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A closer look at the locked-wheel pavement friction data in the ltpp database for selected states

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Abstract: Pavement friction data from the Long-Term Pavement Performance (LTPP) database were treated and analyzed in order to examine its quality, patterns, and potential use. Data from a number of states along with Puerto Rico, Ontario, and Saskatchewan were sorted by availability of traffic information, testing temperature, and pavement type. The majority of the sections considered have relatively low ESAL. There is evidence of good quality control in Friction Number (FN) measurements. The difference in FN values between the beginning and end of a section is consistent with ASTM standards. The distribution of FN measurements can be used as a pavement management tool to identify sections that may need maintenance for friction restoration. There is a great deal of variability in the FN data in spite of temperature correction, especially at higher values of ESAL. Many of the selected sections display a trend of general decrease in FN at higher ESAL. However, factors other than traffic, such as mix design properties, may also need to be considered. Some testing information, such as the tire type used, is not available

ABOUT THE AUTHOR

Maher M. Murad is a Professor of Civil Engineering at the University of Pittsburgh at Johnstown. He had overseas teaching and professional experience. Dr. Murad worked as a technical manager at Modern Contracting and as highway project manager at Hyder Consulting. His teaching interests include transportation, highway design, and pavement design and management. His technical research interests include pavement friction, highway safety, and pavement management systems. He collaborated with Dr. Khaled Abaza on several research projects. In the pavement friction area, his published research focused on modelling pavement friction and wet-pavement traffic accidents as well as on developing programs aimed at reducing crashes. In pavement management, the published research focused on pavement rehabilitation project ranking using probabilistic-based indicators as well as on long-term pavement restoration programs and on predicting remaining strength of flexible pavement thickness using stochastic modeling. Dr. Murad is a licensed professional engineer (P.E.) in the state of Ohio.

PUBLIC INTEREST STATEMENT

Pavement friction is an important pavement surface property which can be described as the force developed at a tire-pavement interface when that tire slides along a pavement surface while being prevented from rotating. In the US, the most accepted method for measuring pavement friction is the locked-wheel trailer method. The result of the test is reported as FN40. Lack of pavement friction contributes to a portion of vehicle accidents, especially those known as wet-pavement accidents

The Long-Term Pavement Performance (LTPP) database is a source of data on pavement friction. Data from the LTPP database were treated and analyzed in order to examine its quality, patterns, and potential use. Friction measurements were found to be consistent with ASTM standards. The distribution of FN measurements can be used as a pavement management tool to identify sections that may need maintenance for friction restoration. Friction data in the LTPP database can be more useful for researchers and professionals if updated to include some missing parameters.

in the database and was obtained by an external survey. Traffic data in the form of Equivalent Single Axle Load (ESAL) are available, but not for the entire life of the pavement, and had to be supplemented with projections. The friction data in the LTPP database can be more useful for researchers and professionals if updated to include some missing parameters.

Subjects: Civil, Environmental and Geotechnical Engineering; Transportation Engineering; Pavement Engineering;

Keywords: pavement friction; skid resistance; LTPP; trends; maintenance; ESAL

1. Introduction

As part of the Strategic Highway Research Program (SHRP), the LTPP program was initiated in 1987. The program has thousands of test sections on in-service highways at hundreds of locations throughout the United States and Canada. The data include inventory, material testing, pavement performance monitoring, climatic, traffic, maintenance, rehabilitation, and seasonal testing modules. About a third of the LTPP sections was selected from existing highway pavements, and those sections are the subjects of the LTPP General Pavement Studies (GPS). The remaining sections were constructed by state highway agencies for the LTPP Specific Pavement Studies (SPS).

Pavement friction related data can be found in the Monitoring section of the LTPP database in the table MON_FRICTION (2019). The table gives data collected for seventeen different variables related to friction. The variables in the friction table can be organized in two categories. The first category deals with variables related to the location of a test section and the equipment used, while the second deals with data on friction and other related variables. In the table, two friction values are recorded at the beginning and end of a section. The construction number recognizes the changes in pavement structure since initially accepted into the LTPP program. Detailed information is provided on the testing equipment such as calibration date, equipment brand, and model. The provision of air temperature allows for the correction of friction for testing temperature variations. An indication of the general quality of the data is also provided.

