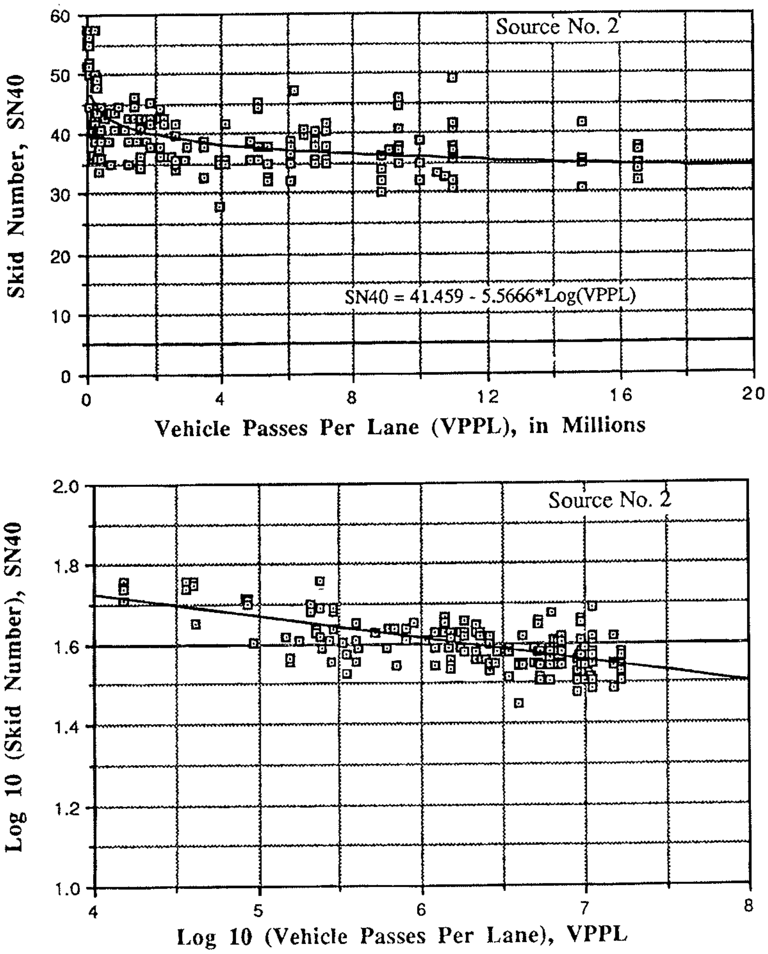

FIGURE 3 **Skid performance history for Texas Aggregate Source 2:** ***top*****, linear scale;** ***bottom*****, logarithmic scale.**

tinue to produce good in-service performance. This approach, therefore, deserves further investigation to determine its potential to be incorporated into the skid accident reduction program. However, during the use of the alternative approach, several deficiencies in the current procedure used for developing the skid performance history have been identified. These deficiencies are discussed in detail in the sections that follow.

TABLE 2 **Design Guidelines for Minimum Acceptable SN_{40} for Given Traffic Speeds and Surface Types (*7*)**

Mean Traffic Speed	SN_{40}	
	Surface Treatment	ACP
64 km/hr	33	33
80 km/hr	33	34
96 km/hr	33	35

Note: 1 km/hr = 0.625 mph

DEFICIENCIES AND LIMITATIONS IN CURRENT SKID PERFORMANCE HISTORY PROCEDURE

Variability in Skid Number Measurements

The primary difficulty with applying the skid performance history approach on a more routine basis is the *variability* (or *lack of reproducibility*) associated with skid measurements. As explained earlier, the skid performance histories such as those shown in Figures 2 and 3 are developed from skid measurements made on different pavement sections built with aggregates of the same type and source. A number of possible reasons for the data scatter seen in these plots can be identified.

