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EVALUATION OF TRAFFIC AND ENVIRONMENT EFFECTS ON SKID RESISTANCE AND SAFETY PERFORMANCE OF RUBBERIZED OPEN-GRADED ASPHALT CONCRETE

Prepared for California Department of Transportation

California PATH Research Projects
Task Order 6218

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GLOSSARY OF ACRONYMS AND TERMS

PFTB: Pavement Field Testing Branch
OGAC: Open Graded Asphalt Concrete
GP: Groove Pavement
R-OGAC: Rubberized Open Graded Asphalt Concrete
TASAS: Traffic Accident Surveillance and Analysis System
AADT: Annual Average Daily Traffic
SN: Skid Number
SN40: Denotes a skid number measured at the speed of 40 mph or adjusted as an equivalent value with the value measured at 40 mph when it is measured at speeds other than 40 mph
ASTM: American Society for Testing and Materials
AC: Asphalt Concrete
PCC: Portland Cement Concrete
PSV: Polished Stone Value
GLS: Generalized Least Square
CRF: Collision Reduction Factor

Evaluation of Traffic and Environment Effects on Skid Resistance and Safety Performance of Rubberized Open Graded Asphalt Concrete

ABSTRACT

Wet pavement-related collisions represent a significant traffic safety concern, due in part to the lack of adequate friction between tire and pavement, known as skid resistance. State agencies employ a skid number (SN) system, based on a standard test procedure in which a locked wheel is towed at 40 mph and the skid number (SN40) is calculated from the measured resistance. SN40 is used as a reference value for speeds both greater than and less than 40 mph. For most Departments of Transportation (DOTs) in the nation, excluding California, pavements for which the SN40 is below 30 are deemed unacceptable and corrective actions are required.

The main objectives of this study are (1) to evaluate and analyze skid test results from the test data inventory, and (2) to identify and analyze before-and-after collision data at sites where three experimental types of pavements (Open Graded Asphalt Concrete [OGAC], Groove Pavement [GP], and Rubberized Open Graded Asphalt Concrete [R-OGAC]) have been implemented.

Study results suggest that a significant relationship exists between SN40 and seasonal effects (temperature, average monthly precipitation, and the number of dry months prior last precipitation). A significant relationship also exists in high-risk locations where average daily traffic (ADT) is higher, and in the more heavily-used shoulder lanes. If highway agencies wish to prioritize pavement improvements using SN40, SN40 must be standardized. The model developed in this study can provide the needed adjustment factors.

In addition, while further research is needed, results suggest that new pavement types such as OGAC can improve safety performance of roadways.

Keywords: Freeways, Skid Resistance, Wet Weather Accident, Open Graded Asphalt Concrete, Groove Pavement, Rubberized Open Graded Asphalt Concrete, Partners for Advanced Transit and Highways California, Safety, Traffic Accidents.

EXECUTIVE SUMMARY

INTRODUCTION

According to a U.S. study of collision data, in 2001 more than 22 percent of collisions nationwide were weather-related. More than 16 percent of fatalities and over 20 percent of injuries in passenger vehicles occurred in adverse weather and/or on slick pavements. Research indicates that a major factor in wet pavement accidents may be the lack of adequate friction between the tire and the pavement.

Skid resistance is a measure of the friction that develops when a tire is prevented from rotating and instead skids along the pavement surface. To determine the safety of roadway pavement, state agencies employ a skid number system. In the United States, the most commonly used skid resistance measuring techniques involve measuring the force required to drag a non-rotating tire over wet pavement. In terms of physics or mechanics, the coefficient of friction is commonly used to describe the friction properties of the pavement and the object in contact. For the skid resistance properties of a pavement surface, a skid number (SN) is specified based on a standard test procedure according to American Society for Testing and Materials (ASTM) E 274.

In this test procedure, a locked wheel is towed at 40 mph and from the measured resistance force, the skid number at 40 mph, SN40 is calculated. SN40 is used as a reference value when skid resistance is measured at speeds other than 40 mph. For most Departments of Transportation (DOTs) in the U.S., pavements for which the SN40 is below 30 are deemed unacceptable and corrective actions are required. In California, however, there are no specific guidelines for how to control skid resistance, and skid resistance is not regularly measured.

The California Department of Transportation (Caltrans) has recently employed different types of pavement materials experimentally, to improve drainage systems and increase skid resistance. This study investigates three different types of pavement currently in use on California roads:

- Open Graded Asphalt Concrete (OGAC), which contains a high percentage of air voids.

- Groove Pavement (GP), which has longitudinal or transverse cuts on its surface.

- Rubberized Open Graded Asphalt Concrete (R-OGAC)--asphalt modified by the incorporation of rubber, which helps to increase the fatigue resistance of the asphalt.

OBJECTIVES

The main objectives of this study are as follows:

Evaluation of Traffic and Environment Effects on Skid Resistance and Safety Performance of Rubberized Open-Graded Asphalt Concrete

1. Evaluate and analyze skid test results from the test data inventory collected by Pavement Field Testing Branch (PFTB) at the Caltrans Sacramento Laboratory.
2. Identify and analyze before-and-after historical collision data at operational test sites where the three experimental types of pavements have been used.

METHODS

The first part of the study involved evaluating the effects of traffic and environment on skid resistance. The data set contains more than 50,000 observations along five routes of freeway in seven districts of California from 1988 to 2008. To begin with, the characteristics of skid resistance as a function of traffic, temperature, precipitation, and roadway attributes were established. Two estimations were made: one focusing on large variations in measured skid resistance using a broad range of data excluding the time variable, and the other on the deterioration model with all possible variables, including time, using relatively limited data from asphalt concrete pavement on four routes in California. To evaluate the effects of traffic and environmental factors on skid resistance, the research team attempted to model SN40 as a function of all potential factors affecting skid resistance.

The second part of the study focuses on the safety performance of each of the experimental pavement types. Before-and-after comparisons using collision data from Traffic Accident Surveillance and Analysis System (TASAS) were conducted to assess the safety performance of resurfacing pavement with OGAC, GP and R-OGAC. Because the experimental pavement types are expected to improve drainage, the focus of the before-and-after study was on the reduction in wet pavement-related collisions, specifically.

FINDINGS FOR EVALUATION OF TRAFFIC AND ENVIRONMENT EFFECTS ON SKID RESISTANCE

Large variations in measured skid resistance were observed even at the same location. The potential sources of the variations were estimated using SN40. It was found that seasonal conditions and temperature variations are the primary factors causing the variations in measurement. Skid resistance is typically higher in fall and winter when temperatures are lower, and lower in spring and summer, when temperatures are higher. Other findings were as follows:

- The location of the measured lane also has a significant effect on skid resistance. The shoulder lane tends to have lower skid resistance than the center lane.
- Variation due to testing devices was not observed However, the estimated results indicate that this factor represents a relatively small proportion of the total variation.

A skid resistance deterioration model was estimated for evaluating the effects of traffic and environment on skid resistance. The estimated results are as follows:

- SN40 significantly decreases with average daily traffic (ADT).

- SN40 in the shoulder lane is significantly lower than the average SN40 values. This is due to heavy traffic.
- Temperature causes significant decreases in SN40 at the 90% confidence interval.
- Months with higher levels of precipitation have a significant negative impact on SN40.
- SN40 decreases with the increased length of dry periods.
- Increased age of pavement causes a decrease in SN40.

FINDINGS FOR SAFETY PERFORMANCE OF PAVEMENT TYPE

Compared with wet-related collision rates before and after the new pavement types were implemented, we observed the following:

- Resurfacing with Open-Graded Asphalt Concrete (OGAC) significantly decreased the number of collision by 10-73 percent.
- Resurfacing with OGAC decreased the number of collisions by a total of 25.86 collisions over a two-year period, although the reduction was not statistically significant.
- Each of the implementation sites for Groove Pavement (GP) and Rubberized Open Graded Asphalt Concrete (R-OGAC) were analyzed, but due to the small sample set, no conclusions could be drawn.

CONCLUSIONS

Our results suggest that there is a significant relationship between SN40 and weather, particularly the temperature at the time of measurement, average monthly precipitation, and the number of dry months prior to the last significant precipitation. The combination of these factors can cause seasonal variations in SN40. Therefore, if highway agencies want to prioritize pavement improvements using SN40, SN40 must be standardized. The model estimated in this study can provide the adjustment factors.

Findings from our analysis of the safety performance of the three new pavement types indicate that resurfacing with OGAC significantly decreased the number of wet-related collisions. Unfortunately, we do not currently have sufficient data to draw any significant conclusions for resurfacing with GP or R-OGAC. This would be a fairly straightforward extension of our study and could be conducted by including additional sites in our analysis.

In general, our study demonstrates that seasonal effects, average daily traffic (ADT), and age of pavement need to be considered in order to maintain safe levels of skid resistance. SN40 needs to be monitored selectively in high-risk locations where ADT is higher and in the more heavily-used shoulder lanes, rather than across all sections of freeway. In addition, while further research is needed, results suggest that new pavement types such as OGAC can improve the safety performance of roadways.