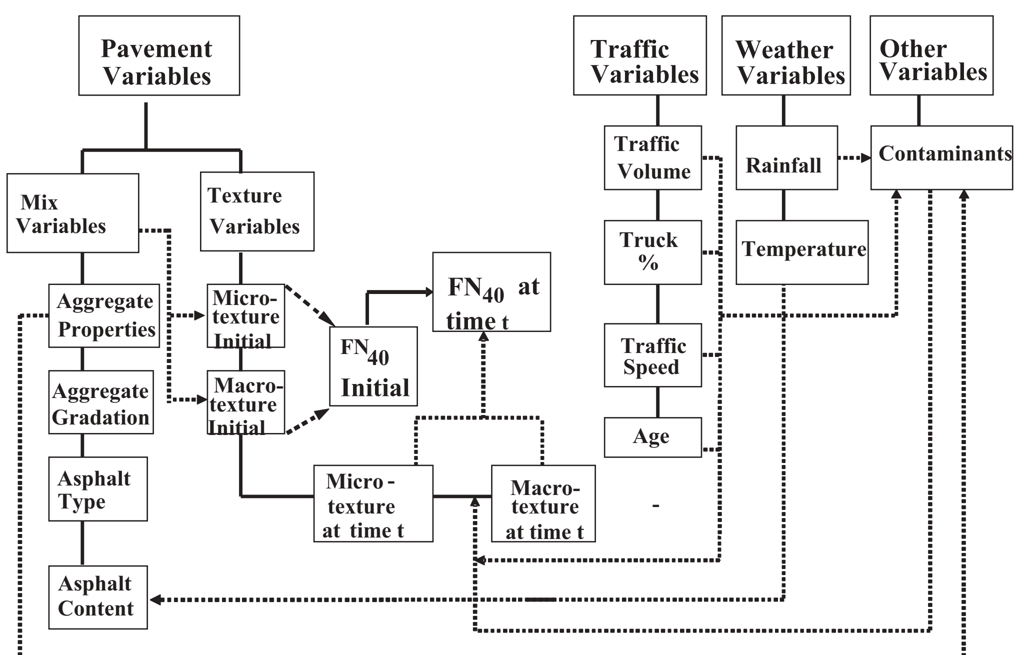
In the United States, the most accepted method for measuring pavement friction is the locked-wheel trailer method in accordance with the American Society for Testing and Materials Method E-274 (American Society for Testing and Materials, 2016). Other methods for measuring pavement friction include sideway force, fixed slip, and variable slip (Mataei, Zakeri, Zahedi, & Nejad, 2016). The result of the locked—wheel test is reported as Skid Number SN40, if the speed of the test trailer is 40 mi/hr (65 km/hr). SN or FN is obtained by measuring the forces with a towed trailer riding on wet pavement, equipped with standardized ribbed or smooth tires. If the test speed is not 40 mi/hr, adjustment factors can be used to convert friction numbers from one speed to the standard speed (Flintsch, Izeppi, McGhee, & Najafi, 2010; Jackson, Choubane, & Holzschuher, 2009).

Data collection guidelines for friction recommend using the ASTM E-274 as the preferred method for obtaining friction data along with the following criteria (Titus-Glover & Tayabji, 1999):

- Once every two years and prior to and after maintenance or rehabilitation.
- At the most appropriate time of the year for the locality, considering seasonal variations, and at the same time of the year for each round of friction testing.
- With a calibrated tester at 65 km/hr, or less, if necessary.
- At two locations, one within the beginning 60 m and the other within the last 60 m.
- Along the centre of the inner wheel path, which is the left wheel track for a two-wheel trailer.
- When the air temperature is in the range of 4°C to 40°C.

Friction of pavement immediately after construction, FN40 (0), is generally dependent on pavement variables such as mix design variables and initial surface characteristics. For example, aggregate type, shape, and gradation have been linked to initial level of friction (Kabir, King, Abadie, & Cooper, 2012; Murad, 2004; Rezaei, Masad, Chowdhury, & Harris, 2009; Schram, 2011; Wu, King, Abadie, & Zhang, 2012). Figure 1 illustrates the general concept (Murad, 2004). Micro-texture refers to the small-scale texture of the pavement aggregate component while macro-texture refers to the large-scale texture of the pavement as a whole due to the aggregate particle arrangement (American Association of State Highway and Transportation Officials (AASHTO), 2010). The initial micro-texture of a pavement surface, either harsh or polished, has an effect on initial friction number, especially at low speeds. The macro-texture, either smooth or rough, affects initial FN especially at high speeds (Murad, 2004). In particular, the initial micro-texture and macro-texture are mainly dependent on aggregate properties such as shape, angularity, and gradation of both fine and coarse aggregate. For example, when the proportion of limestone exceeds 40%, pavement displayed undesirable FN values in the first five years of service (Schram, 2011). Limestone is defined as those aggregates containing less than 15% magnesium oxide. Another study (Wu et al., 2012) confirms that sandstone mixtures, irrelevant of the mix type, have significantly higher friction resistance than their counterpart mixtures with limestone. Also, mixtures with the combination aggregate blends were found to have better friction resistance than the limestone-only mixtures. It has been shown (Rezaei et al., 2009) that the same aggregate can have different contributions to mixture friction depending on gradation. The friction numbers of open graded mixes were shown to be generally higher than their Superpave and stone matrix asphalt (SMA) counterparts and show good macro-texture (Kabir et al., 2012; Kowalski, McDaniel, Shah, & Olek, 2009). Pavement friction at time "t" after construction, FN40 (t), depends on two main variables: FN40 (0) and the characteristics of surface texture at time "t". Texture characteristics at time "t" are a function of other variables that are also time-dependent such as traffic. In addition to traffic, aggregate characteristics and mixture gradation have a significant effect on the friction loss over time (Kassem, Awed, Masad, & Little, 2013).

Figure 1. Fundamental variables related to FN (0) and FN (t).



