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Evaluation of Pavement Safety Performance

PUBLICATION NO. FHWA-HRT-14-065

FEBRUARY 2015

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

FOREWORD

The research documented in this report was conducted as part of Phase VI of the Federal Highway Administration (FHWA) Evaluation of Low-Cost Safety Improvements Pooled Fund Study (ELCSI–PFS). The FHWA established this pooled fund study in 2005 to conduct research on the effectiveness of the safety improvements identified by the National Cooperative Highway Research Program Report 500 Guides as part of the implementation of the American Association of State Highway and Transportation Officials Strategic Highway Safety Plan. The ELCSI-PFS studies provide a crash modification factor (CMF) and benefit-cost (BC) economic analysis for each of the targeted safety strategies identified as priorities by the pooled fund member states.

The intent of the study was to isolate the effects of various low cost pavement treatments on roadway safety. This was a retrospective study for pavement safety performance, looking back at crash data both before and after treatments were installed. Both flexible and rigid pavement treatments were analyzed, with the majority typically used for pavement preservation or minor rehabilitation purposes. Although state highway agencies recognize that most of these treatments generally improve pavement friction, they are not typically installed explicitly for safety improvement. The one exception is high friction surfacing, which is typically applied as a spot safety treatment. Under this effort, CMFs and BC ratios were developed for various low-cost pavement treatments.

Monique R. Evans
Director, Office of Safety
Research and Development

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16. Abstract

The intent of this study was to isolate the effects of various low-cost pavement treatments on roadway safety. This was a retrospective study of pavement safety performance, looking back at crash data before and after treatments were installed. Both flexible and rigid pavement treatments were analyzed, with the majority typically used for pavement preservation or minor rehabilitation purposes. Although State highway agencies recognize that most of these treatments generally improve pavement friction, they are not typically installed explicitly for safety improvement, with one exception, high-friction surfacing, which is typically applied as a spot safety treatment.

The research was conducted as part of Phase VI of the Federal Highway Administration Evaluation of Low-Cost Safety Improvements Pooled Fund Study (ELCSI–PFS). This pooled fund study (PFS) was established to conduct research on the effectiveness of the safety improvements identified by the National Cooperative Highway Research Program Report 500 guides as part of implementation of the American Association of State Highway and Transportation Officials Strategic Highway Safety Plan. The intent of the work conducted under the various phases of the ELCSI-PFS is to provide a crash modification factor (CMF) and benefit-cost (BC) economic analysis for each of the targeted safety strategies identified as priorities by the PFS States. Under the effort described herein, CMFs and BC ratios were developed for various low-cost pavement treatments.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ABBREVIATIONS

AADT	Average Annual Daily Traffic
AASHTO	American Association of State Highway and Transportation
BC	Benefit-Cost
Caltrans	California Department of Transportation
CDOT	Colorado Department of Transportation
C-G	Comparison Group (study)
CMF	Crash Modification Factor
CMFunction	Crash Modification Function
CPI	Consumer Price Index
EB	Empirical Bayes
ELCSI–PFS	Evaluation of Low-Cost Safety Improvements Pooled Fund Study
FHWA	Federal Highway Administration
GLM	Generalized Linear Modeling
GP	Groove Pavement
HFS	High-Friction Surfacing
HIS	Highway Information System
HMA	Hot Mix Asphalt
HSIS	Highway Safety Information System
KDOT	Kansas Department of Transportation
KTC	Kentucky Transportation Cabinet
MDOT	Michigan Department of Transportation
MDT	Montana Department of Transportation
MnDOT	Minnesota Department of Transportation
NCDC	National Climatic Data Center
NCDOT	North Carolina Department of Transportation
NCHRP	National Cooperative Highway Research Program
NYSDOT	New York State Department of Transportation
OGAC	Open Graded Asphalt Concrete
OGFC	Open-Graded Friction Course
PennDOT	Pennsylvania Department of Transportation
R-OGAC	Rubberized Open Graded Asphalt Concrete
ROR	Run-Off Road
RTM	Regression to the Mean
SCDOT	South Carolina Department of Transportation
SCRIM	Sideway-Force Coefficient Routine Investigation Machine
SEAHC	Surface Enhancements at Horizontal Curves
SHRP2	Strategic Highway Research Program 2
SPF	Safety Performance Function
TDOT	Tennessee Department of Transportation
TRIMS	Tennessee Information Management System
UTBWC	Ultra-Thin Bonded Wearing Course
WisDOT	Wisconsin Department of Transportation

EXECUTIVE SUMMARY

The intent of this study was to isolate the effects of various low-cost pavement treatments on roadway safety. This was a retrospective study of pavement safety performance, looking back at crash data before and after treatments were installed. Both flexible and rigid pavement treatments were analyzed, with the majority typically used for pavement preservation or minor rehabilitation purposes. Although State highway agencies recognize that most of these treatments generally improve pavement friction, they are not typically installed explicitly for safety improvement, with one exception, high-friction surfacing (HFS), which is typically applied as a spot safety treatment.

The research was conducted as part of Phase VI of the Federal Highway Administration (FHWA) Evaluation of Low-Cost Safety Improvements Pooled Fund Study (ELCSI–PFS). This PFS was established to conduct research on the effectiveness of the safety improvements identified by the National Cooperative Highway Research Program (NCHRP) Report 500 guides as part of implementation of the American Association of State Highway and Transportation Officials (AASHTO) Strategic Highway Safety Plan. The intent of the work conducted under the various phases of the ELCSI-PFS is to provide a crash modification factor (CMF) and benefit-cost (BC) economic analysis for each of the targeted safety strategies identified as priorities by the PFS States.

With respect to pavement surfaces, NCHRP Report 500, Volume 6, which addresses reducing run-off-road (ROR) crashes, presents Strategy 15.1 A7, "Skid-Resistant Pavements," as a key to reducing ROR crashes. Volume 7, which addresses reducing collisions on horizontal curves, likewise discusses Strategy 15.2 A7, "Provide Skid-Resistant Pavement Surfaces," as a key strategy for reducing crashes at horizontal curves. The report recognizes that there had been only limited research conducted on site-specific treatments as of 2003. However, given the results of other research on general effectiveness of decreased skidding, the report places this strategy in the "proven" category. The report also recognizes that the effectiveness of friction-enhancing treatments will diminish over time; therefore, States using this strategy must conduct a dynamic program to target the appropriate sites for new treatment and to maintain the safety benefit from existing treatments.

In a similar manner, the FHWA Low-Cost Treatments for Horizontal Curve Safety guide recommends "skid-resistive pavement surface treatments" as a low-cost treatment for reducing crashes at horizontal curves. This guide specifically mentions remedial treatments such as hot-mix asphalt (HMA) overlays, surface treatments, grinding, and grooving of pavement surfaces for both concrete and asphalt pavements where friction demand is higher.

A further literature review revealed important insights to consider, including the following:

- Confounding factors that influence collision risk and may interact with the safety effects of skid resistance include location type (segment, intersection approach, curve, etc.), area type, speed limit, traffic volume, rainfall propensity, roadway geometry, temperature, and pavement structure.

- Expected collision reductions from friction improvements depend on both the level of friction prior to and after treatment. Reductions in wet-road crashes up to approximately 75 percent may be expected.

- Friction of various low-cost pavement treatments tends to decrease with time, and therefore the safety benefit may also be expected to decrease with time.

- Evaluations of improved skid resistance have typically not applied statistically rigorous before–after study designs.

The ultimate outcome of this effort to build on knowledge from previous work, while overcoming the shortcomings of those studies, is to gain a better understanding of the effects that various common, low-cost pavement treatments have on roadway safety. Two of the more tangible ways for quantifying this is through CMF and BC ratios for each treatment type. These products will potentially help State transportation departments in the decisionmaking process for selection of a pavement treatment for a particular project.

In achieving these outcomes, the state-of-the-art empirical Bayes (EB) before–after methodology was applied to evaluate the effects on various crash types—total, injury, wet road, dry road, wet-road ROR, and all ROR—of the following treatments, based on data from California, North Carolina, Pennsylvania, and Minnesota.

- Chip Seal (single and double layer).
- Diamond Grinding (concrete pavement only).
- Grooved Concrete Pavement.
- Microsurfacing (asphalt and concrete pavement).
- Open-Graded Friction Course (OGFC) (asphalt and concrete pavement).
- Slurry Seal (asphalt pavement).
- Thin HMA (asphalt and concrete pavement).
- Ultra-Thin Bonded Wearing Course (UTBWC) (asphalt and concrete pavement).

In addition, a simple before–after evaluation was completed for HFS treatments based on limited data from several States, including Colorado, Kansas, Kentucky, Michigan, Montana, South Carolina, Tennessee, and Wisconsin. HFS was analyzed separately because it is typically used specifically for safety improvement (through friction enhancement) and not pavement preservation, as with other treatments. Although the HFS treatment data were insufficient to apply the EB method, it still revealed tremendous crash reduction potential for this treatment.

The combined results for all treatment types subjected to the rigorous EB evaluation (except grooving, for which there were very few sites) suggest that the treatments resulted in benefits for wet-road crashes, with the exception of thin HMA for two-lane roads (for both California and North Carolina, the two States with large enough samples for a definitive result), and for OGFC for two-lane and multilane roads, for which the effect was negligible.

For dry-road crashes, crashes increased for microsurfacing on two-lane roads (except for North Carolina), thin HMA and OGFC on two-lane roads, and OGFC and chip seal on multilane roads.

There were indications of a benefit for UTBWC, chip seal, and slurry seal on two-lane roads, and diamond grinding on freeways.

The CMFs for treatments by road and crash type may be considered for use in the *Highway Safety Manual* and the CMF Clearing House.

A thorough disaggregate analysis of the before–after evaluation data was undertaken in which regression analysis was used to investigate the effects on the CMFs of a number of variables, including traffic, precipitation, expected crash frequency before treatment, and environment (urban/rural). In the end, the crash modification functions (CMFunctions) developed were not robust enough to recommend them. Nevertheless, there were useful insights that suggest that it would be worthwhile to pursue the development of robust CMFunctions in future research. The results did suggest that there is a relationship between CMFs and average annual daily traffic (AADT) and sometimes precipitation, urban versus rural setting, and expected crash frequency. However, the direction of the effect is not always consistent, varying by crash type, site type, and treatment. Future research is needed to reconcile (i.e., explain) these apparent inconsistencies.

An economic analysis was conducted for treatments and States for which the sample size was large enough and for which there was a statistically significant (5-percent level) benefit for total crashes based on the EB evaluation. The results indicate that BC ratios larger than 2.0, considering impacts on safety only, are attainable for the following:

- Chip seal on two-lane roads (California only).
- Diamond grinding on freeways.
- Thin HMA on multilane roads (North Carolina only)
- OGFC on freeways.
- Slurry seal on two-lane roads.
- OTBWC on two-lane roads.

For other treatments/road classes/States, sample sizes were too small in some cases and, in other cases, overall safety benefits were not achieved or were statistically insignificant.

For HFS treatments, the results of the cursory before–after analysis suggest that HFS can be a highly safety- and cost-effective treatment for which implementation should continue. It is strongly recommended that additional data be collected to conduct a robust EB before study to derive a CMF that could be recommended to practitioners and for which a BC ratio could be confidently estimated.

CHAPTER 1. INTRODUCTION

IMPORTANCE OF PAVEMENT SAFETY

Roadway safety is a complicated issue to say the least. Any time human behavior is a factor, predicting how drivers will respond to road conditions is difficult at best. Variables such as weather, roadway geometry, visibility issues, pavement surface conditions, and the like, further complicate the ability to quantify the safety of a particular roadway.

One factor that is fairly well understood is the link between pavement friction and safety, or more specifically, the probability of wet-weather skidding crashes. The probability of wet-skidding crashes is reduced when friction between a vehicle tire and pavement is high. The FHWA and National Transportation Safety Board estimate that up to 70 percent of wet-pavement crashes can be prevented or minimized (in terms of damage) by increasing pavement friction.(1) While we cannot control human response to road conditions, we can control the properties of pavement surfaces to help reduce the probability of skid-related crashes.

Pavement surfaces affect several factors related to roadway safety. First, the frictional properties of pavement surfaces affect the resistance to tires sliding across the pavement surface. Pavement friction helps to keep vehicles on the road when brakes are applied, particularly when the wheels lock up, and when navigating curves or steering aggressively. This is particularly important in wet weather when a thin film of water on the surface of the pavement reduces contact between the tire and pavement surface. Another important factor is the ability of the pavement surface to channel water out from beneath the tire. The texture and porosity of a pavement surface help to provide a path to channel water away from beneath the tire to reduce the potential for hydroplaning. Texture and porosity also affect the splash and spray potential of a roadway in wet conditions, which can significantly impact visibility in wet weather.

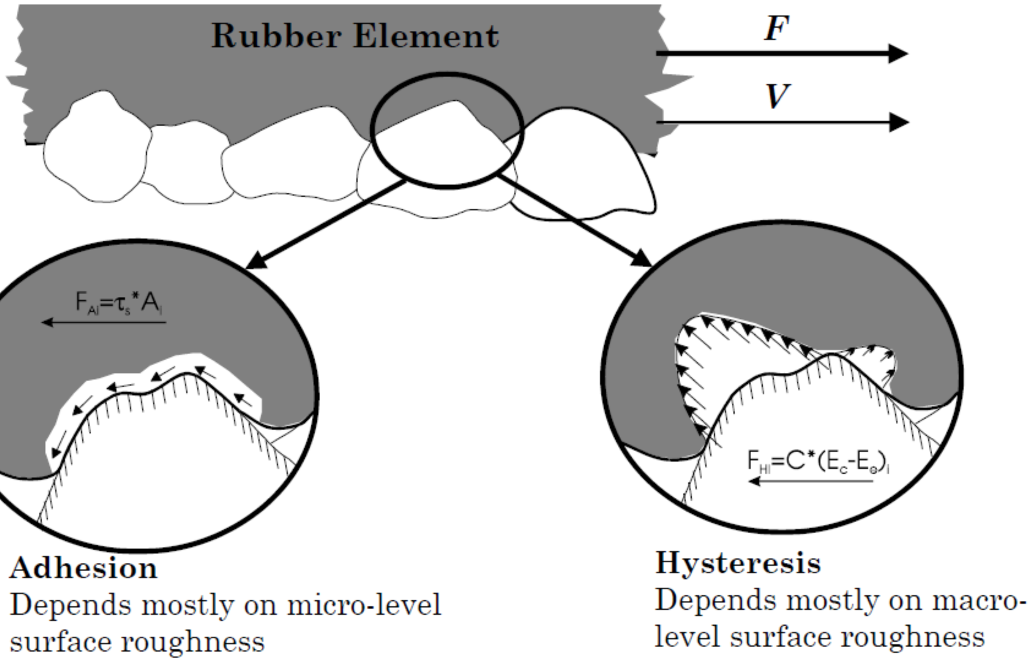
PAVEMENT SURFACE CHARACTERISTICS

Pavement surface characteristics are primarily functional parameters that affect the safety and comfort of the road user. The most commonly studied surface characteristics are friction, smoothness, tire–pavement noise, and texture. Briefly summarized below are two key characteristics as they relate to roadway safety: friction and texture.