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Evaluation of Traffic and Environment Effects on Skid Resistance and Safety Performance of Rubberized Open-Graded Asphalt Concrete

1. INTRODUCTION

Wet pavement-related collisions represent a significant concern in traffic safety. According to a U.S. study of collision data, in 2001, more than 22 percent of collisions nationwide were weather-related. Over 16 percent of fatalities and more than 20 percent of injuries in passenger vehicles occurred in adverse weather and/or on slick pavement. Research has indicated that a major factor in wet pavement accidents may be the lack of adequate friction between the tire and the pavement: when the pavements are wet, emergency or panic braking or turning maneuvers may cause vehicle tires to slide, due to decreased friction between the tires and the pavement.

Skid resistance is a measure of the friction developed when a tire is prevented from rotating and instead skids along the pavement surface. Skid resistance is one of the important serviceability indicators of pavement systems in terms of roadway safety, especially on wet pavements. The lower the skid resistance of a roadway, the less safe it is. In order to determine the safety of roadway pavement, state agencies employ a skid measuring and numbering system. In the United States, the most commonly used skid resistance measuring techniques involve measuring the force required to drag a non-rotating tire over wet pavement. In terms of physics or mechanics, the coefficient of friction is commonly used to describe the friction properties of the pavement and the object in contact. For the skid resistance properties of a pavement surface, a skid number (SN) is specified based on a standard test procedure according to American Society for Testing and Materials (ASTM) E 274 (American Society for Testing and Materials 2004). In this procedure, a locked wheel (as shown in Figure 1) is towed at 40 mph and from the measured resistance force, the skid number at 40 mph, SN40, is calculated. SN40 is used as a reference value when skid resistance is measured at speeds other than 40 mph. For most Departments of Transportation (DOTs) in the U.S., pavements for which the SN40 is below 30 are deemed unacceptable and corrective actions are required. If the SN40 is between 30 and 35, the pavement section is monitored, and more frequent tests are performed. In California, however, there are no specific guidelines for controlling skid resistance, and nor is it regularly measured. For this study, to evaluate the effects of traffic and environmental factors on skid resistance, the research team attempted to model SN40 as a function of all potential factors affecting skid resistance.

Figure 1 ASTM E-274

In light of the critical safety importance of skid resistance in roadway surfaces,, it is in the interest of the traveling public as well as state agency divisions of highway design, maintenance, and materials testing divisions, to explore the effectiveness of various safety improvements. This study was is intended to support and enhance the considerable amount of research and development that already undertaken by the California Department of Transportation (Caltrans), which has installed different types of pavement materials to improve drainage systems and increase skid resistance. These materials include a higher percentage of void space in the pavement itself, which allows water to seep through these voids more rapidly and improves drainage systems. This leads to an expected reduction in wet pavement-related collisions.

This study investigates three different types of pavement: (1) Open Graded Asphalt Concrete (OGAC), which contains a high percentage of air voids; (2) Groove Pavement (GP), which has longitudinal or transverse cuts on its surface; and (3) Rubberized Open Graded Asphalt Concrete (R-OGAC), which is asphalt modified by the incorporation of rubber, which helps to increase the fatigue resistance of the asphalt.

2. PREVIOUS STUDIES

The relationship between adequate friction on wet pavements and highway safety was first investigated and documented in the 1930s (Moyer 1934), and became the focus of intense research efforts following the large increase in vehicle ownership and highway travel at high speeds after World War II.

A 1960s California study appeared to reveal a slight increase in the coefficient of friction on pavement during field tests after winter rains (Zube et al. 1968). Screenings from selective California sources did not show excessive reduction in friction values under heavy traffic, and also appeared to show low rates of wear and polish. However, there was a noticeable decrease in friction during the first 100 days of installation.

There have been numerous studies on pavement skid resistance over the past several decades. In a 1972 study, Szatkowski et al. documented the correlation between traffic intensity and the skidding characteristics of wet road surfaces (Szatkowski et al. 1972). It was determined that the three major categories of factors that affect the frictional properties of road surfaces are:

1. Micro-texture (material ingredient and resistance to polishing).
2. Macro-texture (water drainage and energy dissipation).
3. Traffic and other factors (traffic density, temperature, road layout, etc.).

There is a definite association between the "weathering" of a road surface and the observed seasonal variations in pavement skid resistance. The study's findings emphasized that the results of measurements of skid resistance must be considered strictly in relation to the time of year they are taken, as the lowest values were recorded during the summer. Within about one year, the skid resistance on a newly laid surface rapidly decreased to a relatively constant value for several years hence, as shown in Figure 2.

The Szatkowski study also determined that the effect of traffic on skid resistance is not cumulative from year to year. A possible explanation, and one that is generally accepted, is that at while traffic is likely to polish the surface, other factors usually identified as "weathering" are acting in the opposite way, restoring the micro-texture of the exposed aggregate. Thus, the resultant skid resistance represents equilibrium between the effects of certain naturally-occurring conditions on one hand, and those of traffic on the other.

When considering the effect of traffic on road surfaces, it is reasonable to expect that the polishing effect of heavy-duty vehicles will be many times greater than that of regular passenger cars. The ratio of commercial vehicles and passenger cars vary significantly on different sections of roads and different lanes on the same stretch of roadways. Earlier studies confirmed that the skid resistance is correlated more closely with the number of commercial vehicles per lane per day as a measure of traffic, rather than with the total number of all vehicles.

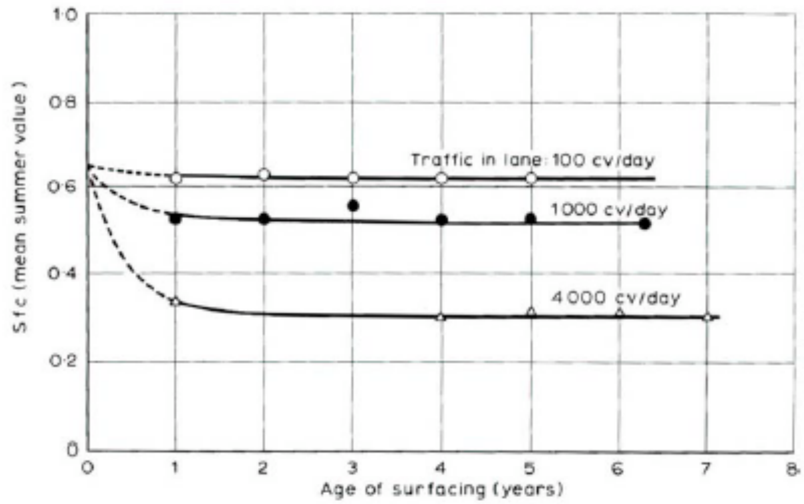


Fig. 3. EFFECT OF TRAFFIC ON SKIDDING RESISTANCE OF A TYPICAL MOTORWAY-STANDARD SURFACING (ROLLED ASPHALT WITH PRECOATED CHIPPINGS OF PSV 58-60)

Figure 2 Effects of Traffic Exposure on Skid Resistance (Szatkowski et al. 1972)

The relationship between variables affecting pavement skid resistance requirements was explored by Dunlap, et al. Findings from their 1976 study suggested that skid test data alone do not indicate a level of skid resistance at which corrective surface treatments become mandatory. An examination of wet weather accident frequencies is of the utmost importance, and roadway geometries should also be considered. The study also found that sections of roadways on tangent alignment, free of merging or weaving lanes, intersections, or steep grades, represent examples of relatively ideal conditions as far as skid resistance demands are concerned (Dunlap et al. 1976). However, a combination of wet weather accidents and low skid numbers at a given location indicate that corrective surface treatments are likely to be needed.

A National Cooperative Highway Research Program (NCHRP) synthesis of practices highlighted the benefits of open-grade surface (Highway Research Board, 1972). Open-graded or coarse-textured roadway surfaces are advisable for high-speed, wet-weather traffic. They provide drainage relief at the tire-pavement interface, reduce the steepness of the speed gradient, decrease the likelihood of hydroplaning, minimize splash and spray, reduce the glare from wet pavements, and improve high-speed skid resistance. The skid number increases as the texture depth increases, while the wet-pavement accident rate decreases as the skid number increases.

The same report discusses the effects of traffic volume.. Figure 3 presents a reproduction of Figure 62 from the report, which shows how the side friction factor was influenced by the truck and passenger car daily volume as well as by the total passenger car equivalent volume. The curves shown in the figure indicate that traffic volume is a critical factor for roadway surface skid resistance.