Speed of traffic may also have an effect on pavement friction through its influence on surface texture. If friction is to remain satisfactory at higher speeds, a rough surface texture is required. Alternatively, speed limits may be reduced for adequate friction (Praticò, Filippo., 2018). Precipitation may have a short-term effect on FN through a decrease or an increase in FN40 (t). Temperature is also likely to affect pavement friction through its influence on surface texture and on the behaviour of tires. A study (McDonald, Crowley, & Turochy, 2009) concludes that there is strong evidence supporting the hypotheses that seasonal variations result from temperature-related causes. Higher air or pavement temperature will result in a lower friction for a given pavement surface. The study also showed that a higher pavement temperature or ambient temperature resulted in a lower hysteretic friction for a given pavement surface and a given tire slip ratio (Anupam, Srirangam, Scarpas, & Kasbergen, 2014). Contaminants in the form of dust, oil, de-icing agents, etc. tend to fill the texture asperities and consequently may reduce FN.

2. Study objectives

The objectives of this study are:

(1) To download asphalt and concrete pavement friction data from the LTPP database.

(2) To treat the friction data and examine its quality control.

(3) To utilize FN distribution as a tool for making decisions related to pavement friction restoration.

(4) To develop trends of pavement friction variation with traffic and age.

3. Treatment of friction data

3.1. Friction data in the LTPP database

The friction table was downloaded from the General Pavement Studies (GPS) section of the LTPP database. The data were saved as an Excel file. The State_Code Table was used to sort the complete data file in order to get the friction data for different states and Canada that utilize either the ribbed or smooth tire in friction testing. Because the friction table does not provide information on the type of tire used, a survey (National Cooperative Highway Research Program (NCHRP), 2000) was used to sort the data by listing the states that use either the ribbed or smooth test tire. This step ended up splitting the friction data into two files.

Twenty-five states along with two Canadian provinces and Puerto Rico were in the file containing the friction data with ribbed tire. Five other states appeared in the other file of friction data measured with smooth tire. States that use both testing tires were excluded due to the difficulty in determining which tire was used to test a given section. Other states that did not participate in either the LTPP or in the survey were also excluded. The selected states share similarities in testing equipment and procedures. Each section was tested for friction at least three times starting as early as 1990. Table 1 gives the names of the states included in the study and their numerical codes.

The data were also stratified by test section Identification Number assigned by the LTPP program. Tables that summarize inventories on mix design and aggregate properties were also downloaded from the INVENTORY section. The main categories considered are Age Table, Major Improvements Table, Aggregate Durability Table, Aggregate Composition Table, Aggregate Gradation Table, and Layer Inventory Table. A road section in the LTPP is 150 m with a 15.2 m materials sampling section at each end. A maintenance control section is established around each test section.

The following criteria were used to decide on what sections to keep in the study:

- Sections that were tested more than twice in their life time to help establish time related trends and models.

Table 1. States included in the study

State	LTPP Code	Testing Tire	State	LTPP Code	Testing Tire
Alaska	2	Ribbed	New Mexico	35	Ribbed
Arkansas	5	Ribbed	New York	36	Ribbed
California	6	Ribbed	Oklahoma	40	Ribbed
Connecticut	9	Ribbed	Rhode Island	44	Ribbed
Florida	12	Ribbed	South Carolina	45	Ribbed
Hawaii	15	Ribbed	South Dakota	46	**Smooth**
Idaho	16	**Smooth**	Texas	48	**Smooth**
Kansas	20	Ribbed	Utah	49	Ribbed
Kentucky	21	Ribbed	Vermont	50	Ribbed
Maine	23	Ribbed	Virginia	51	**Smooth**
Maryland	24	Ribbed	Washington	53	Ribbed
Michigan	26	Ribbed	Wisconsin	55	Ribbed
Mississippi	28	Ribbed	Wyoming	56	Ribbed
Missouri	29	**Smooth**	Puerto Rico	72	Ribbed
Montana	30	Ribbed	Ontario	87	Ribbed
Nebraska	31	Ribbed	Saskatchewan	90	Ribbed
New Jersey	34	Ribbed			

- Sections with available test temperature so that the friction data can be adjusted for temperature effect.
- Sections with available traffic information to allow the consideration of traffic variables in the trends.
- Sections that are made either with asphalt (flexible) pavements or concrete (rigid) pavements, but exclude sections with mixed pavements.
- Sections that did not change their surfaces because friction changes with surface change.

The variable Layer Type Table was used in order to sort the friction data by pavement type such as asphalt (A) or concrete (P). As a result, two new friction data tables were created that give the friction data for all asphalt and concrete sections for both ribbed and smooth tires. The SECTION_LAYER_STRUCTURE Table was used to further sort the data into the categories of single, if pavement structure did not change, or multiple, if pavement structure changed more than once. A change can be in the form of a surface treatment, overlay, or reconstruction. Given the importance of traffic as a variable, the friction data had to be further sorted to ensure the availability of traffic history for the study sections included. Traffic is represented by the accumulated 80 KN Equivalent Single Axle Load applications, available in the TRF_MON_EST_ESAL Table of the LTPP database. The friction data was once again sorted by availability of traffic information (ESAL), and the estimated ESAL was added to the friction

Table 2 shows a breakdown of the data after the series of sorting described earlier. The study analyzed the four data sets that went through all the sorting methods. The titles of these files appear in bold in Table 2. The files retained only the relevant information. The following observations pertain to Table 2:

- The absence of test tire used in the measurement of friction made it difficult to sort data by test type. Instead, other sources had to be consulted for assistance. Many states did not participate in the survey though, and others had mixed testing methods.