Friction

In short, pavement friction is the force that resists the relative motion between a vehicle tire and pavement surface. This force is generated when a tire rolls or slides over the pavement surface and is measured as the nondimensional coefficient of friction.(2) Although a number of factors affect the actual frictional resistance in a given situation, in general, the higher the coefficient of friction of a pavement surface itself, the lower the probability that a tire will slide across the surface in a fully locked braking condition.

The two key mechanisms involved in tire-pavement friction are adhesion and hysteresis, as illustrated in figure 1. Adhesion is the friction that results from the small-scale bonding/interlocking of the tire rubber and pavement surface. Hysteresis is the frictional force that results from energy loss during deformation (or enveloping around the pavement texture) as the tire moves across the surface.(2) In general, for wet conditions, the adhesion component decreases with speed while the hysteresis component increases. Both mechanisms are directly affected by pavement texture, as discussed below.



Source: National Cooperative Highway Research Program

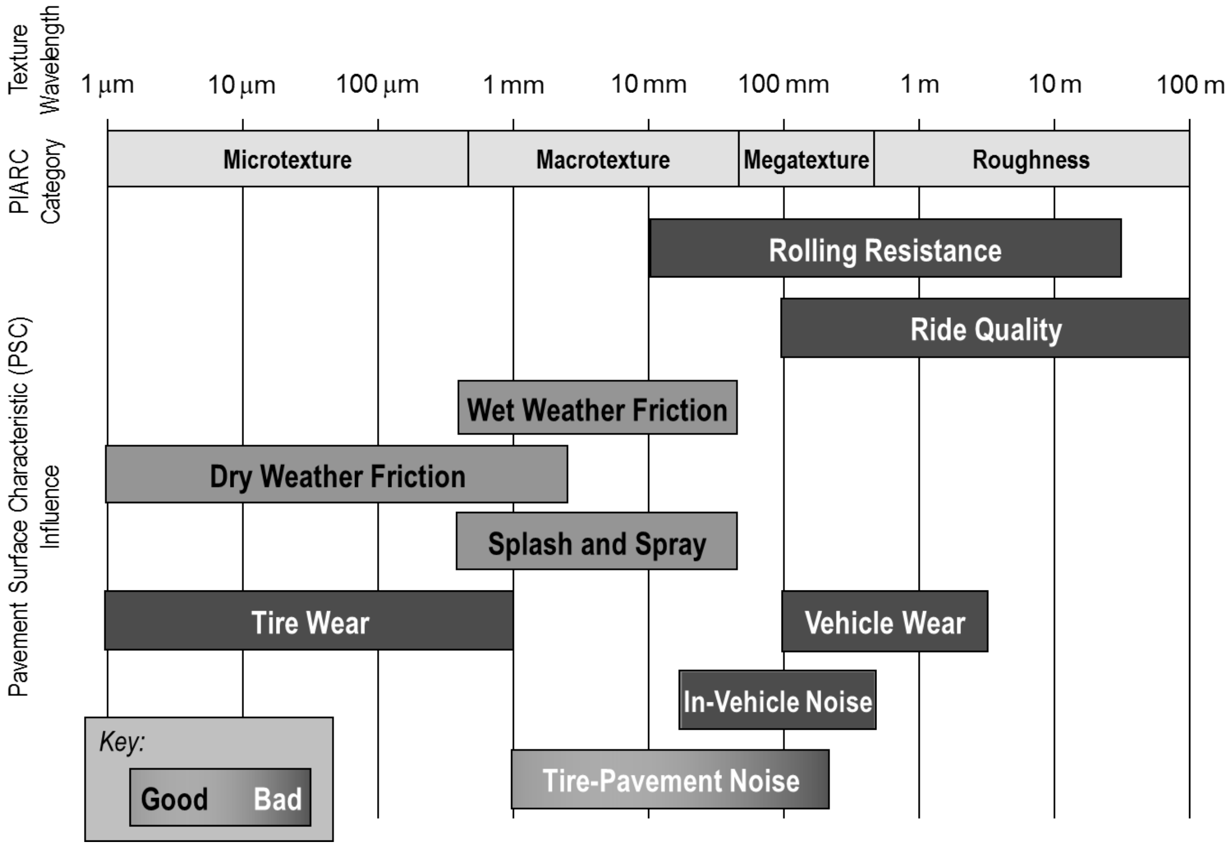
Figure 1. Illustration. Key mechanisms of pavement–tire friction.(2)

As documented in the AASHTO Guide for Pavement Friction, although a basic relationship exists between pavement friction and wet-crash rates, no specific threshold values have been established for pavement friction that make a pavement more or less safe.(3) Pavement friction demand, which is specific to the characteristics of a particular roadway, must be considered when establishing any sort of threshold. Pavement friction demand is dictated by site conditions (grade, superelevation, radius of curvature, terrain, climatic conditions, etc.), traffic characteristics (volume and mix of vehicle types), and driver behavior (prevailing speed, response to conditions, etc.). These conditions are continually changing over time and are different for every roadway, making it difficult to establish a “one size fits all” friction threshold.

Although one could err on the side of providing a level of friction that is exceptional and expected to be above friction demand for the vast majority of situations, there are other considerations and potential costs associated with this approach. The cost to construct these types of treatments could potentially be much higher than for a conventional surface treatment if nonconventional and/or nonlocally available materials are required. There are also the costs to the users, such as increased rolling resistance and therefore decreased fuel economy, and increased tire wear.

Pavement Texture

Pavement surface texture directly affects pavement friction as well as other factors related to roadway safety. Texture affects not only the coefficient of friction of a pavement surface, but also the ability of the pavement to shed or channel water away from beneath the tire. Pavement texture is typically broken up into four different types, as illustrated in figure 2. Of primary concern for pavement safety are microtexture and macrotexture.

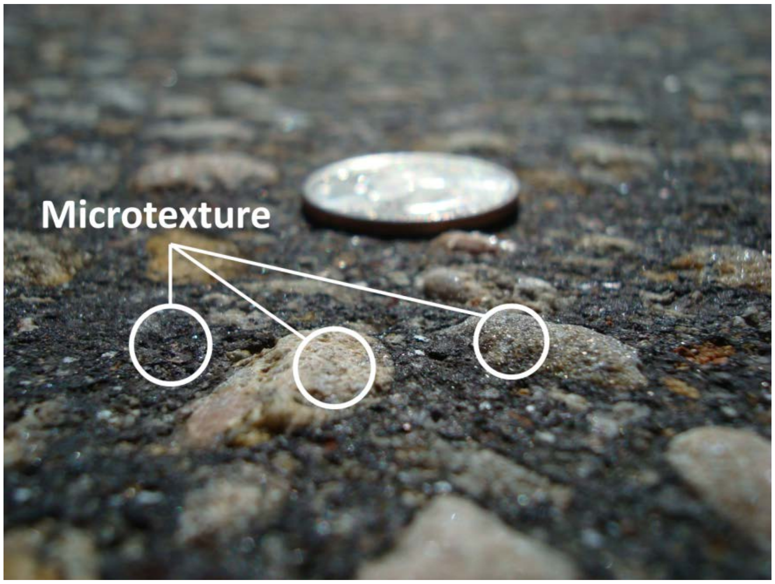


Source: The Transtec Group, Inc.

Figure 2. Graph. Pavement texture categories and their effect on surface characteristics (adapted from Henry).(4)

Microtexture—Microtexture is the fine-scale roughness that is not necessarily visible to the naked eye, but is apparent to the touch (see figure 3). It provides a degree of "sharpness" necessary for the tire to break through any residual water film that remains after the bulk water has run off and interacts directly with the tire rubber on a molecular scale to provide adhesion.(3) Microtexture is affected primarily by the surface properties of the aggregate particles that make up the pavement surface, and primarily affects the frictional properties of a pavement surface at lower speeds.

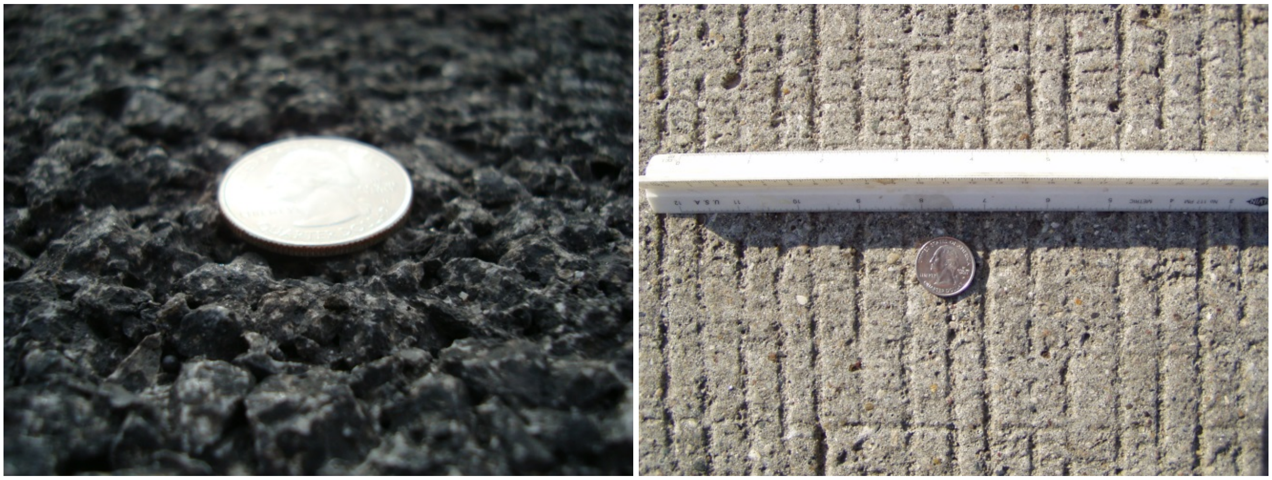
For asphalt pavements and asphalt surface treatments, the coarse aggregate generally provides microtexture. For concrete pavements, the mortar (fine aggregate and cement paste) provides microtexture until the coarse aggregate is exposed (e.g., through diamond grinding or polishing), at which point the coarse aggregate also contributes to microtexture. For this reason, there are generally very restrictive requirements on the coarse aggregates for asphalt pavements and fine aggregates for concrete pavements.



Source: The Transtec Group, Inc.

Figure 3. Photo. Microtexture provided by aggregates on an asphalt pavement.

Macrotexture—Macrotexture is a larger-scale, visible roughness component of pavement texture formed by the size and shape of the aggregate particles themselves, the porosity of the pavement surface, or from texture imparted to the pavement surface from grooving, tining, etc. (figure 4). The primary function of macrotexture is to provide a path for bulk water drainage from beneath the tire so that the adhesive component of friction provided by microtexture is reestablished.(3) However, macrotexture also affects the hysteresis component of friction because macrotexture causes the deformation of the tire rubber. As such, macrotexture has a significant effect on friction at higher speeds.



Source: The Transtec Group, Inc.

Figure 4. Photo. Macrotexture for an asphalt pavement surface (left) and concrete surface from tining (right).

For asphalt pavements and surface treatments, macrotexture is primarily controlled by aggregate properties (size, shape, gradation) as well as the porosity of the finished surface. For concrete pavements, macrotexture is primarily controlled by the finish or texture imparted to the surface (carpet/turf drag, tining, diamond grinding, grooving, etc.).

Pavement texture is typically quantified in terms of macrotexture depth, reported as either mean texture depth, measured using volumetric techniques such as ASTM E 965, or mean profile depth, measured using laser-based devices and quantified according to ASTM E 1845.(5,6) Chapter 2 discusses some previous studies that have examined the relationship between macrotexture depth and crash rates, and chapter 3 presents some typical macrotexture depths for the various treatments considered under this effort.

Durability

As discussed above, properties of pavement surface treatments have a direct impact on texture, friction, and ultimately safety. As such, selection of the materials used in a pavement or surface treatment is a critical aspect of pavement design and treatment selection. Constituent materials and mixture designs must provide the necessary microtexture and macrotexture components to ensure good friction.

Materials must also be durable, however, if pavement friction is to be sustained over time. Pavements, by their very nature, are completely exposed to weather and are subjected to potentially millions of wheel passes over their lifespan. The repeated application of wheel loads tends to wear down or wear away paving materials. Weather, likewise, can slowly wear away pavement surfaces through oxidation, erosion, or freeze–thaw related deterioration. There must be a balance between providing the necessary friction characteristics and providing a durable, long-lasting surface, while not ignoring the importance of cost.

Drainage

Although not explicitly considered a pavement surface characteristic, drainage is a critical factor in pavement safety. Even the most aggressive (high-friction) pavement surface can be rendered ineffective if water does not drain from the pavement surface. While the porosity of a surface or drainage "channels" (e.g., tining or grooving) imparted to the pavement surface can aid with channeling water from beneath a tire, pavement cross-slope is a key component of drainage and may need to be addressed first for any low-cost surface treatment to be effective. (Note: Because of a lack of cross-slope information on the pavement surfaces analyzed in this study, the effect of inadequate cross-slope could not be accounted for.)