First of all, it must be recognized that although all skid measurements correspond to the same aggregate source, there can be inherent differences in the pavement sections from which the data have been collected. Such differences may include variations in pavement macrotexture (e.g., open-graded versus dense-graded mix) and traffic characteristics (percentage trucks, light versus heavy truck traffic, etc.). In addition to these, other factors cause variability in skid measurements even if all the measurements were taken on the same pavement section. Such factors include seasonal changes, variability in the test surface, pavement distress such as flushing or raveling, improper calibration, and operator error. Many factors may contribute to variability in skid data, but it is evident that the success of this approach will depend largely on the ability to control variability in skid data. This may be demonstrated with the aid of Figure 4. In this figure, the skid data for Aggregate Source 1 have been reproduced at a larger scale, and the 60, 80, and 90 percent confidence limits for the data are shown in addition to the best-fit linear regression model. In the example discussed in the previous section, it was demonstrated that the regression model predicts that the pavement can sustain a maximum VPPL of 10 million during its useful service life. This means that, on average, the pavement will be able to carry a VPPL of 10 million before its SN deteriorates to a value of 35. In other words, there is a probability of 50 percent that the actual VPPL for the SN to reach 35 is less than that predicted by the model.

The confidence limits shown in Figure 4 allow one to calculate the actual VPPLs (or pavement useful service lives) associated with higher probabilities. For example, in considering the 60 percent confidence limits, it is found that there is a 20 percent probability (i.e., half of 40 percent outside confidence limits) that the actual VPPL is less than 2.0 million (i.e., antilog of 6.3; see Figure 4). In other words, one out five times the actual service life of the surface course can be as low as one-fifth of the life predicted on the basis of historical performance data. Similarly, other service lives corresponding to 10 and 5 percent probabilities can be calculated using 80 and 90 percent confidence limits. The probabilities associated with the actual pavement service life during which the skid resistance is maintained above specific SN values (such as 35, 34, and 33) are calculated and presented graphically in Figure 5.

Figure 5, which provides information on reliabilities (reliability = 100 − percentage probability of failure) associated with the prediction made on the basis of historical performance data, is a desirable extension to the current procedure. As explained, this information can be generated easily with the data that are already available. The bold lines represent the reliabilities corresponding to actual skid performance data for Aggregate Source 1. The broken lines represent a hypothetical situation in which the same regression model was obtained except that in this case there was less variability in the skid data. Two important observations can be made from the information presented in Figure 5. First, because of the large variability in skid data, the reliability of the current procedure is rather poor even when as many as 150 data points were used in the development of the skid history. Second, the use of reliability curves such as those shown in Figure 5 provides a more rational basis for design. Therefore, it is a desirable extension to the current procedure.

The preceding example clearly demonstrates that the success of the skid performance history approach depends on controlling the variability of measured skid numbers. Extensive research has been conducted to identify the factors that contribute to such variability. It must be noted that variability can be classified broadly into two categories: systematic variability and random variability. Systematic variability can be minimized by independent measurement of the factors that control such variability and by normalizing the skid measurements to a standard condition. An example of such variability is variation of skid number with ambient temperature. However, similar normalization is not possible with random variability, which can be minimized by specifying a minimum number of skid measurements. For example, the skid number varies with the position of the wheel on the test surface at the time of measurement. By taking a sufficient number of readings and averaging them, one can obtain a skid number that represents the test surface as a whole.

The various factors that contribute to variability in skid number measurements are not discussed here in detail. Instead, this information is summarized in Table 3. It identifies the major factors causing variability, whether the influence can be considered to be systematic or random, and possible corrective action to minimize such variability.