Table 2. Sections included in the study

Sorting Type	Number of States	Other Countries and Provinces	Number of Sections	Number of Friction Tests
Original	46	10		8359
Ribbed Tire	25	3		3859
Smooth Tire	5	None		545
Ribbed/AC	16	3		1426
Ribbed/PC	15	1		881
Smooth/AC	2	None		279
Smooth/PC	2	None		266
Ribbed/AC/SI	14	2		286
Ribbed/AC/MU	14	3		1133
Ribbed/PC/SI	12	None		429
Ribbed/PC/MU	12	1		452
Smooth/AC/SI	2	None		89
Smooth/AC/MU	2	None		190
Smooth/PC/SI	2	None		113
Smooth/PC/MU	2	None		153
Ribbed/AC/SI/TR	**11**	**1**	**34**	**164**
Ribbed/PC/SI/TR	**11**	**1**	**34**	**215**
Smooth/AC/SI/TR	**2**	**None**	**11**	**59**
Smooth/PC/SI/TR	**2**	**None**	**17**	**91**

- A large number of sections have some kind of maintenance that resulted in a change of surface. Such sections were excluded from further analysis because friction changes with surface change.
- Traffic information was not available for all sections. Therefore the number of sections selected for analysis was further reduced by availability of traffic information.
- The filtering process resulted in the last four data sets that are the focus of further analysis.

Abbreviations in Table 2: AC: asphalt pavement, PC: Portland cement concrete pavement, SI: single pavement, MU: multiple pavements, and TR: traffic ESAL availability.

3.2. Availability and quality of the LTPP friction data

Different tables in the LTPP database indicate that the following descriptions are available:

- variables listed for each category
- improvement variables and the description of major improvement types and the corresponding codes
- codes of durability tests and aggregate texture
- fine and coarse aggregate composition
- codes of layer types and materials

FN values may vary due to random errors. ASTM E – 274 accepts a standard deviation up to 2 FN which is established by repeated friction tests. However, friction values in general are expected to either remain the same or decrease due to the polishing effect of traffic and other environmental conditions (Murad, 2004; Saito & Henry, 1983; Wambold, 1988).

Table 3. Control, estimation, and prediction of friction variables

Controlled	Estimated	Predicted
Mix variables: aggregate properties, aggregate gradation, asphalt type, asphalt content, air voids, and mix procedure	Traffic volume, traffic speed, precipitation, and temperature	Micro-texture, macro-texture, contaminants, and Friction Number

If friction numbers increase by more than 4 FN with age, then the friction numbers will be considered questionable. Titus-Glover and Tayabji (Titus-Glover & Tayabji, 1999) reported evidence of questionable friction data in the LTPP database primarily due to variations in test locations and test equipment as well as the influence of test tire and test temperature. Table 3 lists the variables related to pavement friction, sorted by being controlled, estimated, or predicted. Controlled variables are variables that may be related to FN40 (0) or FN40 (t) and which the designer has some control over. Estimated variables include those which the designer has no control over but may be estimated to a certain degree of precision. Predicted variables include those that can be predicted from controlled and estimated variables. The variables identified as causes of variation in FN over time may operate in three different ways: long-term variations, seasonal variations, and short-term variations. The period for long-term variations is generally greater than one year, while the period for seasonal variations is only three months. Also, the period for short-term variations can only be a few days.

Table 4 summarizes the availability of friction related variables in the LTPP database. Some of the variables related to the properties of coarse and fine aggregates are available in the LTPP database, including the aggregate type and specific gravity. The availability of data related to other aggregate properties, such as polish value, soundness, shape, size, and gradation is very limited. Some testing information is not available in the LTPP database, such as the tire type used and the inner or outer wheel path that was tested. The incompleteness in the data collected, as Table 4 shows, may limit the potential use of LTPP friction data. For instance, developing predictive models of FN for a pavement immediately after construction requires the availability of a number of mix design variables, some of which are not available in the LTPP database. Of special interest is the polishing susceptibility of aggregate in the form of aggregate test results such as the Polished Stone Value, Los Angeles Abrasions, and Acid Insoluble Residue. The most critical variable not available in the LTPP database is the FN measured immediately after construction. The absence of this variable may limit conducting useful statistical analysis including developing predictive models of initial pavement friction which is usually the dependent variable.

Table 4. Availability of other data in the LTPP database

Variable	Availability in the LTPP database		
	Fully Available	Partially Available	Not Available
Aggregate Properties		X	
Pavement Type	X		
Asphalt Properties		X	
Air Temperature	X		
Pavement Temperature		X	
Annual Precipitation	X		
Pavement Age	X		
Traffic Data		X	
Contaminants			X
Accident History			X

Table 5. Summary of average friction for different pavement categories

	Average FN			
	Ribbed/Asphalt	Ribbed/Concrete	Smooth/Asphalt	Smooth/ Concrete
Mean	43.9	45.3	43.7	46.5
Median	44.0	46.5	43.5	49.5
Mode	43.0	45.0	45.0	55.0
Standard Dev.	8.1	8.2	10.0	8.2
Minimum	20.0	18.0	23.0	30.5
Maximum	67.0	64.5	64.5	61.5
Count	164	215	59	91

In order to predict FN at any given time after construction, traffic data must be available. Traffic data in the form of Annual Average Daily Traffic (AADT) and ESAL are available but not for the entire life of the pavement for many sections. Some of the traffic data had to be supplemented with projections and historical estimates. In addition, maintenance activities, such as patching and diamond-grinding, are well-documented while temporary maintenance activities are not documented.