BACKGROUND OF ELCSI PFS

In 1997, the AASHTO Standing Committee on Highway Traffic Safety, with the assistance of the FHWA, the National Highway Traffic Safety Administration, and the Transportation Research Board Committee on Transportation Safety Management, met with safety experts in the field of driver, vehicle, and highway issues from various organizations to develop a strategic plan for highway safety. These participants developed 22 key areas that affect highway safety. The NCHRP published a series of guides to advance the implementation of countermeasures targeted to reduce crashes and injuries. Each guide addresses 1 of the 22 emphasis areas and includes an introduction to the problem, a list of objectives for improving safety in that emphasis area, and strategies for each objective. Each strategy is designated as proven, tried, or experimental. Many of the strategies discussed in these guides have not been rigorously evaluated; about 80 percent of the strategies are considered tried or experimental.

FHWA organized the ELCSI–PFS, consisting of 38 volunteer States, to evaluate low-cost safety strategies identified by the NCHRP Report 500 guides under this strategic highway safety effort. The intent of the work conducted under the various phases of the ELCSI-PFS is to provide a CMF and BC economic analysis for each of the targeted safety strategies identified as priorities by the PFS States.

NCHRP Report 500 Volumes 6 and 7 address pavement surfaces. Volume 6, which addresses reducing ROR crashes, presents Strategy 15.1 A7 "Skid-Resistant Pavements" as a key to reducing ROR crashes.(7) Volume 7, which addresses reducing collisions on horizontal curves, likewise discusses Strategy 15.2 A7 "Provide Skid-Resistant Pavement Surfaces" as a key strategy for reducing crashes at horizontal curves.(8) The report recognizes that there had been only limited research on site-specific treatments as of 2003. However, given the results of other research on general effectiveness of decreased skidding, the report places this strategy in the "proven" category. The report also recognizes that the effectiveness of high-friction treatments will diminish over time; therefore, States using this strategy must conduct a dynamic program to target the appropriate sites for new treatment and to maintain the safety benefit from existing treatments.

In a similar manner, the FHWA Low-Cost Treatments for Horizontal Curve Safety guide recommends "skid-resistive pavement surface treatments" as a low-cost treatment for reducing crashes at horizontal curves.(9) This guide specifically discusses remedial treatments such as asphalt overlays, surface treatments, grinding, and grooving of pavement surfaces for both concrete and asphalt pavements where friction demand is higher.

Shrinking State highway agency budgets for construction and rehabilitation is one reason for an emphasis on low-cost treatments. Another reason is that although rural roads account for the majority of highway crashes when quantified in terms of vehicle mi traveled, rural roads are often lower priority when it comes to funding rehabilitation or improvements. This was verified by a Government Accountability Office study that found that the large number of rural roads carry relatively low volumes of traffic, often making it difficult to justify the costs of improvements to these roads. Many rural roads also fall under the jurisdiction of local government entities, which do not have the resources to undertake significant projects to increase rural road safety.(10)

PHASE VI STUDY

The goal of the Phase VI study was to isolate the effects of various low-cost pavement treatments on roadway safety, since the pavement itself plays a major role in highway safety. This unique study sought to identify any potential differences in safety performance for various types of pavement treatments because this has not been carefully examined in previous research.

Scope of Phase VI Study

The Phase VI study was a retrospective study of pavement safety performance, looking back at crash data before and after treatments were installed. No test sections were constructed explicitly for this study. Crash data were analyzed to evaluate the effectiveness of low-cost pavement improvement strategies using the EB before–after study methodology for the most part. Both flexible and rigid pavement treatment were analyzed, and CMFs for each type of pavement improvement were developed. BC ratios were developed for those applications for which there were statistically significant overall crash reduction benefits.

Although the definition of a low-cost pavement treatment is not clear in terms of a ceiling on the cost per lane-mi or cost per square yd, in general, these are treatments applied to existing pavement surfaces without substantially changing the pavement structure. These are treatments that will generally change the pavement surface characteristics, but do not necessarily add structural capacity to the pavement. Therefore, full-depth pavement reconstruction and projects that serve to realign or substantially alter the pavement cross-section (e.g., superelevation) were excluded from consideration.

The majority of the treatments considered in this effort are typically used for pavement preservation or minor rehabilitation purposes. Although State highway agencies recognize that most of these treatments generally improve pavement friction, they are not typically installed explicitly for safety improvement, with certain exceptions that are discussed below. These are also primarily treatments that are used for long stretches of pavement preservation/rehabilitation, with the exception of HFS, which is typically used solely for spot safety treatments.

Products and Desired Outcomes

The ultimate outcome of the Phase VI effort is a better understanding of the effects that various common, low-cost pavement treatments have on roadway safety. Two of the more tangible ways this is quantified is through CMFs and BC ratios for each treatment type. These products will potentially help State transportation departments in the decisionmaking process for selection of a pavement treatment for a particular project.

CHAPTER 2. LITERATURE SEARCH

SKID-RESISTANT PAVEMENTS

The following treatment summary is taken from Volume 6 of the NCHRP 500 series guidebooks for addressing ROR collisions (pages V-27 through V-30).(7)

> The 1999 statistics from FARS show that for two-lane, undivided, non-interchange, non-junction roadways, 11 percent of single-vehicle ROR fatal crashes occur on wet roadways, with 3 percent more occurring on roadways with snow, slush, or ice. Accidents on wet pavements are often related to the skid resistance of the pavement. It can also happen that the pavement friction available under dry roadway conditions will be significantly less than specified for the roadway and assumed in establishing design criteria (e.g., superelevation on curves). This can also lead to crashes. However, the major problem appears to be with wet pavement crashes.
>
> A vehicle will skid during braking and maneuvering when frictional demand exceeds the friction force that can be developed at the tire-road interface. While this can happen on dry pavements at high speeds, friction force is greatly reduced by a wet pavement surface. In fact, a water film thickness of 0.002 inches reduces the tire pavement friction by 20 to 30 percent of the dry surface friction. Therefore, countermeasures should seek to increase the friction force at the tire-road interface and reduce water on the pavement surface. The coefficient of friction is most influenced by speed. However, many additional factors affect skid resistance, including the age of the pavement, pavement structural condition, traffic volume, road surface type and texture, aggregates used, pavement mix characteristics, tire conditions, and presence of surface water.
>
> There has been a large amount of research funded by the FHWA, AASHTO, and pavement associations concerning designing better pavements—pavements which are more durable and more cost-effective (e.g., the FHWA/AASHTO Strategy Highway Research Program). The FHWA has issued a series of pavement-related technical advisories on such issues as needed changes in surface finishing of Portland cement concrete pavements for increased safety (FHWA, 1996).(11) An important parameter in all this work is pavement skid resistance, perhaps the major safety-related factor along with pavement drainage design. However, most of this research and implementation effort is oriented toward policy or systemwide changes in new pavements or repaving efforts. While the best safety-related pavement design possible should be used in all paving efforts, the details of pavement design are beyond the scope of this guide.
>
> Instead, this section will concentrate on improvements that can be made to sites that have, or are expected to experience, skidding-related ROR crashes. These usually involve improvements to increase skid resistance (higher friction factor). Such improvements should have high initial skid resistance, durability to retain skid resistance with time and traffic, and minimum decrease in skid resistance with

increasing speed. Countermeasures to improve skid resistance include asphalt mixture (type and gradation of aggregate as well as asphalt content), pavement overlays on both concrete or asphalt pavements, and pavement grooving. Water can also build up on pavement surfaces due to tire rutting, an inadequate crown, and poor shoulder maintenance. These problems can also cause skidding crashes and should be treated when present. While there is only limited research on such site-specific programs, the results of this research coupled with the results of research on the general effectiveness of decreasing skidding would place this in the "proven" category.

Treatment will target locations where skidding is determined to be a problem, in wet or dry conditions. The ultimate target, however, is a vehicle involved in a crash due to skidding, usually on wet pavement. With respect to ROR or head-on crashes, the target vehicle is one that runs (skids) off the road due to insufficient skid resistance or becomes involved in a head-on crash either by skidding into the opposing lane or by crossing into the opposing lane after an overcorrection from an initial ROR maneuver caused by insufficient skid resistance.

There are many different specific countermeasures that may be implemented to improve skid resistance. This may include changes to the pavement aggregates, adding overlays, or adding texture to the pavement surface. The effectiveness of the countermeasure not only depends on that measure selected, but also will vary with respect to location, traffic volume, rainfall propensity, road geometry, temperature, pavement structure, etc.

The New York State DOT has implemented a program that identifies sites statewide that have a low skid resistance and treats them with overlays or microsurfacing as part of the maintenance program. A site is eligible for treatment if its 2-year wet accident proportion is 50 percent higher than the average wet accident proportion for roads in the same county. Between 1995 and 1997, 36 sites were treated on Long Island, resulting in a reduction of more than 800 annually recurring wet road accidents. These results and others within the state support earlier findings that treatment of wet road accident locations result in reductions of 50 percent for wet road accidents and 20 percent for total accidents. While the reductions in ROR or head-on crashes cannot be extracted from the data at this time, it appears that reductions in these types would be at least the same as for total crashes.

While these results could be subject to some regression-to-the-mean bias, the New York staff has found that untreated sites continue to stay on the listing until treated in many cases—an indication that these reductions are clearly not totally due to regression. The New York State DOT is planning a more refined data analysis to account for possible biases in these effectiveness estimates. Based on the current knowledge, this identification/treatment strategy would be classified as "proven."

Monitoring the skid resistance of pavement requires incremental checks of pavement conditions. Evaluation must identify ruts and the occurrence of polishing. Recent research (Galal et al., 1999) has suggested that the surface should be

> restored between 5 and 10 years in order to retain surface friction, but the life span is affected by site characteristics such as traffic volume.(12) In addition, spot- or section-related skid accident reduction programs will be clearly most successful if targeted well. The New York State DOT program noted above provides a methodology for such targeting. In addition, in a 1980 Technical Advisory, the FHWA provided a detailed description of a "Skid Accident Reduction Program," including not only details of various treatments, but also the use of crashes and rainfall data in targeting the treatments. Skid resistance changes over time. This requires a dynamic program and strong commitment. As noted in the preceding section, it also requires good "targeting." When selecting sites for skid resistance programs, it is important to somehow control for the amount of wet-pavement exposure. This will help decrease the identification of sites that have a high wet-accident proportion or rate simply because of high wet-weather exposure with no real pavement-friction problems. Unfortunately, it is difficult or impossible for an agency to develop good wet-pavement crash rates per vehicle mile for all roadway sections due to the lack of good wet-weather exposure data for all sites. Such data would require both good rainfall data for all potential sites and good measures of traffic volume during wet and dry weather. In its Skid Accident Reduction Program, the New York State DOT uses a surrogate for such detailed data. The DOT compares the proportion of wet-weather crashes at each site with the proportion for similar roads in the same county. The assumption here is that rainfall (and thus wet-pavement exposure) would be similar across a county, a reasonable assumption.
>
> Data are needed on traffic crashes by roadway condition. In addition, measures of traffic exposure that identify and reflect both dry and wet periods are needed. Finally, measurements of road friction and pavement water retention should be documented both before and after implementation of a strategy.
>
> New York State DOT estimates that its resurfacing/microsurfacing projects are approximately 0.5 miles long, with an average treatment cost of approximately \$20,000 per lane mile (1995 dollars).

PROVIDE GROOVED PAVEMENT

The following treatment summary is taken from Volume 7 of the NCHRP 500 series guidebooks for horizontal curves collisions (pages V-25 through V-27).(8)

> Pavement grooving is a technique by which longitudinal or transverse cuts are introduced on a surface to increase skid resistance and to reduce the number of wet-weather crashes. The grooves increase skid resistance by improving the drainage characteristics of the pavement and by providing a rougher pavement surface. Several studies show that grooved pavements reduce wet-weather crashes. However, some potential adverse effects should be considered before this strategy is implemented, including the potential of increased noise pollution, accelerated wearing of pavements, and negative effects on steering.

While pavement grooving is a way to add texture to the pavement surface, its primary objective is to improve the drainage and to mitigate hydroplaning. The grooves decrease the water film thickness on a pavement surface and allow for greater tire-pavement surface interaction during adverse weather conditions. Because pavement grooving is such a unique approach to increasing the skid resistance of a pavement, it is treated separately. The section immediately following this one presents results of studies that evaluated the safety effectiveness of pavement grooving. That is followed by a section that presents attributes unique to pavement grooving that should be considered before this type of treatment is implemented.

Numerous studies on the safety effectiveness of pavement grooving have been conducted, but none of these studied have controlled for regression to the mean so the results should be considered with caution. Wong (1990) performed a before-after evaluation of the effectiveness of pavement grooving based upon data from one site in California.(13) The site was a two-lane highway with steep vertical grades and sharp horizontal curves. Based upon accident data from a 3-year before period and a 1-year after period, Wong found a 72-percent reduction in wet-pavement accidents, while only finding a reduction of about 7 percent in dry-pavement accidents. Wong concluded that pavement grooving was effective in reducing wet-pavement accidents.

Zipkes (1976) analyzed the frequency of accidents and the percentage of accidents on wet and dry pavement surfaces during a 7-year period to evaluate the effect of pavement grooving.(14) Accident data were obtained for a 44-km (27-mi) section of highway near Geneva, Switzerland. Transverse grooves were cut into the pavement with varying groove distances over a 2-km (1.2-mi) section of highway. Grooving of the polished road surfaces reduced the hazard of accidents when drainage conditions were unfavorable. Zipkes indicated that the advantage of grooving is the reduction of water-film thickness, which leads to better contact between the tire and the road surface for the transmission of forces.