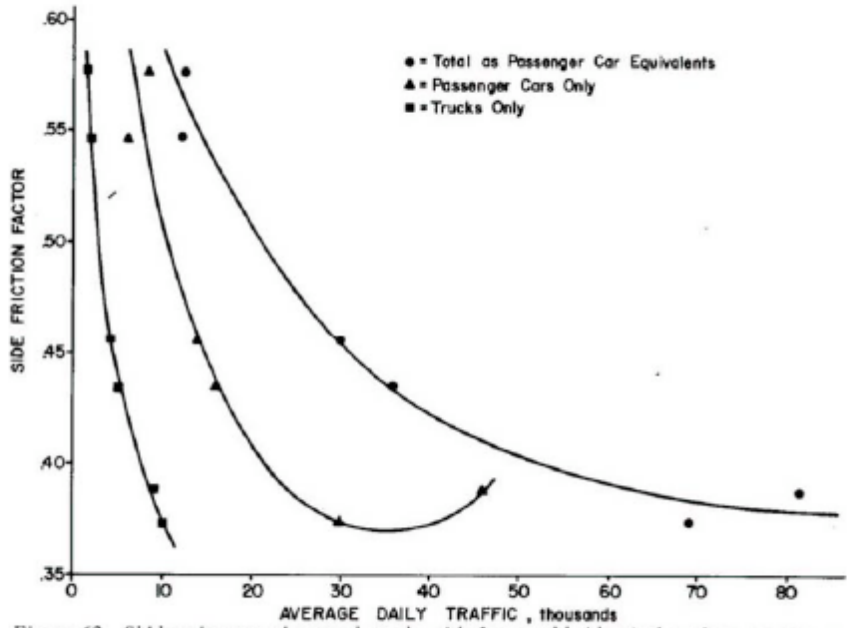


Figure 62. Skid resistance of several roads with 3-year-old, identical surface courses as a function of traffic density (67).

Figure 3 Skid Resistance of Three-Year-Old Roads as a Function of Traffic Density

3. STUDY OBJECTIVE

For this project, the research team proposes a systematic approach to fulfill the two main objectives specified by Caltrans:

1. Evaluate and analyze skid test results, from the test data inventory collected by Pavement Field Testing Branch (PFTB) at the Caltrans Sacramento Laboratory.
2. Identify and analyze before-and-after historical collision data at the operational test sites where new types of pavements, such as open-graded asphalt concrete (OGAC), groove pavement (GP), rubberized open-graded asphalt concrete (R-OGAC), have been installed, in order to quantify the effectiveness of the safety performance of similar pavement improvements.

4. DATA SOURCES

For the first objective of the study, we evaluated and analyzed skid test results from the test data inventory collected by PFTB at the Caltrans Sacramento Laboratory. The dominant factors, truck and traffic volume, were used as the primary variables to explain the correlation between traffic and skid resistance properties. Weather information and geometric features were also used as explanatory variables.

For the second objective of the study, we identified and analyzed before-and-after historical collision data at sites where new types of pavements had been installed. We used the TASAS database to conduct analyses of collision data at the selected sites where OGAC, GP or R-OGAC had been experimentally deployed. Data for the study were collected from the following sources:

Skid Resistance

- SN40 data: the skid resistance test data collected by PFTB.

Traffic

- Annual Average Daily Traffic (AADT): Caltrans Data Branch.
- Truck volume: Caltrans Data Branch.

Weather

- Precipitation data: National Oceanic and Atmospheric Administration (NOAA) (http://www.ncdc.noaa.gov/oa/mpp/index.html).

Geometric Features

- Pavement resurfacing data: California Department of Transportation document Retrieval System (DRS).
- Aerial Photos: Google Earth (http://earth.google.com/): a virtual globe program which maps the earth via the superimposition of images obtained from satellite imagery, aerial photography, and GIS 3D globe.

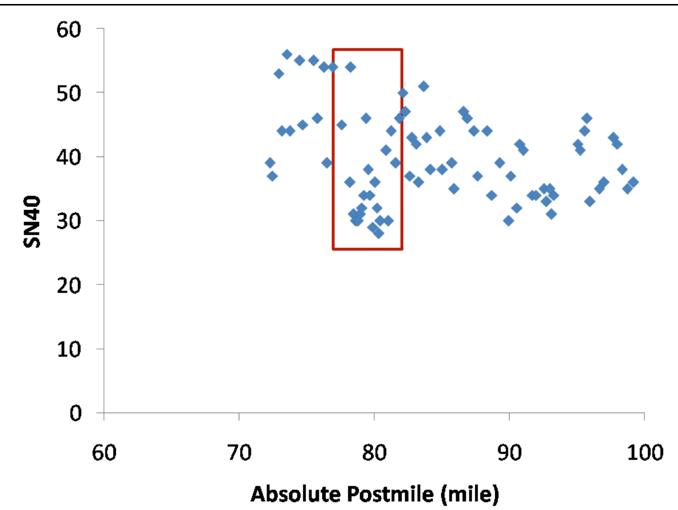
Collisions

- Traffic Accidents Surveillance and Analysis System (TASAS): TASAS is a collision database which records information associated with each collision that occurs within the California state freeway system.

5. EVALUATION OF TRAFFIC AND ENVIRONMENT EFFECTS ON SKID RESISTANCE

To evaluate the effects of traffic and environmental factors on skid resistance, the research team attempted to model SN40 as a function of all potential factors affecting skid resistance. However, in the first phase of the study, a significant challenge arose for SN40 data modeling: the fact that SN40 was rarely observed more than once at a particular location. Only two to three samples were observed on average at the same location for more than 20 years. In addition, lack of surface layer data made it difficult to use time or age information about the pavement as explanatory variables.

Due to these data challenges, an alternative approach was suggested for examining potential patterns in skid data. Large variations in SN40 were observed at almost all locations. Figure 4 shows an example of the large variations in the measured SN40 value. Each point in the plot represents an individual measured SN40 value at a particular postmile along I-80. Although the points in the rectangle were measured within a four-mile section of freeway in a single month, the standard error of measured SN40 is 20%.



SN40 Statistic	Postmile 78~82
Average	36
Standard deviation	7
Standard error	20%
Max	54
Min	28

Figure 4 Large Variation in SN40 Measurement (I-80, October 2003)

For the analysis, a limited set of pavement resurfacing data was used. The data included pavement age information and, based on the provided data, a SN40 deterioration model was estimated as a function of traffic, environmental and geometric variables.

5.1. POTENTIAL SOURCES OF VARIATIONS IN SN40

Potential sources of the large variances in SN40 include: (1) actual change in pavement condition which can be due to geometry, age, type of pavement and traffic; (2) environmental factors that may affect measurement, such as temperature, weather and seasonal variation; and (3) testing device errors. Under the assumption that these factors are independent of each other, the variation of SN40 can be formulated as follows:

$$Var(SN40) = Var(pvmt)+Var(env.)+Var(dev.)$$

Where Var(SN40) : variance of SN40;
Var(pvmt) : variance of SN40 due to the change of pavement;
Var(env.) : variance of SN40 due to the environmental factors;
Var(dev.) : variance of SN40 due to the testing device.

With a lack of pavement resurfacing information, the research team analyzed the variance of SN40 due to environmental factors and testing device errors by controlling Var(pvmt), which represents the variance of SN40 due to the change in pavement condition. The following assumptions were made:

1. In the same postmile, all geometry and traffic factors were the same over a one-year period. The only factors that differed were the specific lane in which the skid resistance was measured, and the measurement environment.
2. There was no resurfacing within a one-year period.
3. There were no significant effects due to age within a one-year period.
4. All variables related to measurement and lane location are linear to SN40.

Under the above assumption, differences in SN40 in the same location within a one-year period can be used to illustrate the effects of explanatory variables. For example, if $SN40_1$ and $SN40_2$ were observed at the same location within a single year, f(pvmt,) which represents all characteristics related to the pavement, would remain same. Therefore, the difference between $SN40_1$ and $SN40_2$ can be described as a function of other factors excluding pavement characteristics, represented as X, Y and Z in the following formula:

$$SN40_1=f(pvmt)+\alpha X_1+\beta Y_1+\gamma Z_1+\varepsilon_1$$
$$SN40_2=f(pvmt)+\alpha X_2+\beta Y_2+\gamma Z_2+\varepsilon_2$$
$$SN40_1-SN40_2=\alpha(X_1-X_2)+\beta(Y_1-Y_2)+\gamma(Z_1-Z_1)+(\varepsilon_1-\varepsilon_2)$$
$$\Delta SN40=\alpha\Delta X+\beta\Delta Y+\gamma\Delta Z+\Delta\varepsilon$$

where X, Y and Z : observable explanatory variables except those related to pavement; and ε: unobservable variables such as device bias and random fluctuation.

Table 1 describes the data used in the analysis. This data set contains more than 50,000 observations along five routes of freeway in seven districts of California from 1988 to 2008. Each observation consists of SN40, location information (route, direction, postmile and lane where measurement was conducted), time information (year and month when measurement was conducted), geometry information (post speed, ADT, surface type, total number of lanes and grade), and measurement information (wheel, weather, temperature and test speed). A total of 641 pairs of observations from this data set satisfied our assumptions and were used in the analysis.

Table 1 Data Description

Studied Routes	I-5, I-10, I-80, I-101, I-299
District	1-7
Time Horizon	1988-2008
Available Variables	SN40, Location, Month, Year, Direction, Lane, Total number of lane, Wheel, Weather, Temperature, Grade, Test speed, Post speed, ADT

Table 2 shows the results of the estimation. From all available explanatory variables described above, the following three were selected: lane difference, temperature difference, and seasonal difference. All variables included in the model are significant at the 95% level and the signs of the coefficients are reasonable.

Table 2 Result of Estimation: Measurement Error in SN40

Variables	Units	Coefficients	t Statistic	P-value
Intercept		0	N/A	N/A
Lane difference	1 lane to the right	-2.40	-9.39	0.00
Temperature difference	1F°	-0.08	-4.29	0.00
Quarterly change from 1 to 2	Quarter 1: Jan-Mar Quarter 2: Apr-Jun Quarter 3: Jul-Sep Quarter 4: Oct-Dec	-3.93	-5.06	0.00
Quarterly change from 2 to 3		3.17	3.57	0.00
Quarterly change from 3 to 4		1.98	2.89	0.00
R^2: 0.20; F-value: 31.84; Significance of F: 0.00; Observations: 641.				