3.3. Descriptive statistics

Table 5 summarizes the basic statistics for average FN. The difference in overall average FN for the beginning and end of sections is found statistically not significant at 95% level of confidence. As shown in Table 5, the average FN values are slightly higher for concrete pavements for both ribbed and smooth tire categories. However, such difference is not statistically significant at 95% level of confidence (P-values are 0.099 and 0.076, respectively).

From visual inspection, the frequency distribution of the average FN values appears normal except for Smooth/Concrete category which displayed a skewed distribution. The difference between the beginning and end FN values was computed for each section. About 97% of data have FN differences of 5 FN or less, between the beginning and end of a section. This is consistent with the maximum difference stated by ASTM. Only six sections have FN differences of 6 or more, but one measurement has as high as 7 FN difference. About 60% of data have 0 or 1 FN difference, and that is an indication of good quality control in FN measurements.

4. Potential use of friction data in maintenance decisions

The cumulative relative frequency distributions for both asphalt and concrete pavements are plotted as shown in Figure 2. The distribution gives the percent of data less than or equal to a certain FN value. Table 6 gives an example showing how the distribution in Figure 2 can be used in pavement management decisions aimed at pavement friction restoration. Therefore, Table 6 is derived from Figure 2 and has some useful interpretations. For example, for asphalt pavements, about 15% of sections may need some treatment to improve their friction if the critical level of FN is set to 35. The percentage of sections in need for corrective maintenance could be more than twice as much if the critical level of FN is raised to 40. This approach can be used as a pavement management tool. It may assist in pavement management decisions aimed at establishing priorities for the level of maintenance work needed given a limited budget (Murad & Abaza, 2006). Figure 2 and Table 6 show that if FN critical level is set to a relatively high value of 40 or more, the number of sections selected for maintenance will be significantly higher for asphalt pavements compared to concrete pavements.

In many states, such critical or minimum friction requirements are based on research findings. However, only a handful of states reported having pavement friction requirements for new pavement construction. The minimum FN requirement for new construction varies from 30 to 45 (National Cooperative Highway Research Program (NCHRP), 2000).

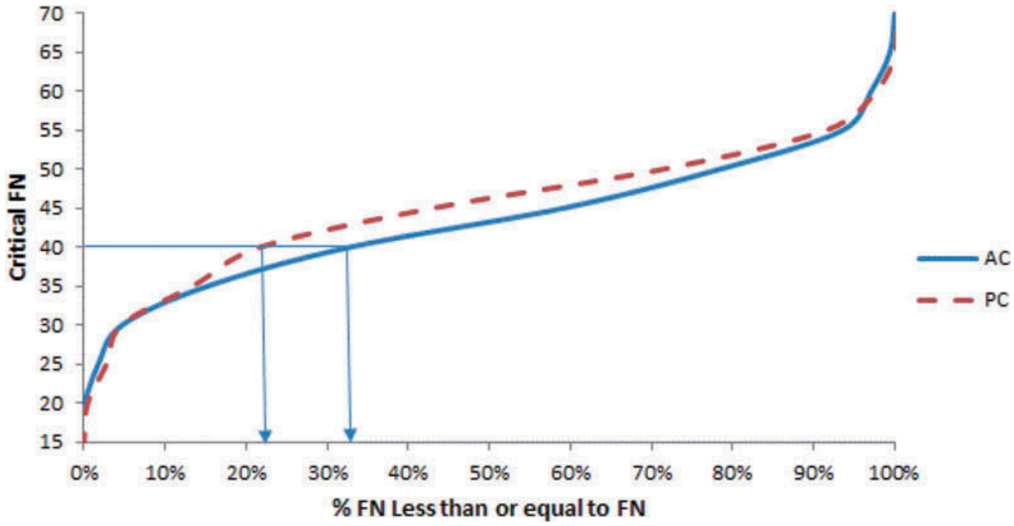


Figure 2. Percentage of data with FN less than or equal to critical levels.

Table 6. Application example of the model in Figure 2

Critical FN Level	% of FN data ≤to a critical level—AC	% of FN data ≤to a critical level—PC
25	1	2.8
30	4.7	4.7
35	15.2	13.5
40	32.8	21.9
45	59.1	43.3

Over forty states reported performing friction testing on a regular basis and using the results in their pavement management system. However, only eleven states indicated having intervention level for friction. The minimum pavement friction requirement varies among the states. The range for FN is 28 to 41 for interstates, 25 to 35 for primary roads, and 22 to 35 for secondary roads. The most common minimum FN reported is 35. A survey (Ksaibati, Cole, & Farrar, 1996) gave a wide range of FN requirements for directing attention to corrective rehabilitation from 20 in Virginia to 43 in Arizona. Another survey (NCHRP, 2000) indicated that eighteen states have investigatory FN levels with a mode of 40, and fifteen states have intervention FN levels with a mode of 30. Investigatory levels set by an agency call for site investigation to determine the need for remedial action while intervention levels require remedial action (National Cooperative Highway Research Program (NCHRP), 2009). Mayora and Pina (Mayora & Pina, 2009) reported that raising the FN value from 33 to 48 may result in a reduction in wet pavement accidents by as much as 60%. Micro-surfacing and resurfacing are examples of maintenance activities aimed at restoring pavement friction. Micro surfacing is generally considered to be effective for five to seven years, while resurfacing with the standard friction top course of 1.5 inches (3.8 cm) is expected to last fifteen years (Lyon & Persaud, 2008).