Smith and Elliott (1975) evaluated the safety effectiveness of grooving 518 lane-km (322 lane-mi) of freeways in Los Angeles, while 1,200 lane-km (750 lane-mi) of ungrooved pavement were used as a control.(15) The analysis was conducted using 2 years of before data and 2 years of after data. Only fatal and injury accidents were included in the evaluation. Smith and Elliott found that longitudinal pavement grooving resulted in a 69-percent reduction of wet-pavement accident rates. Sideswipe and hit object accidents were reduced to the largest extent. Pavement grooving did not change the dry-pavement accident rates.

Mosher (1968) synthesized results from studies conducted by state highway departments on the effects of pavement grooving.(16) Information for the report was obtained from 17 states, including Colorado, Florida, Georgia, Idaho, Illinois, Indiana, Louisiana, Minnesota, Missouri, Nebraska, New York, Ohio, Pennsylvania, Texas, Utah, Wisconsin, and Wyoming. Some sections of highway had longitudinal grooves, while other sections had transverse grooving. Pavement grooving proved very effective, reducing crashes by 30 to 62 percent.

Farnsworth (1968) evaluated the effects of pavement grooving on five sections of California highways.(17) Farnsworth measured the coefficients of friction before grooving and after grooving and found that pavement grooving increased the coefficients of friction, changing the friction values from below critical to above critical. Analysis of accident data revealed a reduction in wet-pavement accidents at each of the sites.

The NYDOT evaluated the safety effectiveness of pavement grooving based on the installation of grooves at 41 sites. NYDOT found that wet-road accidents were reduced by 55 percent, and total accidents (dry and wet) were reduced by 23 percent. The results were statistically significant at the 95th percentile. Regression to the mean was not addressed in the analysis.

Pavement grooving involves making several shallow cuts of a uniform depth, width, and shape in the surface of the pavement (Mosher, 1968).(16) Grooves may be cut longitudinally along the pavement (parallel to the direction of travel) or in the transverse direction (perpendicular to the direction of travel). Transverse grooving has been used to a lesser extent than longitudinal grooving, partially because most grooving equipment lends itself more readily to placing grooves parallel to the roadway. Grooves cut in the longitudinal direction have proven most effective in increasing directional control of the vehicle, while transverse grooving is most effective where vehicles make frequent stops, such as intersections, crosswalks, and toll booths. When pavements are grooved, it is important that the pavement contain nonpolishing aggregate.

While studies have indicated that pavement grooving reduces wet-pavement accidents, there have been several concerns associated with pavement grooving (Mosher, 1968).(16) One concern has been the effect that pavement grooving has on the durability of various pavement types. For example, one of the most frequently asked questions by engineers in northern climates is, “What will water freezing in the grooves do to the concrete pavement?” In an examination of grooved pavement in Minnesota after one winter, there appeared to be no deterioration in the grooved pavement because of the freeze-thaw cycles. Concern also has been expressed about grooves in asphalt pavement losing their effectiveness because the material can be flexible enough to “flow” back together, particularly during hot weather. This phenomenon has been observed under certain conditions with a fairly new asphalt pavement or with a pavement with low aggregate content. Concern has also been expressed over the loss of effectiveness because of grooved pavements wearing down under high-traffic conditions.

Complaints also have been received that longitudinal grooves adversely affect the steering of certain automobiles and motorcycles. In general, no severe problems have been encountered. This finding is supported by research conducted by Martinez (1977), who studied the effects of pavement grooving on friction, braking, and vehicle control by computer simulation and full-scale testing.(18) Martinez considered automobiles, motorcycles, and automobile and towed-vehicle combinations in his evaluation.

In Iowa, residents living adjacent to I-380 near Cedar Rapids complained that transverse grooving was the cause of an especially annoying tonal characteristic within the traffic noise (Ridnour and Schaaf, 1987).(19) As a result of the complaints, the surface texture of a section of I-380 was modified. The transverse grooving was replaced with longitudinal grooving. A before-after analysis of the traffic noise levels showed that the surface modification lowered overall traffic noise levels by reducing a high-frequency component of the traffic noise spectrum.

FURTHER LITERATURE REVIEW

A search of available literature related to the safety effects of improved skid resistance turned up few additional materials. The limited research available does indicate, as would be expected, that higher skid resistance measurements are associated with lower crash rates, particularly wet-road-related collisions. Studies comparing the safety improvement after specific skid resistance improvement treatments are particularly rare, and the data and evaluation methods typically poor. These limited studies do, however, indicate reductions in collisions following treatment. Additional literature was also identified related to low-cost pavement preservation treatments and their properties.

Neuman et al. discuss in general terms specific countermeasures that may be implemented to improve skid resistance.(7) These may include changes to the pavement aggregates, adding overlays, or adding texture to the pavement surface. They state that the effectiveness of the countermeasure not only depends on the measure selected, but also varies with respect to location, traffic volume, rainfall propensity, road geometry, temperature, pavement structure, etc. They indicate that when selecting sites for skid resistance programs, it is important to somehow control for the amount of wet-pavement exposure.

Torbic et al. discuss pavement grooving.(8) Pavement grooving is a technique by which longitudinal or transverse cuts are introduced on a surface to increase skid resistance and to reduce the number of wet-weather crashes. The grooves increase skid resistance by improving the drainage characteristics of the pavement and by providing a rougher pavement surface. Several studies showed that grooved pavements reduce wet-weather crashes between 55 and 72 percent although the evaluation methods applied are not considered state-of-the-art by today’s standards.

Lyon and Persaud evaluated the safety impacts of the New York Department of Transportation (NYSDOT) skid-accident reduction program.(20) In this program, sections of roadway with a high proportion of wet-road accidents are identified and are friction tested. Those locations with poor friction numbers are then treated with a 1.5-inch HMA resurfacing or a 0.5-inch microsurfacing using non-carbonate aggregates. Resurfacing is considered to be effective for 15 years while the microsurfacing is effective up to 7 years, depending on the existing pavement condition and quality of construction. Friction testing was done (using a locked-wheel skid trailer with ribbed tire), and readings under 32 were considered to warrant treatment. The EB before–after study approach was applied to several crash types and both segment and intersection locations. Results for expected accident reductions are shown in table 1. Further results are available in the paper, disaggregated by area type and number of lanes for segments and traffic control type and number of approaches for intersections.

Table 1. Summary of results from NYSDOT skid-accident reduction program analysis.

Accident Type	Road Segments (percent)	Intersection Results (percent)
Total	24	20
Wet-road	57	57
Rear-end	17	42
Wet-road rear-end	42	68
Single-vehicle	30	n/a
Single-vehicle wet-road	60	n/a

Ivan et al. explored the relationship between wet-pavement friction and crashes to identify whether wet-pavement friction explains significant variation in crash frequency between similar locations, and whether this is particularly significant at high crash locations such as sharp curves and intersections.(21) Data for approximately 150 mi of roadway were collected. Three years of crash data were collected where available. The amount of friction at each location was measured using the locked-wheel skid trailer. Negative binomial regression models K, A, or B crashes on the KABCO scale were developed separately for divided and undivided roadways. Additional explanatory variables considered included degree of horizontal curvature, rate of change of vertical curvature, number of intersections and driveways, pavement width, area type (rural, suburban, or urban) and speed limit. Dependent variables considered included total, wet-road, segment related (sideswipe opposite direction, head-on fixed object, and moving object), and intersection related (turning same direction, turning intersecting paths, sideswipe same direction, angle, rear-end, and pedestrian) crashes. The model results indicated that wet-pavement friction is most associated with increased crashes under conditions where increased braking would be demanded, that is in curves and near driveways. Interestingly, increased wet-pavement friction was associated with more total crashes on urban undivided roads with mild curvature and on urban divided roads.

Oh et al. conducted naïve and comparison group before–after studies of three experimental types of pavements: open graded asphalt concrete (OGAC), groove pavement (GP), and rubberized open graded asphalt concrete (R-OGAC).(22) Wet-pavement-related crashes were the focus. The findings included a 29 and 41 percent decrease for the 13 OGAC sites using the naïve and comparison group approaches, respectively. The sample sizes were too small to draw conclusions for the GP and R-OGAC. Calculation of crash rates included the exposure to wet weather, which was collected from the closest weather recording station. Another part of the study found that the friction numbers are dependent on seasonal effects, including temperature, average monthly precipitation, and the number of dry months prior to last precipitation.

Izevbekhai and Watson evaluated the before and after collision data for 14 concrete pavement sections where the pavement was overlaid or rebuilt and the new surface included a longitudinal turf drag, or broom drag.(23) Previously, transverse friction treatments (e.g., tining) had been applied but were discontinued owing to concerns regarding noise. The study sought to determine whether the new longitudinal treatments were as effective in providing adequate friction. Collisions were analyzed to see whether frequencies, collision rates (per million vehicle-mi), proportion of wet-weather collisions, or the ratio of wet to dry collision counts increased following the treatment. Differences were subjected to the Chi-squared and Mann Whitney U tests to measure the statistical significance of any differences between the before and after periods. The segments analyzed were selected to be minimally influenced by other collision risk factors such as curves, poor sight distance, poor surfaces, etc. The results found no significant differences in the various crash measures from before to after the new treatment.

Erwin conducted a naïve before-after study of resurfacing and microsurfacing projects. Results for microsurfacing indicate a 32-percent reduction in wet-weather collisions, 24-percent reduction in intersection collisions, and 29-percent reduction in rear-end collisions.(24)

Reddy et al. evaluated the application of the Tyregrip™ HFS system to a 300-ft section upstream of an on-ramp in Florida.(25) The ramp was treated because a high number of wet-weather ROR collisions had occurred there. Skid testing confirmed that the available skid resistance was much higher (104) after treatment compared with 35 before. It was also observed that vehicle speeds decreased, as did vehicle encroachments to either shoulder. The limited time periods and single location did not allow for a scientific study of collisions, although they were observed to decrease from an average of 2.54 per year before treatment to 2 in a 1-year period after, a decrease of 21 percent.

Mayora and Pina studied the relationship between skid resistance and injury collisions on two-lane rural roads in Spain.(26) Segments including intersections were not included. Average sideway-force coefficient routine investigation machine (SCRIM) skid resistance measurements over a 5-year period were included in the analysis. Categories of alignment (e.g., tangent, radius > 500 m, radius 250–500 m, radius < 250 m) and categories of skid resistance (e.g., SCRIM ≤ 40, 40 < SCRIM ≤ 45, 45 < SCRIM ≤ 50, 50 < SCRIM ≤ 55, 55 < SCRIM ≤ 60, SCRIM > 60) were defined for the analysis. Statistical tests were applied to see whether the mean crash rates differed between SCRIM categories for each alignment category tested. A before–after comparison group study was also conducted to assess the benefits of skid resistance improvements. Because the comparison group crash rate was higher (0.32 to 0.29 wet-road crashes), it was concluded that the treated sites were not selected based on the crash rate and regression-to-the-mean was not a factor. A sample of 419 segments with an average SCRIM value less than 50 was treated to improve the SCRIM value to more than 60. Results of crash rate analyses showed that both wet- and dry-road crash rates decreased as skid resistance increased. Wet-road crash rates were found to be significantly higher in curves than on tangents. For dry-road crashes, no differences were found between curves and tangents. It was concluded that for tangents and curves with a radius less than 500 m, crash rates are significantly lower when the SCRIM value is greater than 55. For curves with a radius greater than 500 m, the SCRIM value cutoff is 60. The before–after study indicates the benefits of increasing the skid resistance (SCRIM value) from less than 50 to greater than 60 is a 68-percent reduction in wet-road crashes. When considering curves only, the reduction was estimated to be 84 percent.

Hughes studied the impacts of thin HMA resurfacing projects on crash performance for two-lane roads with posted speeds greater than 45 mi/h.(27) The purpose of the study was to determine whether new resurfacing projects have any impact on safety, resulting from “the improved ride quality and visual contrast created by new pavement markings on a smooth asphalt surface that could create for the driver the impression of a safer road that can be traversed at a higher speed." This is commonly referred to as a "novelty effect," which may result in more crashes initially after resurfacing before the effect wearing off over time. The study contrasted resurfacing projects that were coupled with minor or major safety improvements with those where only resurfacing was performed. Some of the key findings from this study were as follows:

- The results were inconclusive regarding the effect of resurfacing on crash rates. For some States, there was an improvement, but for others there was no benefit, or even an increase in crash rate following resurfacing. This is likely the result of highly variable conditions (and presumably paving materials) from State to State and project to project, which could not be comprehensively quantified for the study sites.

- There is no evidence to suggest that resurfacing adversely affects crash frequency downstream from the resurfaced section of the road.

- With respect to analysis methodology, selecting sites according to their pavement history (and not crash history), using a long crash history (3 to 5 years), and using a large sample size (e.g., long stretches of highway) help to mitigate regression-to-the-mean and the random nature of data.

Li et al. evaluated the long-term friction performance of pavement preservation treatments commonly used by the Indiana Department of Transportation to assist in the decisionmaking process regarding when and where to use various preservation treatments.(28) Treatments evaluated included chip seals, fog seals, microsurfacing, thin and ultra-thin asphalt overlays (including UTBWC), and diamond grinding. Key findings for the various treatments were as follows:

- For chip-sealed surfaces, the greater the friction number on the old pavement, the greater the friction on the new chip-sealed surface. Surface friction decrease occurred after 12 mo in service, and when the surface reached an age of approximately 30 mo, friction started to decrease continuously over time. Also, truck traffic was observed to affect the performance of a chip seal more significantly than AADT.

- For microsurfacing, friction increased significantly in the first 6 months and peaked after 12 mo. After 12 mo, friction tended to decrease continuously over time, but never to what might be considered an intervention level, even after 42 mo.

- For UTBWC, friction numbers tended to peak after 6 mo of service, "about 6 mo earlier than conventional HMA mixes." UTBWC provided good texture depth (macrotexture), much better than conventional HMA surfaces. However, significant friction decrease occurred over time, with up to a 34-percent decrease after 33 mo in service. Noticeable polishing was observed in the limestone aggregate used.