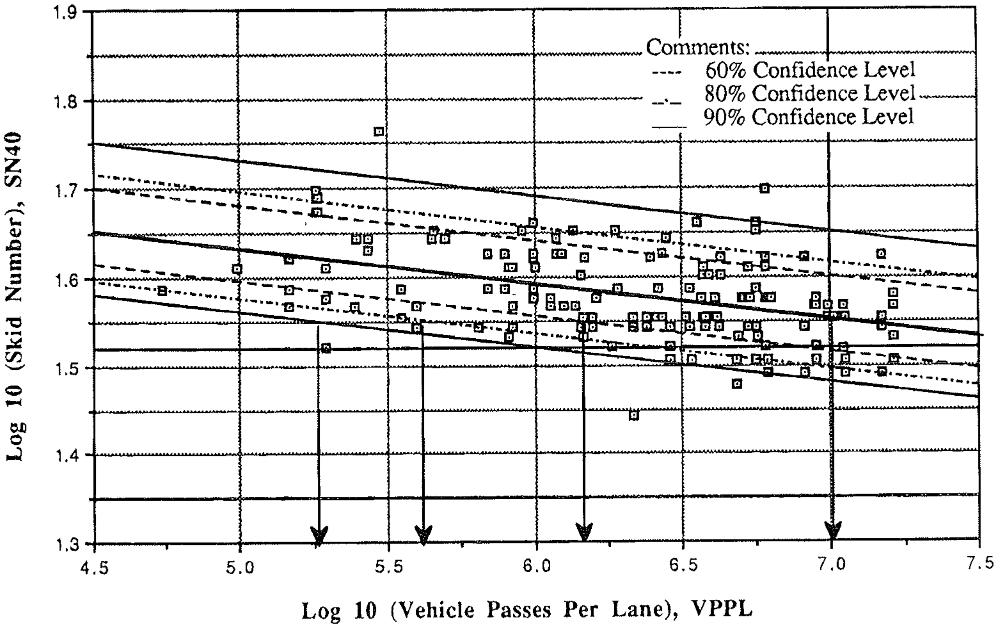

FIGURE 4 Confidence limits corresponding to Aggregate Source 1 data.

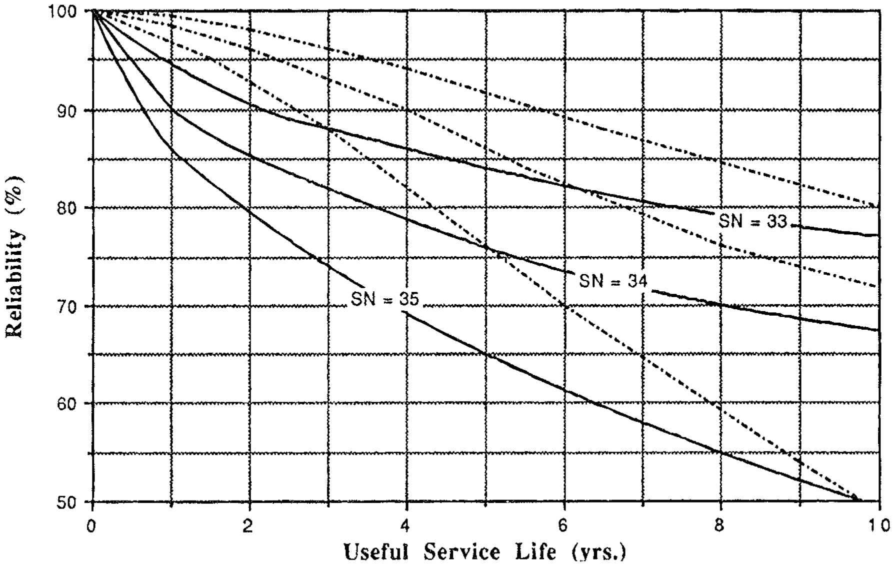

FIGURE 5 Reliability associated with prediction of useful pavement service life based on past skid performance.