The coefficients for lane difference indicate that SN40 decreases by 2.40 units when the measured lane is shifted by one lane to the right. This is because heavy vehicles tend to use the right lane (known as the shoulder lane), or a lane closer to the shoulder than to the center. The increased traffic volume in the shoulder lane leads to increased polishing action and reduces skid resistance, especially for heavy vehicles (Do et al. 2007).

Skid resistance is also affected negatively by temperature as the coefficient for temperature difference shows (Anderson et al. 1986, Bazlamit 2005). The mechanism involved in variation due to temperature changes is attributed to hysteresis in rubber tires. Hysteresis is the energy lost in the form of heat upon elastic recovery of the rubber tire, which is compressed as it slides over the pavement. It follows that at higher temperatures, rubber becomes more flexible, leading to less energy loss. Higher temperatures thus lead to a decrease in the measured skid resistance.

Quarterly change represents the seasonal variation in skid resistance. Previous studies indicate that skid resistance is typically higher in the fall and winter and lower in the spring and summer. These variations can severely skew skid resistance data if they are not compensated for (Jayawickrama 1998). Figure 5 shows SN40 difference based on the quarterly change in the estimated model. The y-axis represents the relative SN40 when SN40 in quarter 1 is set to zero. The graph shows that findings are consistent with previous studies; skid resistance is higher in quarter 4 and lower in quarter 2.

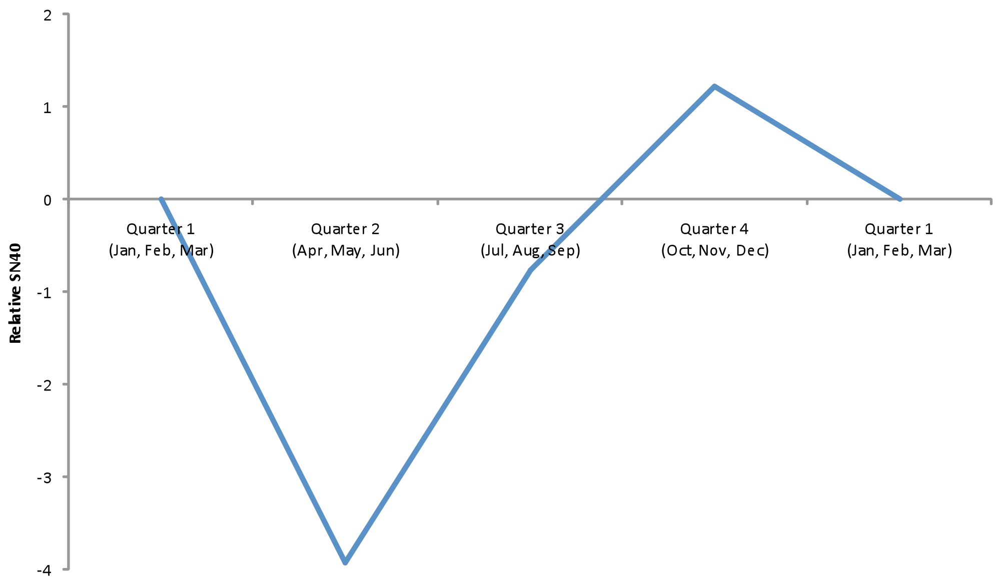


Figure 5 SN40 Difference Versus Quarterly Change

Based on the coefficient estimated in Table 2 and the range of each variable observed in the data, the possible range of SN40 due to each variable is presented in Table 3. As the table indicates, the maximum range of SN40 caused by lane difference is 10 units, and maximum range caused by a difference in temperature is 4 units. In addition, the maximum difference in SN40 caused by seasonal variations is 9 units of SN40. Therefore, based on our model, the maximum variation in SN40 due to environmental factors is 13 units of SN40.

Table 3 Effects of Variables in SN40

Variables	Coefficient	Range of variables in data	Possible range of SN40	Range of variables within 90% confidence interval	Possible range of SN40 within 90% confidence interval
Lane difference	-2.41	4	10	2	5
Temperature difference	-0.08	52	4	32	3
Quarterly change from 1 to 2	-3.92		Max: 9		
Quarterly change from 2 to 3	3.18				
Quarterly change from 3 to 4	2.00				

Based on the estimated model, we controlled the variation in SN40 due to pavement change and explored those variations caused by lane difference and environmental factors. The next possible source of the large variation in SN40 encompasses factors related to the testing device, which includes the variations in trailer characteristics and operator behavior type of tire used, and water nozzle condition. Based on the literature, ASTM E-274 has a standard deviation of 2 SN from numerous tests that varied in terms of speed, surface, and skid trailer (American Society for Testing and Materials 2004). Hegmon reported a range of standard deviations of 1.13~1.84 with 11 operators and Corley found a range of standard deviations of 0.6~4.0 for the same testing device and 25.1 for different testing devices (Hegmon 1978, Corley-Lay 1998).

As determined in previous studies, testing device error was precisely detected in field tests when other factors were controlled. Even though we did not conduct a controlled field test, our model controls for factors of geometry, lane location, temperature, and quarterly changes. Therefore, Var(dev.) which is unobservable from our data set, can be captured by residuals in our model. Standard deviation of residuals in our model is 4.06. This contains all unobserved variables and random fluctuations. If we assume that the residuals are independent and identically distributed, we can create the following formula:

$$\square_{\square_1} = \square_{\square_2} = 4.06$$
$$\square_1 \sim N(0, \square_{\square_1}^2),\ \square_2 \sim N(0, \square_{\square_2}^2)$$
$$\square_1 - \square_2 = \square \sim N(0, 2\square_{\square}^2)$$
$$\square_{\square} = 2.87$$

The estimated standard deviation of SN40 caused by device error is about 2.87, which is similar to the standard deviation of standard testing devices in previous literature.

To sum up, estimated sources of large variation in SN40 are shown in Table 4.

Table 4 Estimated Sources of Large Variation in SN40

Factors	Description	Estimated Amount (Unit of SN40)
Lane	Lane difference	10
Environment	Seasonal variation (Quarter changes) Temperature difference	13
Unobservable	Random fluctuation	3

5.2. DETERIORATION MODEL OF SN40

Measurement error estimations indicate that there is a meaningful relationship between SN40 and environmental variables. However, measurement error does not indicate a relationship between SN40 and factors of age and traffic, which are the primary factors affecting SN40. Pavement resurfacing project data from five counties in California provides pavement age information and makes possible the estimation of the deterioration model of SN40. This data set includes resurfacing location, type of pavement and the duration of construction, from which the age and surface type information of the pavement section can be inferred. Truck volume information at each observation point was estimated by interpolation, using annual truck volume data from Caltrans. Weather information such as precipitation and temperature at each observation point was collected from daily records from the closest weather station available via the National Oceanic and Atmospheric Administration (NOAA) Climatic Data Center.

After combining all data, there were a total of 2,848 observations of the skid resistance of asphalt concrete pavements, including all variables. The studied routes are shown in Table 5, and the study time period was from 1992 to 2007.

Table 5 Studied Routes

Routes	District	County	Miles
I-5	6	Kern	44
I-80	3	Yolo and Nevada	46
I-101	1	Humboldt	133
I-101	5	Monterey	90
Total			313

Unless all possible factors that may impact skid resistance are considered, modeling skid resistance using field data can produce biased or inconsistent parameter estimates. Therefore, careful consideration of unobserved variables is required. Table 6 shows all possible factors affecting skid resistance as determined by the previous literature, and indicates each factor's availability in the data set used in this study. Unobservable variables are polished stone value (PSV), aggregate type, lane AADT, tester device error, and type of tire used. PSV and aggregate type are attributes of pavement section. These variables can cause problems in correlation of residuals within each pavement section. These issues can be resolved by using a panel data model which considers the unobservable characteristics of individuals (i.e., pavement sections) (Ruud 2000). Second, lane AADT is an attribute of the specific lane in which skid resistance is measured. This is a significant variable because the distribution of traffic, especially heavy vehicles, differs between lanes. To account for this effect, the location of the lane (median, middle or shoulder lane) is considered an explanatory variable. Finally, unobservable measurement factors such as tester device error and type of tire used are assumed as random components, meaning that each of them is independent and identically distributed.