- For thin, fine graded (4.75 mm) HMA overlays, friction is high after construction but decreases quickly and dramatically over time after exposure to traffic. In some sections, friction decreased by 25 percent after 6 mo and by 36 to 48 percent after

12 mo, depending on traffic volume. Friction tended to stabilize after 12 to 18 mo. The use of steel slag in these mixes is recommended for better friction performance.

- For diamond grinding on concrete surfaces, the steady-state friction should be maintained over time, but was highly dependent on the aggregate properties and grinding texture configuration.

Roe et al. examined the relationship between pavement surface texture and crashes based on an extensive analysis of texture, friction, and crash data in the United Kingdom.(29) Some of the key findings from this study included the following:

- Macrotexture has a marked effect on all accidents, whether or not they involve skidding or whether conditions are wet or dry. High macrotexture has a beneficial effect in all circumstances.
- Injury accidents are less likely to occur at high texture depths. This is possibly due to the higher hysteresis component of friction, providing drivers with additional control and maneuverability in all conditions to reduce severity of the crash.
- In terms of guidance for desirable macrotexture depth, the cross-over point falls between 0.6 mm and 0.8 mm, indicating that the risk of accidents is greater for roads with an average texture depth less than about 0.7 mm than for those above this level.
- Crash rate rises markedly with decreasing texture less than about 1 mm, but is essentially constant at a low level greater than 1 mm.
- Skidding resistance (as measured by SCRIM) is normally independent of texture depth, but may be reduced when the macrotexture is unusually low, for example on a worn surface dressing (chip seal).
- The idea of a minimum level of macrotexture does not affect in any way the existing requirements for minimum levels of skidding resistance. Both macrotexture and skidding resistance are needed for safe roads.

Davies et al. used highway data from 1997 to 2002 in New Zealand from the entire State Highway network to try to look for any correlations between crash rate and road characteristics (traffic, texture, skid resistance, curve radius, cross-fall, roughness, and rut depth).(30) Only two-lane roads were included in the analysis. Some of the key findings from this study included the following:

- As traffic volume decreases, crash rate increases. This was not unexpected because the quality of the road reflects daily traffic.
- As skid resistance increases, the greatest percent reduction in crash rate occurs for wet-road crashes.

- The percent reduction in crash rate is constant for a given absolute increase in skid resistance value, regardless of the initial skid resistance value.

- Crash risk is reduced with increasing texture, although not at a statistically significant level. The relationship between crash rate and texture is not strong.

- The primary emphasis should be on increasing skid resistance rather than texture.

- In percentage terms, increasing skid resistance (e.g., SCRIM) has a greater effect in reducing "wet-road crashes" than in reducing "all crashes."

Peshkin et al. developed guidelines for the use of pavement preservation treatments on high-volume roadways as part of a Strategic Highway Research Program 2 (SHRP2) Renewal research project.(31) Agencies traditionally tend to shy away from preservation on high-volume roadways, and this project sought to provide substantial guidance for preservation practices on high-volume roadways. High-volume roadways were defined under this effort as those with an average daily traffic of at least 5,000 and 10,000 vehicles per day for rural and urban roadways, respectively. This report provided valuable information on the expected design life and cost of various pavement preservation treatments. It also addressed some of the appropriate applications and risks associated with various treatments, and should serve as a ready reference for agencies in selecting preservation treatments.

The literature review, while sparse, did reveal important insights to consider, including the following:

- Pavement friction is dependent on seasonal effects, including temperature, average monthly precipitation, and the number of dry months prior to last precipitation. The readings must be standardized across sites and years.

- Confounding factors that influence collision risk and may interact with the safety effects of skid resistance include location type (segment, intersection approach, curve, etc.), area type, speed limit, traffic volume, rainfall propensity, roadway geometry, temperature, and pavement structure.

- Expected collision reductions from friction improvements depend on both the level of friction prior to and after treatment. Reductions in wet-road crashes up to approximately 75 percent may be expected.

- Friction of various low-cost pavement treatments tends to decrease with time, and therefore the safety benefit may also be expected to decrease with time.

- Evaluations of improved skid resistance have typically not applied statistically rigorous before–after study designs.

- While good texture (depth) is important, it does not guarantee a good skid resistance or a safer pavement.

CHAPTER 3. PAVEMENT TREATMENT TYPES

The pavement treatment types considered in this study were identified in the original proposal by FHWA and the project team. This list was further refined based on the treatment types that were provided by the various volunteer States.

PHASE VI TREATMENTS CONSIDERED

Table 2 lists the treatment types considered in the study, with the treatments that were included in the final analysis highlighted in bold.

Table 2. Flexible and concrete pavement treatment strategies considered in Phase VI.

FLEXIBLE PAVEMENT TREATMENT STRATEGIES	CONCRETE PAVEMENT STRATEGIES
Thin HMA Overlay	**Thin HMA Overlay**
Open Graded Friction Course (OGFC)	**Open Graded Friction Course (OGFC)**
Ultra-Thin Bonded Wearing Course (UTBWC)	**Ultra-Thin Bonded Wearing Course (UTBWC)**
Microsurfacing	**Microsurfacing**
Shotblasting/Abrading	Shotblasting/Abrading
High Friction Surfacing (HFS)	**High Friction Surfacing (HFS)**
Chip Seal (various binder types)	**Diamond Grinding**
Cape Seal	**Grooving**
Scrub Seal	Next Generation Concrete Surface
Slurry Seal	
Micro-Milling	

Bold entries are treatment types that were included in final analysis.

The decision was made early in the data collection effort to focus primarily on the most common treatments that are used throughout the United States, while also considering experimental-type treatments, if appropriate. As discussed previously, the majority of these treatments are typically used for pavement preservation purposes to extend the life of an existing pavement while also potentially improving skid resistance and ride quality. The notable exception is HFS, which is almost exclusively used for safety improvement purposes. The following sections summarize each of these treatment types.

Thin Hot-Mix Asphalt Overlay

Thin HMA overlays (figure 5) are commonly used to correct minor to moderate pavement surface defects to restore ride quality and improve friction while protecting the underlying pavement structure. Thin overlays may be applied to either concrete or asphalt pavements, or over existing surface treatments, and are typically not considered a structural layer. Industry convention generally defines thin overlays as no more than 1.5 to 2 inches thick, typically constructed as a single lift, and therefore was the criterion used by the project team under this effort. In the list of thin HMA overlay candidate sites, the team included “mill and fill” projects, which included milling off the existing surface before applying the new overlay. Although the milling operation adds to the cost of the treatment, best practice generally dictates that the existing surface be milled off for best performance of the overlay. While thin overlays are not typically constructed explicitly to improve friction, mixtures are still designed to standards that will ensure appropriate friction levels.

Source: The Transtec Group, Inc.

Figure 5. Photo. Placement of thin asphalt overlay (top) and surface texture of new (bottom left) and worn (bottom right) dense graded asphalt surfaces.

Open Graded Friction Course

An OGFC treatment (figure 6) is a type of thin HMA overlay, but uses an open graded or porous asphalt mixture that allows water to quickly drain away from the surface by flowing through the mixture itself. This helps to minimize sheeting or standing water on the surface and the potential for hydroplaning. The porosity of an OGFC can also significantly reduce tire–pavement noise and splash and spray potential of the pavement surface. Similar to conventional thin HMA overlays, OGFCs are not typically considered a structural layer and are typically used to renew the functional performance of a pavement, including ride quality, friction, and tire–pavement noise. They can be placed over pavement with minor to moderate surface defects, but not those with substantial distresses caused by subsurface issues. OGFCs are beneficial for locations with high amounts of rainfall, but generally are not used in colder climates because of their poor performance during freeze–thaw cycles. Because a specialty asphalt mixture is used to achieve the open graded texture, they are typically more expensive than conventional dense-graded asphalt. However, superior functional performance makes this treatment desirable for high-priority urban areas.

Source: The Transtec Group, Inc.

Figure 6. Photo. Surface texture of OGFC.

Ultra-Thin Bonded Wearing Course

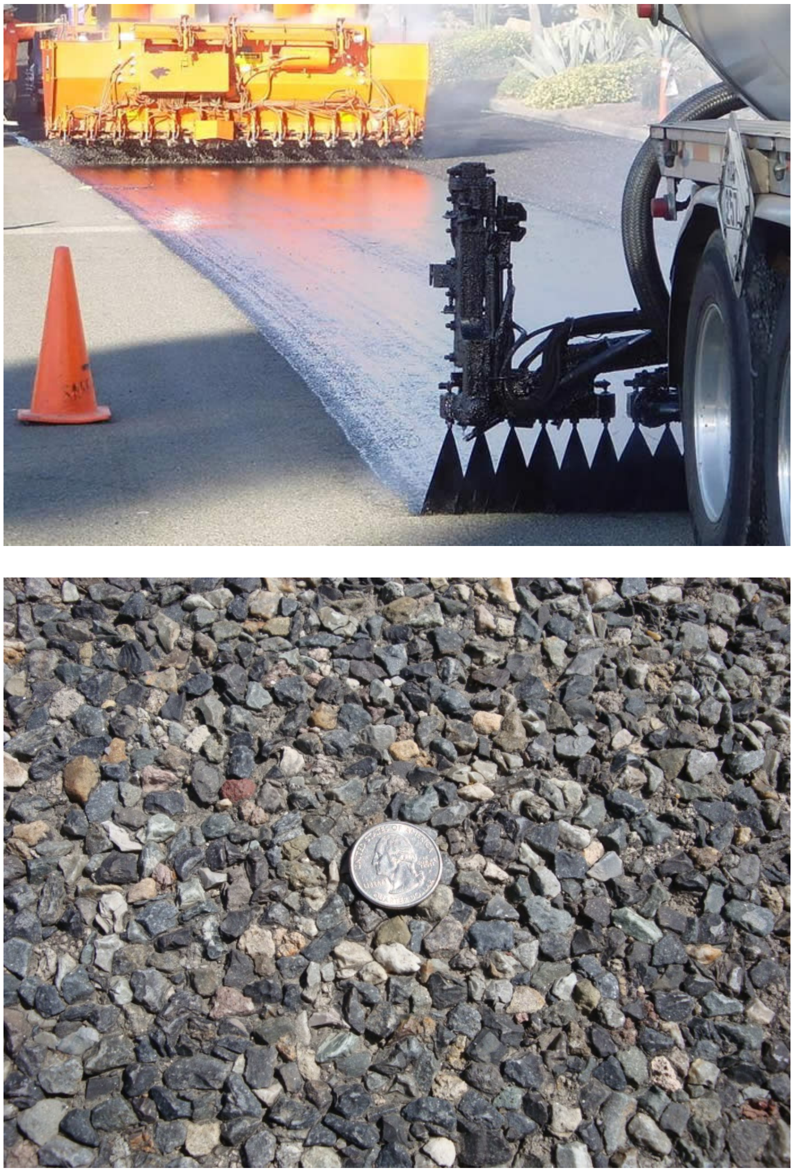
UTBWC is a specialty ultra-thin asphalt overlay used to restore ride quality while sealing and protecting the underlying pavement. It can also be used to mitigate shallow (less than 0.5-inch) rutting and can help retard fatigue cracking.(32) UTBWC is a non-structural layer, typically only 0.5- to 0.75-inch thick and generally uses a gap-graded aggregate and polymer-modified asphalt. One of the primary differences between UTBWC and conventional ultra-thin asphalt overlays is how the treatment is placed. An emulsion layer is applied to the pavement surface immediately in front of the paving screed using a self-priming paver (figure 7). The emulsion helps to seal the underlying pavement surface while also immediately bonding it to the new asphalt surface. UTBWC was originally developed as a proprietary product called NovaChip, but since the patent expired, several State transportation departments have developed their own specification for this treatment. UTBWC can be applied to existing asphalt or concrete pavement or over other surface treatments. The underlying pavement must be structurally sound with only minor rutting, minor to moderate cracking, and minor to moderate bleeding and raveling.(33)

Sources: top: Roadtec; bottom: The Transtec Group, Inc.

Figure 7. Placement of an UTBWC using a self-priming paver (top) and surface texture of an UTBWC (bottom).(34)

Chip Seal (Seal Coat)

Chip seals or seal coats are a common bituminous pavement preservation treatment used to seal fine cracks in the underlying pavement surface and prevent water intrusion into the underlying pavement structure, while sustaining or improving pavement friction.(35) Chip seals are constructed by first applying a bituminous membrane onto the existing pavement followed by a layer of aggregate or "chips," which are dropped onto the surface then rolled to embed them in the binder. (See figure 8.) The bituminous membrane is typically a polymer-modified asphalt emulsion, but can also be a liquid asphalt material (asphalt cement or cutback), including rubberized asphalt. Chip seals are typically only applied to existing asphalt pavement or bituminous surface treatments, but have also been used for unpaved roads. Chip seals are not a structural layer, but do provide a very durable wearing surface. They are susceptible to chip loss, which can result in flying chips and broken windshields, and are therefore not commonly used on heavily traveled urban roadways. However, they are commonly used on rural high-speed roadways, including rural interstates and State highways. There are several varieties of chip seals, including single, double, and triple layer treatments that may use a variety of aggregate sizes in the different layers, as well as different types of aggregate such as lightweight material.



Sources: top: California Chip Seal Association; bottom: The Transtec Group, Inc.