5. Trends and models

5.1. Correlation between FN and ESAL

Temperature is believed to affect pavement friction through its influence on asphalt. Temperature also affects the behaviour of rubber and consequently the behaviour of tires. The availability of air temperature in the friction table allowed for the correction of FN measurements for the variation in air temperature during testing. The temperature is available for most FN measurements. The state of Virginia reported applying corrections to measured FN values for seasonal variations such that a zero correction is applied for July and an FN correction of −3.7 is applied for January (Titus-Glover & Tayabji, 1999). A study (Flintsch, Lou, & Al-Qadi, 2005) concluded that temperature correction factors may not be needed when friction measurements are conducted at a routine speed of 64 km/hr. One model (Murad, 2004) corrects FN for test air temperature deviation from a standard temperature of 70°F as follows:

$$CFN = FN + 0.15 \times (T - 70) \quad (1)$$

Where,

CFN = Corrected Section Average Friction Number

T = Air Temperature in °F at the time of FN measurement

Another study (Kabir et al., 2012) developed a model that predicts change in FN based on temperature variation as shown in Equation 2 which gave similar results to that in Equation 1.

$$CHFN = -0.138 \times (CHTM) \quad (2)$$

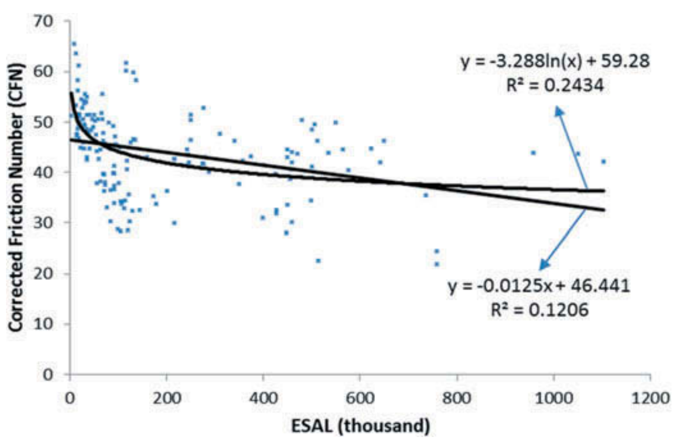
Where,

CHFN = Change in Friction Number

CHTM = Change in Maximum Air Temperature in °F

The traffic variable (ESAL) was added to the other variables in the friction table for analysis. Figure 3 shows average corrected FN versus ESAL in thousands, displaying a trend of reduction in FN with higher ESAL. It should be noted that the range of ESAL is relatively small as most values are within one million. One can also see that there is a great deal of variability in the data. The large variation in FN indicates that factors other than traffic are also significant. For example, age is found to be significant when used as another independent variable, but the model remained weak with significant unexplained variability. When age was used alone as an independent variable, however, the variation of FN was found to follow a similar trend to that

Figure 3. Corrected FN vs. ESAL-Ribbed-AC.



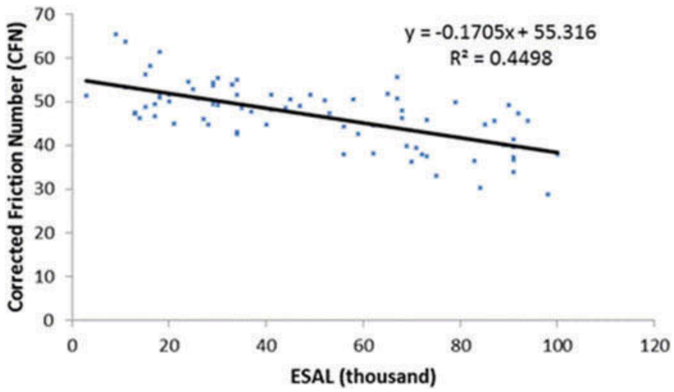


Figure 4. Corrected FN vs. low values of ESAL- Ribbed-AC.

of ESAL. This indicates that much of the variation in FN over time is due to the influence of traffic. The variability is further reduced when a nonlinear model is used as shown.

When sections with ESAL of only 100,000 or less are considered as Figure 4 shows, the variation appears smaller and the correlation is higher. Scatter plot for ribbed-tire-PC pavements showed a similar trend to that of AC pavements but with relatively lower variability, especially at lower values of ESAL. Figures 5 and 6 show an example of an individual section (SHRP_ID 1034, State Code 21) that behaves as expected, that is lower FN values as ESAL or years in service increase, whether or not the data was corrected for temperature. Figure 6 shows that the variation of FN with traffic appears to be nonlinear.