Table 6 Factors Affecting Skid Resistance and Their Availability in the Data Set

Factors	Available Variables in Data Set	Unobservable Variables
Pavement factors	- pavement type	- polished stone value (PSV) - aggregate type
Traffic Factors	- number of commercial vehicles/day - AADT - cumulated traffic	- lane AADT
Environmental Factors	- seasonal effects - temperature - amount of precipitation preceding measurement - dry periods preceding measurement	
Time Factors	- age of pavement (time after resurfacing)	
Measurement Factors	- test speed	- tester device error - type of tire used

The form of the random effect panel data models used in this analysis is as follows:

$$\mathrm{Ln}(\mathrm{SN40}_{it}) = \beta_1 \mathrm{Ln}(\mathrm{TRRAFIC}_{it}) + \beta_2(\mathrm{LANE}_{it}) + \beta_3(\mathrm{TEMP}_{it}) + \beta_4(\mathrm{PRCP}_{it}) + \beta_5(\mathrm{DP}_{it}) + \beta_6 \mathrm{Ln}(\mathrm{AGE}_{it}) + \alpha_0 + u_{it}$$

where

$\mathrm{SN40}_{it}$ = measured skid resistance (skid number) at 40 mph in section i at time t;

$\mathrm{TRRAFIC}_{it}$ = variable representing traffic conditions in section i at time t;

LANE_{it} = dummy variable representing the lane location observed in section i at time t;

TEMP_{it} = variable representing temperature conditions in section i preceding or at time t;

PRCP_{it} = variable representing amount of precipitation received at section i before time t;

DP_{it} = variable representing dry periods at section i preceding time t;

AGE_{it} = variable representing age of pavement in section i at time t;

β_i = regression coefficients (i = 1, 2, … , 6);

α_0 = constant;
$u_{it} = \varepsilon_{it} + (\alpha_i - \alpha_0)$;
α_i = intercept term which varies across section i;
ε_{it} = random term accounting for the unobserved characteristics of section i at time t.

The random term u_{it} has the following properties; $E[u_{it}] = 0$, $Var[u_{it}] = \sigma_\varepsilon^2 + \sigma_\alpha^2$ and $Cov[u_{it}, u_{js}] = 0$ if $i \neq j$ and $t \neq s$, $Cov[u_{it}, u_{is}] = \sigma_\alpha^2$ if $t \neq s$, for all i, j, t, s. Therefore, this model can be viewed as a generalized regression model which has parameters β and α_0. These parameters can be estimated using generalized least squares (GLS).

The use of the logarithm of SN40 as the dependent variable is to ensure that the SN40 value is always positive. The choice of this particular form of model was primarily based on the findings of previous research. The first explanatory variable, $Ln(TRRAFIC_{it})$ accounts for the possible decrease in SN64 with an increase in traffic. Therefore, the expected sign of β_1 is negative. Because the effect of traffic on pavement sections does not increase at the same rate as the traffic itself, the logarithm function was selected. All possible combinations of variables which can represent $TRRAFIC_{it}$ were tested: (a) ADT, (b) truck volume, (c) truck percentage, and (d) weighted truck volume on axles. The second variable, $LANE_{it}$ accounts for the differences in the mean skid number between median lane and shoulder lane. It is expected that the skid number is higher in the median lane and lower in the shoulder lane. $TEMP_{it}$ accounts for the possible influence of temperature on pavement skid resistance as well as its influence on the measuring system. Since it has generally been observed that skid numbers fall with rising temperatures, the coefficient β_3 is expected to be negative. In this analysis, two variables were used to represent $TEMP_{it}$: (a) temperature at the time of measurement, and (b) average temperature over a month-long period prior to the measurement. $PRCP_{it}$ accounts for the influence of precipitation on SN40. Once again, more than one parameter was used to represent $PRCP_{it}$. DP_{it} accounts for the decrease in SN40 with an increase in the length of the dry period prior to skid measurement. A number of different parameters, including (a) number of dry days since last significant (> 2.5 mm or 0.1 in.) precipitation, and (b) number of dry months since last significant precipitation, were used in the equation for variable DP_{it}. $Ln(AGE_{it})$ is used to represent the age effect which is negative. For the same reason, for $Ln(TRRAFIC_{it})$, the logarithm function is used.

There are two excluded variables among those available as shown in Table 6: pavement type, and test speed. Pavement type is controlled by including only asphalt pavement sections, while test speed is not expected to be significant because SN40 has already been calibrated when comparing different speeds with the standard 40 mph.

Based on the physical characteristics of skid resistance discussed above, the model is estimated using LIMDEP software, and significant variables are selected. Table 7 shows the selected variables and simple statistics of each variable.

Table 7 Simple Statistics of Selected Significant Variables

Variables	Units	Mean	Std. Dev.	Min.	Max.
SN40		44.32	7.83	6.00	71.00
ADT	1000 vehicle/day	26.49	28.80	3.41	128.00
Dummy for shoulder lane		0.76	0.43	0.00	1.00
Temperature at the time of the measurement	□	63.99	10.16	37.00	108.00
Average precipitation of month	inch	4.00	7.58	0.00	38.65
The number of dry month since the last significant precipitation	Month	0.59	0.96	0.00	4.00
Age of pavement	Month	55.89	45.79	1.00	240.00

Table 8 Estimation Results: Deterioration Model

Variables	Coefficient	Standard Error	t-statistic	P- value
Constant	4.1425	0.0458	90.5400	0.0000
Ln(ADT)	-0.0593	0.0055	-10.7490	0.0000
Dummy for shoulder lane	-0.1206	0.0084	-14.2920	0.0000
Temperature at the time of the measurement	-0.0010	0.0006	-1.7120	0.0869
Average precipitation of month	0.0014	0.0007	2.0600	0.0394
The number of dry month since the last significant precipitation	-0.0204	0.0049	-4.1800	0.0000
Ln(Age)	-0.0078	0.0040	-1.9780	0.0480
Note: Number of observations = 2,848; R^2=0.70; L(B)=2263.14; L(0)=563.87.				

The estimated results are shown in Table 8. Among all variables related to traffic, ADT is the most significant variable. The coefficient for Ln(ADT) is as expected. SN40 decreases with ADT. The coefficient for the shoulder lane dummy variable is also as expected. The SN40 in the shoulder lane is significantly lower than the average SN40 values, due to the distribution of heavy traffic. Temperature at the time of measurement is the most significant variable among all variables represented by TEMP_{it}. The sign of the coefficient is intuitive. However, the P-value is 0.08. That is, temperature is significant at the 90% confidence interval, but not at 95%. This might be due to the time unit of SN40 measurement. The day of measurement is not recorded, and the month of measurement is the most precise time variable and can vary considerably. For the same reason, the p-value of average monthly precipitation is high relative to other variables. A shorter time period such as average five-day precipitation might result in a better p-value. Nonetheless, the coefficient of the average monthly precipitation is within the 95% confidence interval and has the right sign. The number of dry months since the last significant precipitation also has an intuitive result. SN40 decreases with the increased length of the dry period (Jayawickrama 1998). Ln(Age) shows the deterioration of SN40 over time, which is also expected.

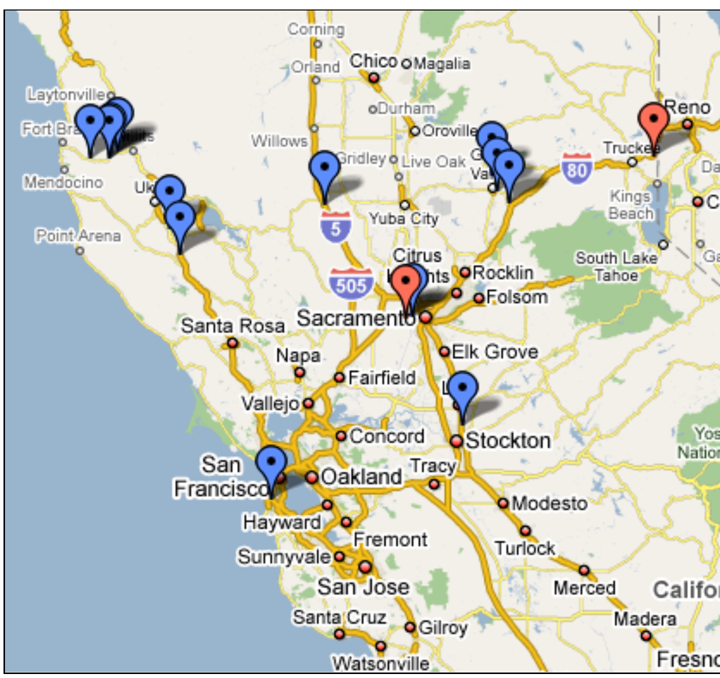
In summary, there is significant relationship between SN40 and weather, especially in terms of temperature at the time of measurement, average monthly precipitation, and the number of dry months since the last significant precipitation. The combination of these factors can cause seasonal variations in SN40. In addition, SN40 is inversely related to ADT. Shoulder lane tends to exhibit lower SN40 compared with the average, due to heavier traffic. Age of pavement also has a negative relationship with SN40. However, the effects of ADT and shoulder lane are larger than that of age.

6. SAFETY PERFORMANCE OF PAVEMENT TYPE

Caltrans has employed different types of pavement materials with the aim of improving drainage systems. These materials include a higher percentage of void space within the pavement itself. Due to the improvement of drainage systems, water will seep through these voids more rapidly, which is expected to reduce wet pavement related collisions. There are three different types of pavement considered in this study: (1) Open Graded Asphalt Concrete (OGAC), which contains a high percentage of air voids; (2) Groove Pavement (GP), which has longitudinal or transverse cuts on its surface; and (3) Rubberized Open Graded Asphalt Concrete (R-OGAC), which is asphalt modified by the incorporation of rubber which helps to increase the fatigue resistance of the asphalt.