Figure 8. Photo. Placement of a chip seal (top) and surface texture of a single layer chip seal (bottom).(36)

Slurry Seal

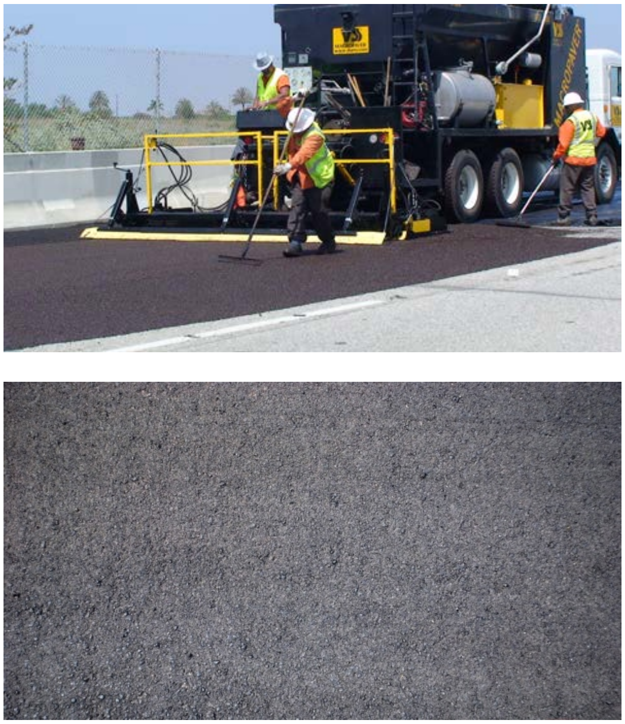
Slurry seal is a low-cost bituminous surface treatment used to seal the underlying surface from water infiltration, fill surface cracks and voids, and improve friction and appearance of an existing pavement.(24) Slurry seal is a mixture of emulsified asphalt, water, fine aggregate, and mineral filler that is mixed into a slurry and applied or screeded onto the pavement surface in a thin layer using squeegees or a spreader box (figure 9). Slurry seals do not provide any structural benefit to the pavement, but are a very cost-effective treatment for preserving the existing pavement surface, improving appearance, and restoring or enhancing friction.

Source: Ace Asphalt

Figure 9. Photo. Placement of a slurry seal (top) and surface texture of a cured slurry seal (bottom).(37)

Microsurfacing

Microsurfacing is a surface treatment very similar to slurry seal, but is typically a more durable treatment that is used for higher volume roadways. Like slurry seal, microsurfacing is a slurry mixture consisting of emulsified asphalt, water, fine aggregate, and mineral filler. Microsurfacing, however, typically uses a polymer-modified asphalt emulsion, which gives it more flexibility than a conventional asphalt binder. Microsurfacing is primarily used to mitigate raveling and oxidation of asphalt pavement surfaces, but also improves friction and appearance of both asphalt and concrete surfaces. Microsurfacing can be designed with larger aggregate for use in filling shallow to moderate depth ruts in asphalt pavement, and can also seal low-severity cracks.(31) Microsurfacing is applied in a similar manner to slurry seal, using a spreader box behind a slurry truck. (See figure 10.)



Sources: top: International Slurry Surfacing Association and VSS MacroPaver; bottom: Ace Asphalt

Figure 10. Microsurfacing placement (top) and surface texture of cured microsurfacing treatment (bottom).(38,37)

Diamond Grinding

Diamond grinding is a process used to shave a thin layer (typically less than 0.25-inch) of the surface of pavements, primarily for improving ride quality, but also for restoring or improving skid resistance and reducing tire–pavement noise. Diamond grinding is performed using grinding equipment that uses a cutting head consisting of a stack of concrete cutting saw blades with diamond-encrusted teeth. The saw blades on the cutting head are spaced 0.08 to 0.10 inches apart, leaving shallow grooves in the pavement surface that provide macrotexture (figure 11). Although diamond grinding can be used to grind out localized roughness in asphalt pavements, it is most commonly used more for concrete pavements to mitigate slab curing and faulting at joints, and to restore surface texture.

Source: The Transtec Group, Inc.

Figure 11. Photo. Diamond ground concrete pavement surface.

Grooving

Grooving is a treatment in which narrow grooves are sawcut into the pavement surface, typically in the direction of traffic, and typically 0.75-inches apart. (See figure 12.) The grooves increase pavement macrotexture, providing a path for bulk water drainage. Grooving is a surface treatment that can be used when it is undesirable to apply any topical treatment to the pavement surface (e.g., bituminous surface treatments) or to remove any of the pavement surface (e.g., milling or diamond grinding). Grooving effectively ensures a certain level of macrotexture regardless of how the pavement surface wears over time. Grooving is commonly used for airfield runways and bridge decks, but is becoming more common for highway pavements as well. Grooving is typically used on concrete pavements, but can also be done on asphalt. A surface treatment termed "Next Generation Concrete Surface," which combines diamond grinding and grooving was developed over the past decade and provides a standardized solution for grooving while also improving ride quality.(39)

Source: The Transtec Group, Inc.

Figure 12. Photo. Grooved concrete pavement surface (top) and Next Generation Concrete Surface (bottom).

Micro-Milling

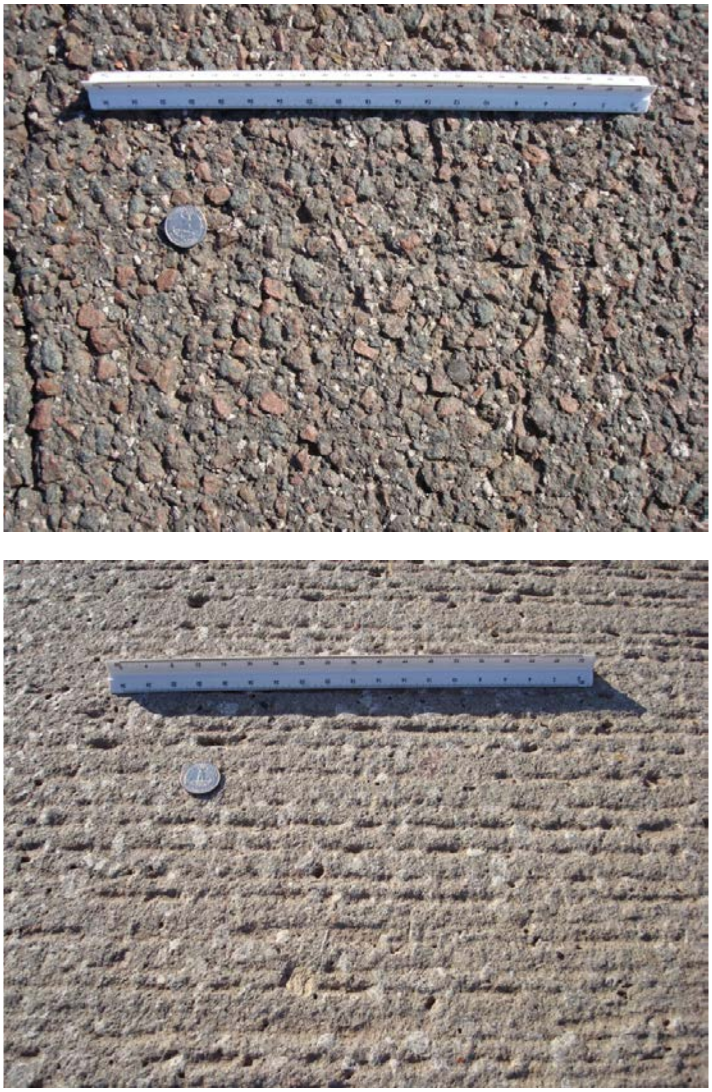
Micro-milling is a surface treatment in which a milling head is used to remove a thin layer of the pavement surface. Unlike diamond grinding, in which the cutting head shaves or grinds the surface away, micro-milling is an impact technique in which the milling teeth effectively chip away the pavement surface. Micro-milling differs from conventional milling in that the cutting head uses teeth that are spaced closely together, leaving a much less aggressive surface texture than conventional milling (figure 13). Whereas milling is typically used to remove pavement in preparation for an overlay, micro-milling leaves a much less aggressive surface texture that can be opened to traffic as a final surface. Although this is a promising treatment for improving pavement friction, it was excluded from this effort because of its very limited usage to date.

Source: Pavia Systems

Figure 13. Photo. Micro-milled asphalt pavement surface.(40)

Shotblasting/Abrading

Shotblasting/abrading is a surface treatment in which steel pellets or "shot" are fired at the pavement surface at high velocity to pit or abrade away a superficial layer of the pavement surface (figure 14). Shotblasting removes any loose material from the surface and also pits the surface of the aggregates to improve microtexture. It is frequently used to remove rubber or oil deposits on the pavement surface. This treatment is commonly used by airports to remove rubber deposits on runways.



Source: The Transtec Group, Inc.

Figure 14. Photo. Shotblast asphalt pavement (top) and concrete pavement (bottom).

For roadways, this treatment is more commonly used for surface preparation prior to applying another surface treatment (e.g., HFS) to bridge decks or highway pavements. This treatment was ultimately excluded from consideration under this study because of the lack of highway treatment sites.

Cape Seal

Cape seal is a surface treatment consisting of a chip seal followed by a slurry seal. After the chip seal is applied and cured, the slurry seal is used to cover the chip seal. The advantage of this treatment is that the chip seal seals and protects the underlying pavement, while the slurry seal helps to protect the chip seal, locking the chip seal aggregate in place to minimize chip/aggregate loss and providing a smoother final surface. Ultimately, this treatment was excluded from this study because of the limited number of States that use the treatment (and therefore the limited number of lane-mi), but also because the finished surface will be similar to that of a slurry seal or microsurface, which are already considered separately.

Scrub Seal

A scrub seal is a treatment in which a bituminous material (emulsion or asphalt binder) is literally scrubbed into the surface of a heavily cracked asphalt pavement using brushes (figure 15). A cover aggregate is then broadcast over the surface, in a similar manner to a chip seal. The scrubbing action helps to ensure the bituminous seal penetrates any cracks in the pavement surface to help preserve the asphalt and seal the surface from water infiltration through the cracks. This treatment is more suitable for heavily cracked asphalt pavements whose underlying pavement structure is still sound. Scrub seals were excluded from this study because of the limited number of lane-mi available for study, and also because the finished surface is effectively the same as a chip seal. Although it has slightly different applications, such as for more distressed pavement, the surface properties (texture and friction) should not differ significantly from a chip seal.

Source: FP2, Inc.

Figure 15. Photo. Emulsion material is scrubbed into the pavement surface for a scrub seal surface treatment.(41)

High Friction Surfacing

HFS is a specialty pavement treatment used specifically to restore or enhance friction. It is commonly used for spot treatments of curves, intersections, and steep grades where friction demand is higher than can be provided by conventional paving materials. HFS is installed by spreading a resin binder (epoxy, methacrylate, polyester, etc.) over the pavement surface followed by broadcasting or dropping a 1- to 3-mm abrasion and polish-resistant aggregate onto the resin (figure 16). Calcined bauxite, which exhibits exceptional polish resistance, is the most commonly used aggregate for HFS worldwide. However, similar aggregates that maintain excellent microtexture properties over time have also been used as the aggregate. Although a form of HFS has been used extensively for bridge decks and provides the additional benefit of sealing the bridge deck surface, it does not provide any documented preservation benefit for pavements. However, it is one of the treatments considered in this study that is typically used specifically as a safety improvement. Recognizing the safety benefit of HFS, FHWA recently deployed HFS as a focus technology under the Every Day Counts 2 program.(42)

Source: The Transtec Group, Inc.

Figure 16. Photo. Installation of HFS (top) and finished surfaces (bottom).

COMPARISON OF TREATMENT MACROTEXTURE PROPERTIES

The properties of the various treatments considered under this study vary widely from State to State and project to project. Unfortunately, it was not possible to quantify these properties for each treatment site considered under this study for use in the statistical analysis. Although there is no codified typical friction value for any given treatment, some typical macrotexture depths for the various treatments are provided in table 3. As discussed in chapter 2, several studies have documented the importance of pavement macrotexture (texture depth) and its effect on crash rates. Good friction, however, is not guaranteed by good macrotexture.

Table 3. Typical macrotexture depth for various pavement treatments.

Pavement Treatment	Typical Macrotexture Depth(3)
Slurry Seal	0.3 to 0.6 mm
Thin Hot Mix Asphalt Overlay	0.4 to 0.6 mm (Dense Graded) > 1.0 mm (Stone Matrix Asphalt)
Microsurfacing	0.5 to 1.0 mm
Diamond Grinding	0.7 to 1.2 mm
Grooving	0.9 to 1.4 mm
Ultra-Thin Bonded Wearing Course (UTBWC)	> 1.0 mm
Chip Seal (various binder types)	> 1.0 mm
Open Graded Friction Course (OGFC)	1.5 to 3.0 mm
High Friction Surfacing (HFS)	> 1.5 mm

HMA = Hot mix asphalt

CHAPTER 4. DATA COLLECTION

OVERVIEW OF DATA COLLECTION PROCESS

Because this was retrospective study, gathering data on existing low-cost pavement treatments was the most time-intensive aspect. The project relied heavily on the PFS volunteer States to provide the types and quantities of treatments available for analysis. The PFS volunteer States worked hard to provide information on the treatments, crash data, and roadway information. The following sections briefly outline the process used by the project team to gather the data necessary for this study.

Contact ELCSI-PFS Volunteer States to Identify Treatment Types and Availability of Crash and Roadway Data

The data collection process began by contacting the various ELCSI-PFS volunteer States to determine what treatment types would be available for evaluation under this study and to ascertain the availability of crash data for these sites. Because the treatments considered under this study were not necessarily installed as safety improvements, it was necessary for the State transportation department safety engineers to work closely with the pavements/materials/ maintenance engineers to identify what treatments are typically used and exact locations for those treatments.

Request Treatment Locations and Crash and Roadway Data

After the team had narrowed down the list of treatment types and the State transportation departments that were able to provide data, the team formally requested a list of treatment locations, crash data, and roadway data from the participating State transportation departments. This information was provided to the project team in various formats and further compiled into a consistent format by the project team for assessing the sample size.

Narrow List of Treatment Types and States Based on Sample Size

Based on the quantity (number and length) of treatment sites and availability and quality of crash data from the States, the team was able to further narrow the list of treatments and states. Having an adequate sample size for each treatment and for each State was important for evaluating the performance of each treatment, but also for being able to compare performance of the treatments between States. The only exception to this occurred with HFS, for which there are a relatively small number of installations nationwide, let alone in a given State.