Figure 7 presents two examples on how the correction of FN for temperature may help reveal a reasonable trend by showing a decrease in friction with an increase in ESAL. The standard deviation for the three values is less than 2, indicating that the trend can be explained by random variations as specified by ASTM.

6. Conclusions

The LTPP database is a source of data on pavement friction. An external survey was utilized to obtain the type of test tire used in friction measurements because this information is not available in the database. Traffic data in the form of ESAL are available in the LTPP database,

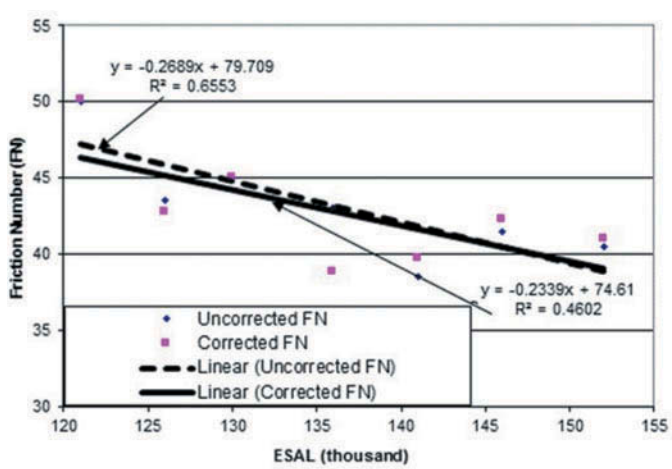


Figure 5. Average FN vs. ESAL (linear).

Figure 6. Average FN vs. ESAL (nonlinear).

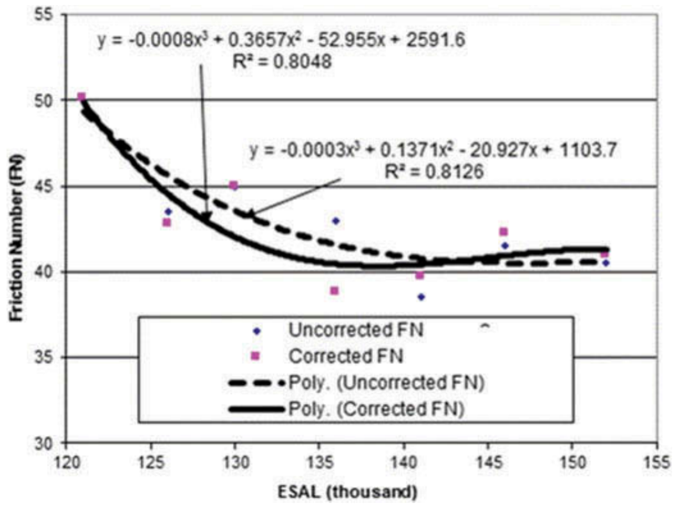
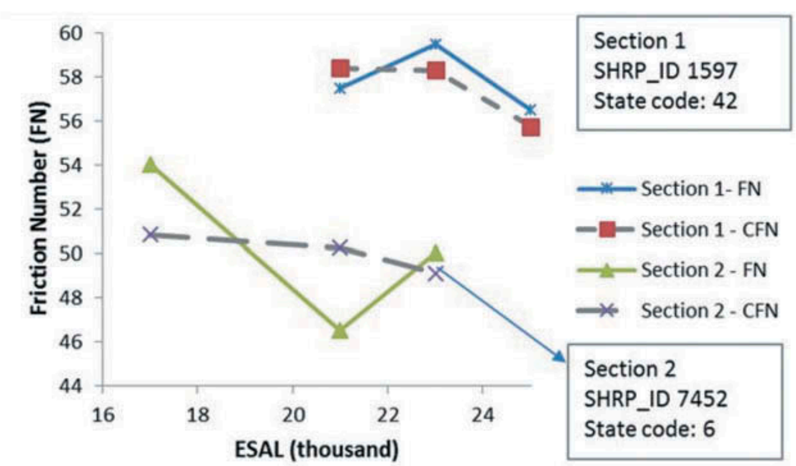


Figure 7. Average FN vs. ESAL.



but are not for the entire life of the pavement, and had to be supplemented with projections and historical estimates. Data not available in the LTPP database may limit the usefulness of the available data. The difference in FN between the beginning and end of a section is consistent with ASTM standards, and there is evidence of good quality control in FN measurements. The average FN values are slightly higher for concrete pavements for both ribbed and smooth tire categories. However, the difference in FN averages is not statistically significant. The FN distribution from the LTPP database can be used as a pavement management tool to estimate the percent of sections that may need maintenance for friction restoration given a limited budget. There is a great deal of variability in the FN data even after correcting for changes in test temperatures. Many of the selected sections displayed an expected trend that shows a reduction in FN with an increase in ESAL values. Much of the variation in the FN trend occurs at lower values of ESAL, indicating that factors other than traffic are responsible for the significant variation. Reasonable trends took both linear and nonlinear forms but appeared nonlinear in most cases.

7. Recommendations

It is recommended that additional data on FN-related variables be collected in order to make the friction data in the LTPP database more useful for researchers and professionals. Needed additional data include but is not limited to tire type used in testing, FN immediately after construction, aggregate polishing properties, and complete records of temperature and traffic.