These different types of material were used at 21 sites throughout California, as shown in Figure 6. Thirteen of the sites used OGAC, four of them used GP, and the remaining four used R-OGAC. The study period was from 1994 to 2005. Collision data from the Traffic Accident Surveillance and Analysis System (TASAS), traffic volume data from Caltrans Traffic Data Branch, and hourly NOAA precipitation data from the nearest weather station were used for the before-and-after comparison.

To find the closest weather stations, all weather stations within the 20 miles of study sites were considered. The weather information included in the TASAS data was compared with the precipitation data from the weather stations. Data from the weather station that best matched the TASAS data was chosen, and number of rainy hours was determined by analyzing the weather station data.



Type of Pavement	The Number of Studied Sites
OGAC	13
GP	4
R-OGAC	4
TOTAL	21

Figure 6 Studied Sites

As mentioned above, the alternative pavement material countermeasures are expected to be effective in reducing wet-related collisions. Figure 7 shows a before-and-after comparison of wet-related collision rates at study site 6. The collision rates per unit of exposure need to be compared , since the number of collisions depends on traffic, mile, and time. The wet and dry collision rates were calculated from the following formula:

$$\text{Wet collision Rate} = \frac{No.\text{ of } WetCollision \text{ (on rainy hour)}}{(mile)\times(AADT/24hr)\times(rainy\_hours)}$$

$$\textbf{DRY COLLISION RATE} = \frac{No.\text{ of } DryCollision \text{ (on not-rainy hour)}}{(mile)\times(AADT/24hr)\times(not-rainy\_hours)}$$

While the dry collision rate did not change significantly, the wet collision rate decreased dramatically. This is because the improved drainage has a positive effect on the collision rate only under rainy conditions. Therefore, the analysis was conducted by comparing wet-related collisions before and after the countermeasure was implemented.

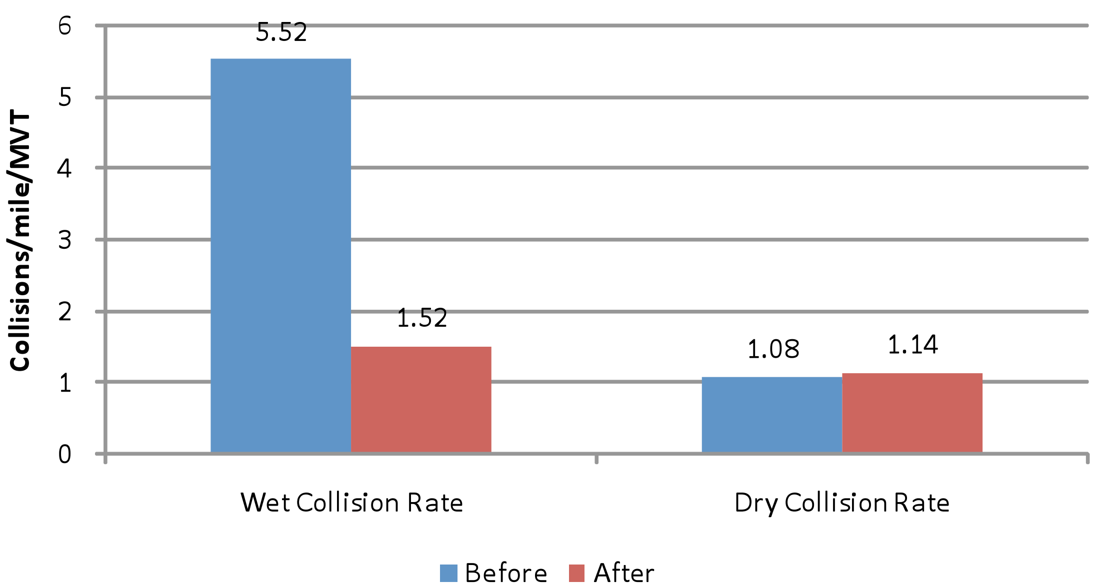


Figure 7 Before-and-After Comparison of Wet-Related Collision Rates at Study Site 6

For the before-and-after comparison, collision data from two years before and two years after implementation were used. The condition of a pavement without improvement remains stable, so that the number of years for the before-implementation period is not critical. However, the condition changes a great deal within a few years following the installation of new pavements, and using the same number of years for the after-implementation period is necessary in order to compare them. Because the minimum number of years available within the data set was two years, a two-year period after implementation was used for all study sites.

Rainy hours were defined as the sum of the number of hours of rainfall and six hours after precipitation ended, in order to account for the lingering effects of precipitation. When the occurrence time of wet collisions from the study sites were compared with the hours of precipitation, it was found that a considerable proportion of them occurred within six hours after the rainfall. This might be due to wet pavement conditions following precipitation. Based on the relative timing, it was assumed that wet collisions could be affected by the exposure to rain within six hours after the rain ended.

To conduct statistical tests on the comparisons, we referred to Hauer's method (Hauer 1997). This method compares the predicted and the observed number of collisions. Let π be the predicted number of collisions under the assumption of no improvement and λ be the observed (actual) number of collisions after improvement. For example, in Figure 8, which shows the collisions in Study Site 1, the red bar represents π, the expected number of collisions if there was no improvement and the blue bar represents λ, the actual number of collisions after improvement. The figure shows that the collision rate decreased after the the improvement.

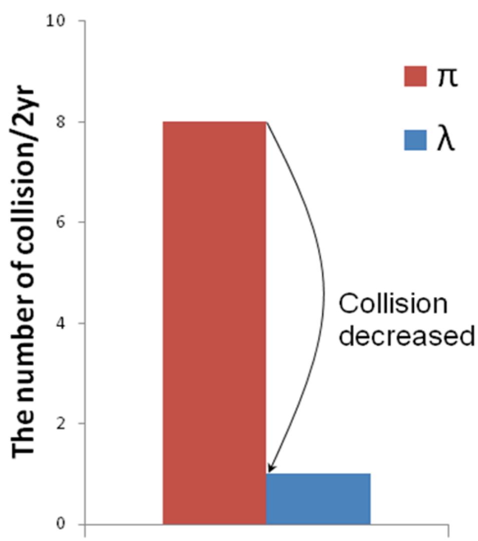


Figure 8 Study Site 1

The question is how to predict π. Under the assumption that the distribution of the number of collisions is assumed to be Poisson, Hauer suggested two different methods for making this prediction. The first is to use only the information about treatment sites, and the second is to use the information from comparison groups. Both methods were applied to our study.

6.1. BEFORE- AND AFTER- STUDIES ON TREATMENT SITES

Using the first method, the number of collisions after the improvement under the assumption of no improvement based on the information from treatment sites before improvement can be predicted. If nothing changes at all, π will be same as the observed number of collisions before the improvement, κ.

$$\pi = \kappa$$

However, AADT and rainy hours change and have an effect on the number of collisions. Therefore, these factors need to be adjusted. By adjusting rainy hours and AADT, the above formula can be changed as follows:

$$\pi = r_d r_{tf} \kappa$$

Where π: predicted number of collision after the improvement under the assumption of no improvement;

κ: observed number of collisions before the improvement;

r_d: adjustment factor for rainy hours;

r_{tf}: adjustment factor for AADT.

The adjustment factor for rainy hours is simply the ratio of before and after rainy hours, because the wet collision rate is proportional to the wet duration, which is represented here by rainy hours.

$$r_d = \frac{Rainy\ hours_{after}}{Rainy\ hours_{before}}$$

In addition, the AADT correction factor, r_{tf} can be expressed as follows:

$$r_{tf} = \frac{f(AADT_{after})}{f(AADT_{before})}$$

However, the AADT correction factor is not a simple ratio of AADT, but rather a function of it, since AADT is not proportional to the number of collisions. In fact, the relationship between AADT and the expected number of collisions is non-linear, necessitating use of the safety performance function of AADT as shown in Figure 9. In this study, the following function was used as safety performance function which is generally informed.

$$f(x) = x^{0.8}$$

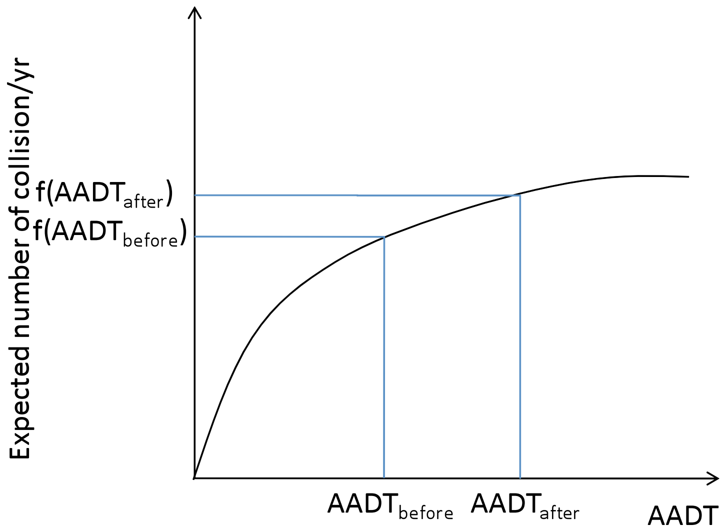


Figure 9 Safety Performance Function

The result of the before-and-after comparison pooled by the three pavement types, OGAC, GP and R-OGAC using only the information from treatment sites, is shown in Figure 10. In the figure, the first red bar represents the total sum of predicted number of collisions under the assumption of no improvement of all thirteen OGAC sites, and the blue bar represents observed collisions. The predicted number of collisions is 59 per two-year period, whereas the actual collision rate is 42 per two-year period. This means that the collision rate decreased by about 17 over a two-year period in the OGAC sites.