Verify Treatment Locations, Installation Date, and Underlying Surface

Once a final list of treatment locations was provided, the project team worked with each State to verify the location and installation date for the purpose of mining crash data for each location. Pavement treatments considered in this study are typically installed over several months. For this reason, the installation year was effectively masked off when analyzing the crash data, leaving the years prior to the installation year as the "before" period, and the years after the installation year as the "after" period. The team worked with each State to verify that no other surface treatment or significant construction had been applied to the study locations during the after period. The team also worked with the States to verify the underlying pavement surface type. Most States were able to provide pavement or maintenance history records for the routes being studied for this purpose. These records were used to reconcile any discrepancies observed between the pavement surface type listed in the crash data records and the expected pavement type.

Identify Reference Sites and Collect Crash Data

A critical aspect of an EB before–after analysis is accounting for regression-to-the-mean, changes in traffic volumes, and time trends in crash reporting, by analyzing reference sites in addition to the actual treatment sites. This proved to be a difficult task as the treatments being considered are typically installed over long sections of a roadway that may have several variations in geometry, shoulders, median, roadway width, and traffic, among other factors. The project team used information in the roadway data file for each treatment site to identify reference site candidates that had characteristics as similar as possible to the treatment locations. One very important characteristic, because it relates to the pavement surface, is the pavement type for the reference sites. The team used a process similar to that described above to verify the pavement surface type at the reference sites. Once valid reference sites were identified, the project team collected crash data for the reference sites for use in the analysis.

Collect additional Data Collection: Climatic Data, Cost Information, and Materials Information

Additional data that were collected for each treatment site included historical climatic data, cost information for the various treatment types, and information on the materials used for each treatment. Climatic data was collected to assess any effects that climate (precipitation and temperature) may have on a particular treatment. Because the treatments were installed in a variety of climates, there is the potential that climatic conditions, precipitation in particular, could have affected crash frequencies and treatment effectiveness.

Cost information was collected for use in the BC analysis. Because of the large number of treatment sites, it was not possible to collect information on the exact cost of each particular treatment or project. Rather, the team looked at recent statewide bid averages to determine a rough unit cost for each treatment in each state.

Materials information was compiled from standard specifications and/or standard practices for each of the treatment types in each State. Of particular interest were any differences in the component materials (aggregates, binders) and tests used to measure various properties of these materials. As with cost information, it was not possible to collect materials information on each individual treatment site; rather the team simply looked at differences in standard specifications for each.

DATA COLLECTION ITEMS

Table 4 summarizes the list of items originally proposed for collection. It was not possible to collect this level of detail for all of the treatment sites because of the limited information maintained by each State for specific projects. However, those items that were actually collected are discussed in more detail later.

Table 4. List of potential data collected for treatment sites.

Crash Data[1]	• Number of crashes • Crash classification (PDO, Injury, Fatal) • Passenger information • Vehicle type • Pavement conditions • Ambient conditions • Reported driver action • Direction of travel • Reference location (milepost) • Other factors affecting crash classification (alcohol, seat belt use, etc.)
Roadway Data	• Roadway classification (rural, urban, interstate, non-interstate) • Traffic volume and directional/lane distribution • Number of lanes • Median information • Geometrics (grade, curvature, superelevation, cross-slope) • Roadway terrain • Shoulder information • Roadside features • Safety devices/features (striping, signage, guardrails, etc.)
Pavement File Data	• Original/existing pavement type (pre-treatment) • Original/existing pavement construction dates • Pavement materials for original/existing pavement • Surface treatment strategy type • Construction dates for treatment strategy • Construction methods and equipment used for treatment strategy • Length of treatment strategy section • Material properties for treatment strategy (includes, but is not limited to, binder type/properties, aggregate properties) • Pavement condition (rutting, polished surface, etc.) • Skid Resistance Measurement (SRV and test type)
Climatic Data	• Average temperatures (by month) • Average rainfall (by month) • Crash-specific weather (if available)

[1] Minimum of 3 years preceding application of the treatment and 3 years following application, as available.
PDO = Property damage only
SRV = Skid resistance value

SUMMARY OF DATA BY STATE

Table 5 and table 6 show the number of treatment sites and/or mi of treatments provided by each of the volunteer States for asphalt and concrete pavements, respectively. Note that these are overall treatment quantities after eliminating nonviable sites, not broken down by facility type.

Table 5. Treatment strategies and quantities provided, by State, for asphalt pavements.

State	Treatments	Approximate Mi/Number of Sites
California	• Chip seal (rubberized and conventional) • Thin HMA overlay (rubberized and conventional) • OGFC (rubberized and conventional) • UTBWC • Microsurfacing • Slurry seal • HFS	948 mi 581 mi 404 mi 57 mi 72 mi 134 mi 7 sites
Colorado	• HFS	2 sites
Connecticut	• UTBWC	3 sites
Kansas	• HFS	2 sites
Kentucky	• HFS	25 sites
Michigan	• HFS	5 sites
Minnesota	• Chip seal • Thin HMA overlay • Microsurfacing	274 mi 204 mi 57 mi
Mississippi	• Scrub seal • Chip seal • HFS	52 mi 29 sites 1 site
Montana	• Chip seal • HFS	15 sites 2 sites
North Carolina	• Chip seal (single, double) • Thin HMA overlay • OGFC • UTBWC • Slurry seal	765 mi 3,154 mi 42 mi 68 mi 5 mi
Pennsylvania	• Chip seal (single, double) • Thin HMA overlay • UTBWC • Microsurfacing	570 mi 1 mi 7 mi 159 mi
South Carolina	• HFS	6 sites
Tennessee	• Chip seal • Cape seal • Thin HMA overlay • Microsurfacing • Scrub seal • UTBWC • HFS	7 sites 9 sites 29 sites 52 sites 4 sites 2 sites 6 sites

State	Treatments	Approximate Mi/Number of Sites
Wisconsin	• Chip seal • HFS	22 sites 1 site
West Virginia	• HFS	24 sites

HMA = Hot mix asphalt
OGFC = Open graded friction course
HFS = High-friction surfacing
UTBWC = Ultrathin Bonded wearing course

Table 6. Treatment strategies and quantities provided, by state, for concrete pavements.

State	Treatments	Approximate Mi/ Number of Sites
California	• OGFC (rubberized and conventional) • Diamond grinding • Grooving	12 mi 85 mi 5 mi
Kansas	• HFS	2 sites
Michigan	• HFS	4 sites
Minnesota	• Thin HMA overlay • Microsurfacing • Diamond grinding	5 mi 37 mi 8 mi
North Carolina	• UTBWC • Diamond Grinding	26 mi 24 mi
Pennsylvania	• Thin HMA overlay • Microsurfacing • UTBWC • Diamond grinding	7 mi 5 mi 13 mi 33 mi

OGFC = Open graded friction course
HFS = High-friction surfacing
HMA = Hot mix asphalt
UTBWC = Ultrathin bonded wearing course

FINAL TREATMENTS AND STATES

Although the team wanted to include all sites and States in the analysis, project timeline and resource limitations made it necessary to focus efforts on analyzing treatments in the States that were able to provide a variety of treatments, for both concrete and asphalt pavement, and a significant quantity of each. Therefore, treatment sites included in the final analysis for conventional (i.e., non-HFS) treatments were the sites provided by California, Minnesota, North Carolina, and Pennsylvania. For HFS treatments, the sites from roughly half of the States that provided them were included in the final analysis.

Conventional treatment sites provided by States that were not included in the final analysis were submitted to FHWA for in-house studies. These included treatment sites provided by Connecticut (UTBWC), Mississippi (cape seal), Montana (chip seal), Tennessee (various treatments), and Wisconsin (chip seal).

CONVENTIONAL TREATMENT DATA COLLECTION

This section describes the process followed to collect and query the data required for the study and provides summary statistics for these data for each of the four States included in the conventional treatment analysis.

Pennsylvania

Data for Pennsylvania were provided by the Pennsylvania Department of Transportation (PennDOT). These data included geometric, pavement, traffic, and crash data for the entire State. The data are linked together using the District Number, County Number, State Route Number, Segment Number, and Segment Offset variables.

Geometric Data

Geometric data were obtained from the PennDOT Roadway Management System and included the following variables:

- Access control.
- Divided/undivided.
- Divided width.
- Surface width.
- Speed limit.
- Number of lanes.
- Urban versus rural environment.
- Surface type.
- Shoulder type.
- Shoulder width.
- Shoulder paved width.

Note that for access-controlled roadways, the data are directional, that is, each record corresponds to only one direction of travel. For non-access-controlled roadways, the data encompass both directions of travel.

PennDOT also provided a list of segments where some change in the route/ segment/offset segmentation system had been made between 2003 and 2011. This is significant because data from different years are being queried and if the segmentation has changed, then the data cannot be matched correctly. This was evident for some locations that appeared to have very large changes in traffic volume from 1 year to the next. Segments with a change were not used for analysis.

Pavement Data

PennDOT provided a file with pavement history statewide. For each section of roadway, data on up to 10 layers of pavement is included. The data indicate the year of resurfacing and the surface type.

Traffic Data

Traffic data in the form of AADT were obtained from PennDOT from 2003 to 2010. The percent of trucks in the traffic mix was also provided. Because the study period extends to 2011 and these counts were not available, it was decided to apply the 2010 AADTs to 2011 as well.

Crash Data

The PennDOT Crash Database is maintained by the Bureau of Highway Safety and Traffic Engineering's Crash Information Systems & Analysis Division. Data from 2003 to 2011 were provided. The compiled crash data contain many variables related to the location, time, and characteristics of each crash. The following notes relate to the exclusion or inclusion of crash data and definition of crash types:

- Included only non-intersection-related mainline crashes (if intersect_type = "mid-block").
- Excluded crashes where harm_event = "hit deer" or "hit other animal".
- Excluded crashes where road condition = "snow", "slush", "ice", or "ice patches".
- Defined injury crashes as those where fatal_count or tot_inj_count is greater than 0.
- Defined ROR crashes as those where relation_to_road = "Outside trafficway".
- Defined wet crashes as those where road_condition = "wet".

Construction Data

PennDOT does not maintain a central file with construction information. For the treatment sites used the PennDOT staff did not indicate any other construction had taken place within the study period. It is possible some other works may have occurred; however, with the large mileage of treatment and reference sites available, if some works did occur at some locations, the impact on the results of the analysis would be negligible.

Treatment Sites

Sites on the initial list of treatment sites eligible for the study were subsequently removed for two reasons.

- Sites with a missing volume between 2003 and 2011 were removed.
- Sites with a change in the segmentation between 2003 and 2011 were removed.

Reference Sites

Reference sites were identified by first identifying road segments in the same county and with the same route number as the treated sites. Then the various geometric and traffic variables were compared to ensure that the range of values for these variables were consistent. The pavement data were linked to these data, and any segments that were resurfaced between 2003 and 2011 were removed.

Similar to the treated sites, potential reference sites were excluded if any year had a missing traffic volume count or the segmentation had changed between 2003 and 2011.

After querying the data, it was found that some sites have highly variable AADTs between years. After consultation with PennDOT, no satisfactory explanation was found for such systemic variation. To avoid biases in the SPFs to be developed due to incorrect traffic volume data it was decided to eliminate any segment where the AADT for any single year deviated from the segment average for the entire study period by 25 percent or more.

Table 7 through table 9 provide summary statistics for the treatment and reference site data in Pennsylvania.

Table 7. Summary statistics for Pennsylvania treatment site geometry.

Treatment	Site Type	Total Length (mi)	Pavement Type (mi)	Width (ft)	No. of Lanes (mi)	Area Type (mi)	Divided/Undivided (mi)	Avgshldwid (ft)
Chip Seal	Two-Lane	570.00	AC—346.78 CS—217.78 Micro—5.42 SS—0.02	Min—16 Max—44 Mean—21.30	2—568.82 3—1.49	Rural—418.06 Urban—151.95	Divided—570.00 Undivided—0.00	Max—0 Min—12 Mean—3.16
Diamond Grinding	Two-Lane	0.47	PCC—0.47	Min—24 Max—24 Mean—24	2—0.47	Rural—0.00 Urban—0.47	Divided—0.00 Undivided—0.47	Max—0 Min—0 Mean—0
	Freeway	32.29	PCC—32.29	Min—24 Max—36 Mean—24.77	2—32.19 3—0.09	Rural—23.37 Urban—8.92	Divided—32.29 Undivided—0.00	Max—5 Min—11 Mean—7.14
Microsurfacing	Two-Lane	152.26	AC—152.26	Min—18 Max—56 Mean—27.82	2—143.00 3—9.27	Rural—128.53 Urban - 23.74	Divided—0.00 Undivided—152.26	Max—0 Min—14 Mean—5.12
	Freeway	6.47	AC—6.47	Min—24 Max—52 Mean—25.71	2—6.47	Rural—2.04 Urban—4.43	Divided—6.47 Undivided—0.00	Max—3 Min—12.5 Mean—6.3
Microsurfacing on PCC	Freeway	5.47	PCC—5.47	Min—24 Max—36 Mean—25.71	2—5.47	Rural—1.56 Urban—3.91	Divided—5.47 Undivided—0.00	Max—7 Min—12 Mean—9.10
Thin HMA	Freeway	0.50	AC—0.50	Min—24 Max—24 Mean—24	2—0.50	Rural—0.50 Urban—0.00	Divided—0.50 Undivided—0.00	Max—7 Min—7 Mean—7
Thin HMA on PCC	Freeway	6.95	PCC—6.95	Min—24 Max—24 Mean—24	2—6.95	Rural—0.00 Urban—6.95	Divided—6.95 Undivided—0.00	Max—7 Min—7 Mean—7
UTBWC	Two-Lane	7.49	AC—7.49	Min—21 Max—48 Mean—26.28	2—7.21 3—0.28	Rural—6.77 Urban—0.72	Divided—0.00 Undivided—7.49	Max—3 Min—8 Mean—5

Treatment	Site Type	Total Length (mi)	Pavement Type (mi)	Width (ft)	No. of Lanes (mi)	Area Type (mi)	Divided/Undivided (mi)	Avgshldwid (ft)
UTBWC on PCC	Two-Lane	4.11	PCC—4.11	Min—24 Max—24 Mean—24	2—9.73	Rural—0.71 Urban—3.40	Divided—0.00 Undivided—4.11	Max—7 Min—8 Mean—7.93
	Freeway	9.73	PCC—9.73	Min—24 Max—24 Mean—24	2—4.11	Rural—2.73 Urban—6.99	Divided—9.73 Undivided—0.00	Max—7 Min—9 Mean—7.18

Avgshldwid = Average of left and right shoulder width
AC = Asphalt
CS = Chip Seal
Micro = Microsurfacing
SS = Slurry Seal
Max = Maximum
Min = Minimum
PCC = Portland cement concrete
HMA = Hot mix asphalt
UTBWC = Ultrathin bonded wearing course

Table 8. Summary statistics for Pennsylvania treatment site AADT and crashes.