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References

American Association of State Highway and Transportation Officials (AASHTO). (2010). *Guidelines for skid resistant pavement design*. Washington, D.C.

American Society for Testing and Materials. (2016). Skid resistance of paved surfaces using a full-scale tire. designation: E 274-97. *ASTM Standards*, 4(3), 902–907.

Anupam, K., Srirangam, S., Scarpas, A., & Kasbergen, C. (2014). Influence of temperature on tire-pavement friction: Analyses. *Transportation Research Record Journal of the Transportation Research Board*, *2369*, 114–124. doi:10.3141/2369-13

Federal Highway Administration. (2019). https://infopave.fhwa.dot.gov/Data/TableExport/

Flintsch, G., Izeppi, E., McGhee, K., & Najafi, S. (2010). Speed adjustment factors for locked-wheel skid trailer measurements. *Transportation Research Record*, *215*, 117–123. doi:10.3141/2155-13

Flintsch, G., Lou, F., & Al-Qadi, I. (2005), Analysis of the effect of pavement temperature on the frictional properties of flexible pavement surfaces. CD-ROM. Transportation Research Board Annual Meeting.

Jackson, N., Choubane, B., & Holzschuher, C. (2009). Practical approach to measuring and reporting friction and macrotexture at variable test speeds. *Transportation Research Record*, *2094*, 103–111. doi:10.3141/2094-11

Kabir, M., King, W., Abadie, C., & Cooper, S. (2012). Louisiana's experience with open-graded friction course mixtures. *Transportation Research Record*, *2295*, 63–71. doi:10.3141/2295-08

Kassem, E., Awed, A., Masad, E., & Little, D. (2013). Development of a predictive model for skid loss of asphalt pavements. CD-ROM. Transportation Research Board Annual Meeting.

Kowalski, K. J., McDaniel, R. S., Shah, A., & Olek, J. (2009). Long-term monitoring of noise and frictional properties of three pavements: Dense-graded asphalt, stone matrix asphalt, and porous friction course. *Transportation Research Record: Journal of the Transportation Research Board*, (2127), 12–19. doi:10.3141/2127-02

Ksaibati, K., Cole, M., & Farrar, M. (1996). Evaluation of surface treatment practices in United States. *Transportation Research Record*, *1545*, 26–34. doi:10.1177/0361198196154500104

Lyon, C., & Persaud, B. (2008). Safety effects of targeted program to improve skid resistance. *Transportation Research Record*, *2068*, 135–140. doi:10.3141/2068-15

Mataei, B., Zakeri, H., Zahedi, M., & Nejad, F. M. (2016). Pavement friction and skid resistance measurement methods: A Literature review. *Open Journal of Civil Engineering*, *6*, 537–565. doi:10.4236/ojce.2016.64046

Mayora, J., & Pina, R. (2009). An assessment of the skid resistance effect on traffic safety under wet-pavement conditions. *Accident Analysis and Prevention*, *41*(4), 881–886. doi:10.1016/j.aap.2009.05.004

McDonald, M., Crowley, L., & Turochy, R. (2009). Determining the causes of seasonal variation in pavement friction observational study with Datapave 3.0 database. *Transportation Research Record*, *2094*, 128–135. doi:10.3141/2094-14

Murad, M. (2004). A review of asphalt pavement friction testing, safety requirements, and their applications in design and maintenance in USA. *International Journal of Pavements*, *3*(2), 63–75.

Murad, M. M., & Abaza, K. (2006). Pavement friction in a program aimed at reducing wet-weather traffic accidents at the network level. *Transportation Research Record (TRR): Journal of the Transportation Research Board*, (1949), 126–136. doi:10.1177/0361198106194900111

National Cooperative Highway Research Program. (2009). Guide for pavement friction. NCHRP Project. 01–43.

National Cooperative Highway Research Program (NCHRP). (2000). Evaluation of pavement friction characteristics. NCHRP Synthesis 291.

Praticò, Filippo. (2018). Speed limits and pavement friction: A theoretical and experimental study. *The Open Transportation Journal*, *12*, 139–149. doi:10.2174/18744478018120100139

Rezaei, A., Masad, E., Chowdhury, A., & Harris, P. (2009). Predicting Asphalt mixture skid resistance by aggregate characteristics and gradation. *Transportation Research Record*, *2104*, 24–33. doi:10.3141/2104-03

Saito, K., & Henry, J. J. (1983). Mechanistic model for predicting seasonal variations in skid resistance. Transportation Research Record No.946. Washington D.C.: TRB, National Research Council, 29–37.

Schram, S. (2011). Specifications for aggregate frictional qualities in flexible pavements case study. *Transportation Research Record*, *2209*, 18–25. doi:10.3141/2209-03

Titus-Glover, T., & Tayabji, S. (1999). Assessment of LTPP friction data. FHWA-RD-99-037. McLean, VA: Federal Highway Administration. doi:10.1046/j.1469-1809.1999.6320101.x.

Wambold, J. C. (1988). Road characteristics and skid resistance. Transportation Research Record No. 1196. Washington D.C: TRB, National Research Council, 294–299.

Wu, Z., King, B., Abadie, C., & Zhang, Z. (2012). Development of design procedure to predict asphalt pavement skid resistance. *Transportation Research Record*, *2306*, 161–170. doi:10.3141/2306-19