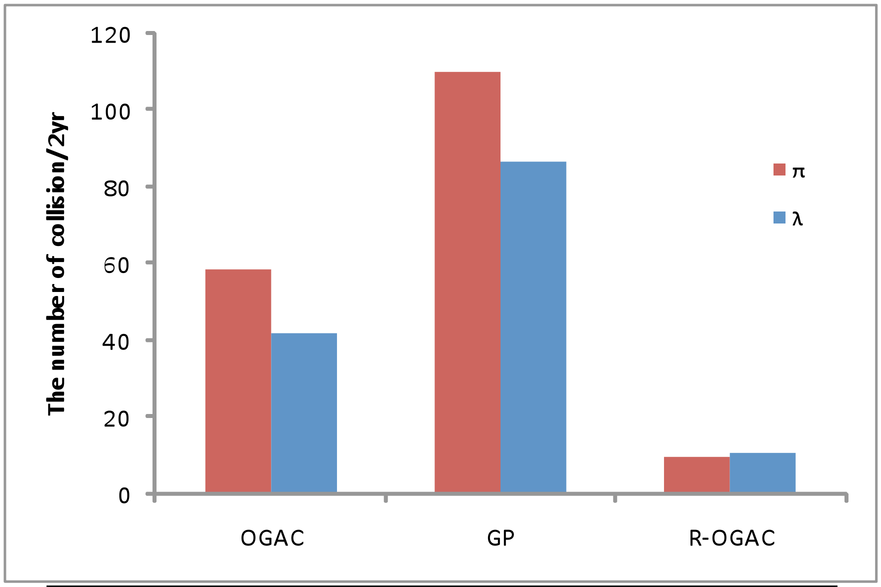
Based on these pooled values, we conducted statistical tests using only the information from treatment sites. We have two measures of comparison; the first is ratio, which represents the percentage increase or decrease in collision rate. The ratio can be calculated using following formula:

Ratio = □= π/□

Therefore, a ratio of less than one indicates that the collision rate decreased after implementation. The second measure is difference:

Difference = □= π-□

A difference of less than zero indicates that the collision rate has decreased. These two measures were compared because some practitioners might be interested in ratio (e.g., the collision reduction factor), whereas others might be interested in the actual numerical reduction in collisions or deaths. Both measures were suggested by Hauer.



Types of Pavement	OGAC	GP	R-OGAC
The Number of Studied Sites	13	4	4
π (Predicted)	58.91	110.17	9.82
□ (Observed)	42.00	87.00	11.00
VAR(π)	27.94	89.88	2.84
VAR(□)	42.00	87.00	11.00

Figure 10 Comparison of the Number of Collisions (Method 1)

Table 9 Statistical Test Based on Ratio (θ = π/λ) (Method 1)

Types of Pavement	OGAC	GP	R-OGAC
The Number of Studied Sites	13	4	4
□	0.71	0.78	1.09
STDV(□)	0.13	0.11	0.37
95% Confidence Interval	(0.46,0.96)	(0.57,1.00)	(0.35, 1.82)
Statistical Significance at 95% Confidence Level	Decreased	Decreased	Not significant

Table 10 Statistical Test Based on Difference (δ= π-λ) (Method 1)

Types of Pavement	OGAC	GP	R-OGAC
The Number of Studied Sites	13	4	4
□	16.91	23.17	-1.18
STDV(□)	8.36	13.30	3.72
95% Confidence Interval	(0.2,33.6)	(-3.4,49.8)	(-8.6,6.3)
Statistical Significance at 95% Confidence Level	Decreased	Not significant	Not significant

Table 9 shows the results of statistical tests for the three different pavement types. The collision rate was reduced to 46-96% of the 'before' level at the 95% confidence level when the pavement was resurfaced with OGAC, and to 57-100% when resurfaced with GP. These results are statistically significant, but due to the availability of only four sites for resurfacing with R-OGAC, there are no significant results for this material.

Based on the difference test as shown in Table 10, collisions decreased by 0.2 to 33.6 wet collisions per two-year period in OGAC sites—a statistically significant reduction. However, conclusions cannot be drawn for GP and R-OGAC due to the lack of study sites.

6.2. BEFORE-AND-AFTER STUDIES USING COMPARISON GROUPS

Even if the collision rate is significantly reduced after the improvement, other factors could also be involved in collision reduction. For example, if safety education was improved, and general wet-related collisions were reduced not only at the treatment sites but also at neighboring sites, then it cannot be conclusively stated that the reduction is due to the new pavement type. Therefore, the neighboring sites, known as comparison groups, should be considered. The second method for predicting the number of collisions after the improvement under the assumption of no improvement is by using the information collected from comparison groups. Comparison groups are the two sites adjacent to the treatment sites, and are of the same length as the treatment sites. Figure 11 is a diagram showing comparison groups. If the treatment site was located in the end of a freeway, only one adjoining comparison site was considered for comparison.

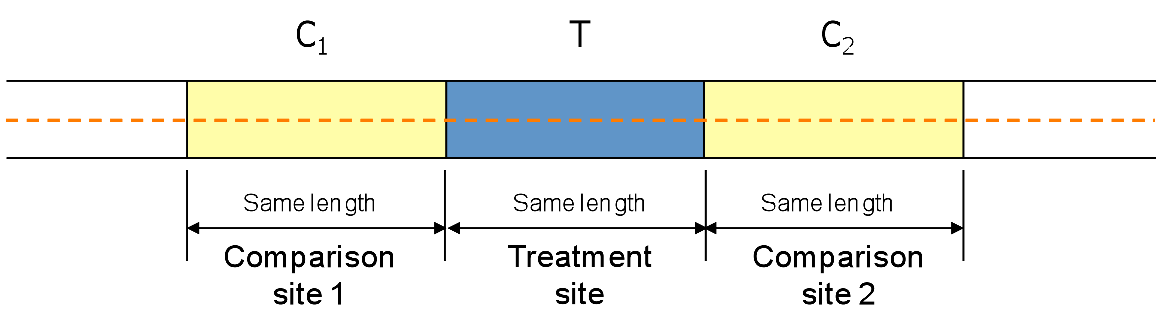


Figure 11 Description of Comparison Groups

While analyzing the comparison group information, two assumptions were made. First, the factors that affect safety have changed from the 'before' to the 'after' period in the same manner, at both the treatment site and within the comparison group. Second, this change in factors influences the safety of the treatment site and the comparison site group in the same way. Under these assumptions, the expected number of collisions was predicted with a correction factor based on the comparison group by adjusting the comparison ratio, i.e., that the ratio of the expected 'after' number to the expected 'before' number of target accidents. The following formula explains the prediction process:

$$\pi = r_c \times k$$

Where π = predicted number of collisions under the assumption of no improvement;
k = observed number of collisions before improvement;

r_c = comparison ratio $= \frac{(C_1+C_2)_{after}}{(C_1+C_2)_{before}}$

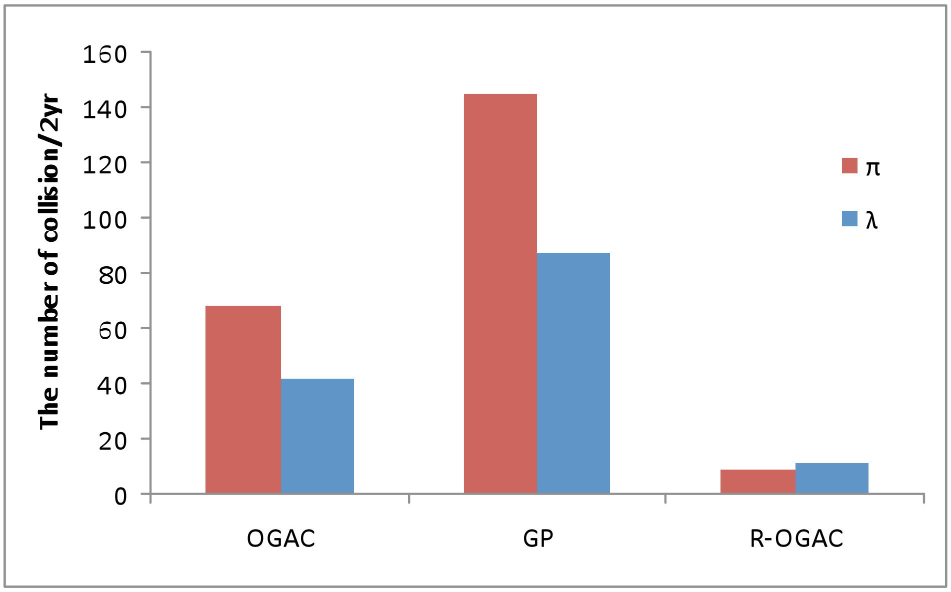
C_1= the number of collisions of at comparison site 1
C_2= the number of collisions of at comparison site 2

The pooled values of π and by pavement type are shown in Figure 12. The predicted number of collisions in all thirteen OGAC sites was 68 collisions per two-year period, whereas the actual number of collisions was 42 collisions per two-year period. This means that collisions decreased as a result of the improvement.