Minimum Number of Data Points Required To Establish Reliable Skid History

The guidelines provided in the current procedure require only six data points to construct the skid performance history for an aggregate. The procedure also recommends the use of 30 data points if such data are available. By contrast, both aggregate sources discussed here consist of approximately 150 data points. From the variability seen in these plots, it is apparent that six data points is a gross underestimation of the minimum amount of data needed to construct a *reliable* skid performance history. The authors' experience with developing skid performance history confirms this observation. However, it should be noted that an increase in the minimum number of required data points will eliminate the possibility of using this approach for newer sources for which a long history does not exist. Therefore, this factor should be taken into consideration when determining the minimum number of data points required. The variability in data is a second factor to be considered when determining a minimum number of data points. If the data provide a more consistent trend, then a reliable history can be developed with fewer data.

Other Constraints To Ensure Proper Distribution in Data

It is important to have proper distribution of data in order to have a reliable skid history. In other words, most data points should not be concentrated at one end of the plot. The current procedure imposes the following constraints to ensure appropriate balance in the data scatter: (*a*) the total range of values for VPPL must be at least 250,000, and (*b*) one of the measurements must have been made

TABLE 3 Factors Contributing to Variability in Skid Number Measurements

Factor Causing Variability	Systematic/ Random	Possible Remedy
Climatic Changes (Temperature & Rainfall)	Systematic	A number of models, both mechanistic and stochastic, have been proposed to "normalize" the skid numbers to a standard end-of-the -season value (*Refs. 13, 14, 15*).
Fluctuations in Test Speed	Systematic	Possibility of SN-Speed Relations must be investigated. Or else an appropriate tolerance for test speed must be specified.
Longitudinal and Lateral Changes in Test Surface	Random	A minimum number of SN measurements must be specified.
Presence of Other kinds of Distress (e.g. flushing/ravelling)	Random	Provide guidance on appropriate selection of test sections.
Improper Calibration, Use of Improper Procedures and Operator Error	Systematic & Random	Making the operators more aware of the problem; Better training.

after a VPPL of 750,000. Once again, a quick examination of the top parts Figures 2 and 3 clearly shows that these constraints require reevaluation. It can be seen that 0.25 million and 0.75 million cover a very narrow range within the entire VPPL range covered in the two example skid histories. In particular, considerable deterioration of skid resistance can occur beyond a VPPL of 0.75 million. With present-day traffic volumes, the maximum VPPL at the end of the service life of the pavement is well beyond 0.75 million.

Reliability in Estimation of Traffic Volumes

The importance of reliable estimation of traffic volumes in the development of the skid performance history cannot be overemphasized. Since VPPL represents total vehicle passes since the time the surface course was opened to traffic, it is necessary to know not only the current traffic volumes but also how the traffic conditions have changed in the past. For major highways, such traffic data are available and can be retrieved from data bases maintained by TxDOT. For urban arterials, however, such accurate estimation of traffic volumes is not possible. Availability of reliable traffic data is an important factor to be considered in the selection of test sections for developing skid performance history.

CONCLUSIONS

The skid performance history approach described in this paper deserves further investigation to determine its potential to be used in the skid accident reduction program. Although this approach offers many advantages over the evaluation of aggregates in the laboratory, some shortcomings and limitations can be identified in the current procedure. The most important among these shortcomings is its poor reliability. The reliability of prediction using this procedure depends on the amount of scatter or variability in the skid data used in the construction of the skid history. As the variability in the data increases, the reliability in prediction decreases. The current procedure for aggregate qualification does not give due consideration to the reliability of prediction. In this paper, the authors demonstrate how the procedure can be extended to include reliability. Such an approach will not only provide a more rational basis for design but also give an incentive to improve the quality of skid data used in developing performance histories. Possible methodologies for improving the quality of skid measurement data as well as traffic data were discussed very briefly.

Another major drawback of the skid performance history approach is that it can be used only for aggregates on which historical performance data are available. In other words, it cannot be used for new aggregate sources or for aggregate sources that have not been in use long enough. Therefore, the appropriate long-term solution will be an aggregate source acceptance procedure that considers both microtexture and macrotexture components of skid performance and the ways in which these are related to aggregate polishing characteristics, gradation, and traffic characteristics.

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