Using these pooled values, we conducted the same statistical test. Based on the ratio shown in Table 11, the collision rate was reduced to 27-90% of the 'before' level at the 95% confidence level when the pavement was resurfaced with OGAC. In addition, use of GP decreases the number of collisions to 12-88% of the 'before' level significantly. However, because of the small size of our sample, the results from R-OGAC cannot be considered significant.

Results from the test in difference, as shown in Table 12, were insignificant due to the relatively large variance in the number of collisions in comparison groups. However, use of OGAC resulted a decrease in wet collisions by 26 over a two-year period. While the reduction is not statistically significant, it is still a large reduction.

To summarize, by adjusting for changes in comparison sites, resurfacing with OGAC significantly decreased the number of collisions by 10-73%. Resurfacing with OGAC decreased the number of collisions by 25.86 wet collisions over a two-year period, but was not proven statistically significant. The limited number sample sets for GP and R-OGAC meant that we were unable conclusions about their effectiveness.



Types of pavement	OGAC	GP	R-OGAC
The number of studied sites	13	4	4
π (Estimated)	67.86	145.05	8.48
□ (Actual)	42.00	87.00	11.00
VAR(π)	255.24	4208.22	14.91
VAR(□)	42.00	87.00	11.00

Figure 12 Comparison of the Number of Collisions (Method 2)

Table 11 Statistical Test Based on Ratio (θ = π/λ) (Method 2)

Types of pavement	OGAC	GP	R-OGAC
The number of studied sites	13	4	4
□	0.59	0.50	1.07
STDV(□)	0.16	0.19	0.49
95% Confidence interval	(0.27,0.90)	(0.12,0.88)	(0.10, 2.05)
Statistical significance at 95% confidence level	Decreased	Decreased	Not significant

Table 12 Statistical Test Based on Difference (δ= π-λ) (Method 2)

Types of pavement	OGAC	GP	R-OGAC
The number of studied sites	13	4	4
□	25.86	58.05	-2.52
STDV(□)	17.24	65.54	5.09
95% Confidence interval	(-8.6, 60.3)	(-73.0,189.1)	(-12.7,7.7)
Statistical significance at 95% confidence level	Not significant	Not significant	Not significant

7. CONCLUSIONS AND IMPLICATIONS

The main objectives of this study were to: (1) evaluate and analyze skid test results, and (2) identify and analyze before-and-after historical collision data at the operational test sites where new types of pavements have been installed, in order to quantify the effectiveness of the safety performance of similar pavement improvements.

On the basis of an analysis of SN40 data from 313 miles of asphalt concrete freeway in California over a period of twenty years, the results suggest a significant relationship between SN40 and weather, especially temperature at the time of measurement, average monthly precipitation, and the number of dry months since the last significant precipitation. The combination of these factors can cause seasonal variations in SN40. Therefore, if a highway agency wants to prioritize pavement improvements using SN40, standardization is necessary. The model developed in this study can provide the adjustment factors.

SN40 is inversely related to ADT, and shoulder lanes tend to experience lower SN40 compared with the average, as a result of heavier traffic in those lanes. Age of pavement also has a negative effect on SN40. However, the impacts of ADT and lane location (specifically, that of the shoulder lane) are more significant than those of age. These findings can provide meaningful information for developing data collecting strategies: for example, SN40 needs to be monitored selectively in high-risk locations where ADT is higher than the average, rather than in all sections of freeway. Also, SN40 needs to be measured in the shoulder lane to detect the possible lowest value of SN40 at a particular postmile.

Our analyses of the safety performance of three new pavement types indicate that resurfacing with OGAC significantly decreased the number of wet-related collisions. But unfortunately, we do not currently have sufficient data to draw significant conclusions about resurfacing with GP or R-OGAC. Incorporating additional sites would be a fairly straightforward extension of the current study.

In general, our study demonstrates that seasonal effects, ADT, and age of pavement must all be considered in order to maintain safe levels of skid resistance. In addition, while further research is needed, results suggest that new pavement types such as OGAC can be effective in improving the safety performance of roadways.

8. SUGGESTIONS AND FURTHER RESEARCH

To better understand skid resistance performance and to establish whether a broader utilization of pavement improvements is needed, it is important to determine the effectiveness of pavement performance in the field. Since some sites resurfaced with the experimental new pavement have been in place for several years, it would also be beneficial to examine the skid resistance values as a function of traffic and weather attributes over several more years by analyzing the test data inventory. Moreover, the collision data observed before and after pavement installation can now be screened from the statewide Traffic Accident Surveillance and Analysis System (TASAS) database to evaluate the safety performance, which can be used as the basis for further cost-benefit analysis.

8.1. ESTABLISH A SKID RESISTANCE DATA COLLECTING STRATEGY

For the present study, the effects of traffic and environmental factors on skid resistance were evaluated. But insufficiencies and inefficiencies in the skid resistance data collection process limited the research to the selected study sites. To maximize the efficiency of measurements, the current method could be improved by the following strategies:

- Measured SN40 should be standardized to account for seasonal effects.
- The date of measurement should be recorded for more detailed seasonal variation.
- SN40 should be measured in the shoulder lane to detect the lowest possible value of SN40 at a particular postmile.
- High-risk locations where ADT is higher than average should be intensively monitored.

8.2. INVESTIGATION OF RELATIONSHIP BETWEEN SAFETY PERFORMANCE AND SKID RESISTANCE

Our findings suggest that pavement age has a negative effect on the skid resistance of asphalt concrete. We also found that the studied types of new pavement significantly reduce wet-related collisions. However, data are insufficient to determine the relative contribution of improved skid resistance to the safety performance of each of the three pavement types. This information is crucial in determining the appropriate type of pavement to be used in different settings. Additional SN40 data would make it possible to:

- Quantify the influence of implementation of new pavement types on SN40 in detail.
- Quantify the relative contribution of SN40 on safety performance.

8.3. ESTABLISH COLLISION REDUCTION FACTORS FOR NEW PAVEMENT TYPES

A Collision Reduction Factor (CRF) for different pavement types can be established if there are relatively small confidence intervals for the amount of collision reduction. The process can be refined by taking into account other factors, such as location (urban or rural), and roadway type in order to establish collision reduction factors for different pavement types. However, it is critical to obtain additional sample sites for all pavement types, especially GP and R-OGAC.

REFERENCES

American Society for Testing and Materials. 2004. Standards, 2004. Designation E274-97. 2004 ASTM Annual Book.

Anderson, D. A., Meyers, W., and Rosenberger, J. L. 1986. Development of Procedure for Correcting Skid Resistance Measurements to a Standard End of Season Value. *Transportation Research Record* 1084. TRB, National Research Council, Washington, D.C. pp. 40-48.

Bazlamit, S., and Reza, F. 2005. Changes in Asphalt Pavement Friction Components and Adjustment of Skid Number for Temperature. *Journal of Transportation Engineering*. ASCE 131. pp. 470–476.

Corley-Lay, J. B. 1998. Friction and Surface Texture Characterization of 14 Pavement Test Sections in Greenville. North Carolina. *Transportation Research Record* 1639. TRB. National Research Council. Washington, D.C. pp.155-161.

Dunlap, D. F., et al. 1976. "Pavement Skid Resistance Requirements." *Transportation Research Record* 584: 15-21.

E. Hauer 1997. *Observational Before-After Studies In Road Safety: Estimating The Effect Of Highway And Traffic Engineering Measures On Road Safety*.

Jayawickrama, P. W., and Thomas, B. 1998. Correction of Field Skid Measurements for Seasonal Variations in Texas, *Transportation Research Record* 1639. TRB. National Research Council. Washington, D.C. pp.147-154.

Highway Research Board. 1972. Skid Resistance, National Cooperative Highway Research Program. *Synthesis of Highway Practice*, #14.

Do, M., Tang, Z., Kane, M., and de Larrard, F. 2007. Pavement Polishing-Development of a Dedicated Laboratory Test and its Correlation with Road Results. *Wear* 1–6 Issues. pp. 36–42.

Moyer, R. A. 1934. *Skidding Characteristics of Automobile Tires on Roadway Surfaces and Their Relation to Highway Safety.* Bulletin No. 120. Iowa Engineering Experiment Station. Ames, Iowa.

Ruud, R. 2000. *An Introduction to Classical Econometric Theory.*

Szatkowski, W. S., and Hosking, J. R. 1972. *The Effect of Traffic and Aggregate on the Skidding Resistance of Bituminous Surfaces.* Transport and Road Research Laboratory. Greta Britain. TRRL Report LR 504.

Zube, E., and Skog, J. 1968. *Skid Resistance of Screenings for Seal Coats.* California Department of Public Works. Division of Highways. Materials and Research Department. Research Report Np. M&R 633126. 47th Annual Meeting of the Highway Research Board.

Hegmon, R. R. 1978. Seasonal Variations in Pavement Skid Resistance—Are These Real? *Public Roads*. Vol. 42. No. 2. pp. 55–62.