ELCSI Treatment Type	Site Type		AADT Before	AADT After	Years Before	Years After	totrateb	totratea	injrateb	injratea	rorrateb	rorratea	wetrateb	wetratea	wetrorrateb	wetrorratea
Chip Seal	Two-Lane	Min	239	233	3.00	3.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Chip Seal	Two-Lane	Max	19,533	17,689	5.00	5.00	60.82	117.58	60.82	88.18	37.79	28.91	32.26	20.75	5.47	3.71
Chip Seal	Two-Lane	Mean	2,618	2,534	4.29	3.71	0.69	0.75	0.40	0.38	0.14	0.14	0.16	0.15	0.03	0.03
Diamond Grinding on PCC	Freeway	Min	10,240	8,844	3.00	3.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Diamond Grinding on PCC	Freeway	Max	109,316	105,526	5.00	5.00	18.24	51.87	12.16	51.87	3.04	0.67	6.08	51.87	3.04	0.00
Diamond Grinding on PCC	Freeway	Mean	41,544	38,322	4.81	3.19	1.27	1.69	0.71	0.99	0.12	0.01	0.31	0.53	0.03	0.00
Diamond Grinding on PCC	Two-Lane	Min	4,568	4,444	4.00	4.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Diamond Grinding on PCC	Two-Lane	Max	4,568	4,444	4.00	4.00	0.97	0.00	0.00	0.00	0.97	0.00	0.00	0.00	0.00	0.00
Diamond Grinding on PCC	Two-Lane	Mean	4,568	4,444	4.00	4.00	0.48	0.00	0.00	0.00	0.48	0.00	0.00	0.00	0.00	0.00
Microsurfacing	Freeway	Min	11,328	11,683	3.00	3.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Microsurfacing	Freeway	Max	74,759	69,328	5.00	5.00	18.56	15.22	10.74	11.68	1.36	2.91	5.37	13.57	0.00	2.91
Microsurfacing	Freeway	Mean	30,530	27,060	4.64	3.36	1.96	2.11	0.75	1.18	0.06	0.07	0.23	0.63	0.00	0.05
Microsurfacing	Two-Lane	Min	679	1,056	3.00	3.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Microsurfacing	Two-Lane	Max	18,838	17,519	5.00	5.00	62.99	70.55	22.92	70.55	32.09	23.52	43.29	37.79	22.92	9.09
Microsurfacing	Two-Lane	Mean	5,752	5,633	3.93	4.07	1.38	1.51	0.72	0.83	0.22	0.18	0.48	0.30	0.10	0.06

ELCSI Treatment Type	Site Type		AADT Before	AADT After	Years Before	Years After	totrateb	totratea	injrateb	injratea	rorrateb	rorratea	wetrateb	wetratea	wetrorrateb	wetrorratea
Microsurfacing on PCC	Freeway	Min	10,547	8,702	3.00	3.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Microsurfacing on PCC	Freeway	Max	74,759	74,332	5.00	5.00	13.15	14.06	5.82	5.27	2.11	1.76	8.76	1.94	1.91	1.76
Microsurfacing on PCC	Freeway	Mean	52,465	49,886	4.33	3.67	3.55	3.67	1.82	1.48	0.33	0.11	1.86	0.69	0.18	0.11
Thin HMA	Freeway	Min	31,394	29,257	4.00	4.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thin HMA	Freeway	Max	31,394	29,257	4.00	4.00	0.00	0.62	0.00	0.62	0.00	0.00	0.00	0.00	0.00	0.00
Thin HMA	Freeway	Mean	31,394	29,257	4.00	4.00	0.00	0.15	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.00
Thin HMA on PCC	Freeway	Min	26,012	27,145	4.00	4.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thin HMA on PCC	Freeway	Max	26,012	27,145	4.00	4.00	1.67	9.96	1.66	3.32	1.66	3.32	1.67	2.30	0.00	0.00
Thin HMA on PCC	Freeway	Mean	26,012	27,145	4.00	4.00	0.49	1.16	0.22	0.39	0.08	0.20	0.13	0.24	0.00	0.00
UTBWC	Two-Lane	Min	2,508	1,936	3.00	4.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
UTBWC	Two-Lane	Max	15,536	14,823	4.00	5.00	63.75	38.34	47.81	29.39	19.17	15.94	47.81	15.94	17.07	15.94
UTBWC	Two-Lane	Mean	12,134	12,036	3.98	4.02	6.40	3.98	2.80	1.86	1.09	0.37	4.35	0.52	0.55	0.32

ELCSI Treatment Type	Site Type		AADT Before	AADT After	Years Before	Years After	totrateb	totratea	injrateb	injratea	rorrateb	rorratea	wetrateb	wetratea	wetrorrateb	wetrorratea
UTBWC on PCC	Freeway	Min	21,043	9,958	3.00	3.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
UTBWC on PCC	Freeway	Max	50,811	39,889	5.00	5.00	8.02	4.85	3.16	4.85	0.39	0.52	4.01	1.72	0.00	0.00
UTBWC on PCC	Freeway	Mean	40,657	29,144	3.49	4.51	0.61	0.47	0.22	0.24	0.01	0.01	0.16	0.09	0.00	0.00
UTBWC on PCC	Two-Lane	Min	4,392	3,645	5.00	3.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
UTBWC on PCC	Two-Lane	Max	8,218	9,093	5.00	3.00	7.64	3.34	3.82	1.67	0.77	0.49	0.30	0.49	0.00	0.49
UTBWC on PCC	Two-Lane	Mean	6,067	5,898	5.00	3.00	0.79	0.47	0.50	0.21	0.11	0.03	0.04	0.03	0.00	0.03

ELCSI = Evaluation of Low-Cost Safety Improvements
AADT = Average Annual Daily Traffic
totrateb = total crash rate per mi-yr in before period
totratea = total crash rate per mi-yr in after period
injrate, wetrate, rorrate, wetrorrate = injury, wet-road, ROR, and wet-road ROR crash rates per mi-year, respectively
Max = maximum
Min = minimum
PCC = Portland cement concrete
HMA = Hot mix asphalt
UTBWC = Ultrathin bonded wearing course

Table 9. Summary statistics for Pennsylvania reference sites.

Site Type	Total Length (mi)	Pavement Type (mi)	Surface Width (ft)	No. of Lanes (mi)	Area Type (mi)	Divided/Undivided (mi)	Avgshldwid (ft)	AADT	Years	totrate	injrate	rorrate	wetrate	wetrorrate
Two-Lane	7,064.58	AC—7,002.91 PCC—61.67	Max—9 Min—82 Mean—24.5	2—6,957.77 3—106.81	Rural—4,919.88 Urban—2,144.70	Divided—0.00 Undivided—7,064.58	Max—0 Min—15 Mean—3.19	201 31,715 5,717	9 9 9	1.52	0.81	0.20	0.33	0.05
Freeway	563.97	AC—298.53 PCC—265.45	Max—19 Min—67 Mean—25.86	2—522.27 3—41.70	Rural—338.49 Urban—225.48	Divided—563.97 Undivided—0.00	Max—0 Min—12 Mean—6.91	1819 174,962 34,788	9 9 9	2.42	1.30	0.10	0.43	0.02

Avgshldwid = Average of left and right shoulder width
AADT = Average Annual Daily Traffic
totrate = total crash rate per mi-year
injrate = injury crash rate per mi-year
wetrate = wet-road crash rate per mi-year;
rorrate = ROR crash rate per mi-year
wetrorrate = wet-road ROR crash rate per mi-year)
AC = Asphalt concrete
PCC = Portland cement concrete
HMA = Hot mix asphalt

North Carolina

Data for North Carolina were provided by the North Carolina Department of Transportation (NCDOT) and the Highway Safety Information System (HSIS). The data provided by NCDOT included a list of potential treatment sites and construction data, including paving projects. The data provided by HSIS included geometric, traffic, and crash data. The data are linked together using the County Number, Route Number, and Milepost variables.

Geometric Data

Geometric data were obtained from HSIS and included the following variables:

- Urban versus rural environment.
- Median width.
- Shoulder type.
- Surface width.
- Terrain.
- Median type.
- Speed limit.
- Surface type.
- Number of lanes.
- Roadway class.
- Shoulder width.
- Paved shoulder width.

Pavement Data

NCDOT indicated which of the treated site segments were asphalt or concrete pavements and provided pavement project history files for helping to verify the underlying pavement type. For the reference sites, the surface type variable was relied on as the existing pavement type.

Traffic Data

Traffic data in the form of AADT were obtained from HSIS from 2000 to 2010. The percent of trucks in the traffic mix was also provided.

After querying the data, it was found that some sites experience very high variability in traffic counts from year to year. After discussing with HSIS staff, it was concluded that this may be owing in large part to re-mileposting of the roadway segments from year to year. By comparing the roadway characteristics of a sample of these sites, it was found that the functional class often changed from year to year. In an attempt to eliminate as many of these re-mileposted locations as possible, the team removed any segment from the data for which the functional class or number of lanes changed from 2000 to 2010.

There was an additional concern with the 2009 AADTs in that many of these counts seemed out of line with the preceding and following years' AADT count. In particular, on divided roadways, the 2009 AADT appears to be roughly half of that reported in either the preceding or following year. The suspicion is that in 2009, the AADT for one direction may be what is reported. No resolution was found for the data, and it was decided to substitute the 2010 AADTs for 2009.

Crash Data

The crash data were provided by HSIS for 2000 to 2010. The compiled crash data contain many variables related to the location, time, and characteristics of each crash. The following notes relate to the exclusion or inclusion of crash data and definition of crash types:

- Exclude intersection-related mainline crashes (if loctype is any type of intersection crash).
- Excluded crashes where acctype = “animal”.
- Excluded crashes where rdsurf = “snow”, “slush”, or “ice”.
- Defined injury crashes as those where severity = fatal, A class, B class, or C class injury.
- Defined ROR crashes as those where acctype = “ran-off-road right”, “ran-off-road left”, or “ran-off-road straight”.
- Defined wet crashes as those where rdsurf=“wet”.

Construction Data

Construction history data was provided by NCDOT for 2000 to 2010. This list includes resurfacing and other projects, as well as concrete pavement ratings for verifying which sites were concrete.

Treatment Sites

Sites on the initial list of treatment sites eligible for the study were removed if they had an AADT under 500. As was discussed under *Traffic Data,* some segments are believed to have been re-mileposted but no record is available indicating the old and new mileposts for the same section of road. In an attempt to eliminate as many of these re-mileposted locations as possible, any segment for which the functional class or number of lanes changed from 2000 to 2010 was removed from the data.

Reference Sites

Reference sites were identified by first identifying road segments in the same county and with the same route number as the treated sites. Then the various geometric and traffic variables were compared to ensure that the range of values for these variables were consistent. The pavement data and construction data were linked to these data, and any segments that were resurfaced or had other construction works between 2000 and 2010 were removed.

Similar to the treated sites, potential reference sites were excluded if the functional class or number of lanes changed from 2000 to 2010.

Similar to the Pennsylvania data, it was found that some sites have highly variable AADTs between years. To avoid biases in the safety performance functions (SPF) to be developed due to incorrect traffic volume data, it was decided to eliminate any segment for which the AADT for any single year deviated from the segment average for the entire study period by 25 percent or more.

Table 10 through table 12 provide summary statistics for the treatment and reference site data in North Carolina.

Table 10. Summary statistics for North Carolina treatment site geometry.

Treatment	Site Type	Total Length (mi)	Pavement Type (mi)	Surface Width (ft)	No. of Lanes (mi)	Area Type (mi)	Divided/Undivided (mi)	Avgshldwid (ft)
Chip Seal	Two-Lane	763.74	AC—763.74 PCC—0.00	Min—14 Max—52 Mean—20.04	2—763.74	Rural—737.15 Urban—26.58	Divided—1.52 Undivided—762.22	Min—0 Max—12.5 Mean—5.21
	Multilane	1.47	AC—1.47 PCC—0.00	Min—24 Max—42 Mean—25.29	4—1.47	Rural—0.12 Urban—1.35	Divided—1.47 Undivided—0.00	Min—3 Max—10.5 Mean—9.64
Diamond Grinding	Freeway	24.09	AC—0.00 PCC—24.09	Min—24 Max—40 Mean—24.29	4—24.09	Rural—13.11 Urban—10.98	Divided—24.09 Undivided—0.00	Min—10 Max—12 Mean—10.79
Microsurfacing	Two-Lane	31.91	AC—31.91 PCC—0.00	Min—18 Max—52 Mean—25.99	2—31.91	Rural—31.89 Urban—0.02	Divided—0.00 Undivided—31.91	Min—0 Max—12 Mean—4.9
	Multilane	4.14	AC—4.14 PCC—0.00	Min—26 Max—36 Mean—29.33	3—1.13 4—3.01	Rural—4.14 Urban—0.00	Divided—0.00 Undivided—4.14	Min—6 Max—6.5 Mean—6.33
	Freeway	3.09	AC—3.09 PCC—0.00	Min—24 Max—24 Mean—24	4—3.09	Rural—3.09 Urban—0.00	Divided—3.09 Undivided—0.00	Min—5 Max—12 Mean—10.3
OGFC	Multilane	0.95	AC—0.95 PCC—0.00	Min—24 Max—60 Mean—54	4—0.95	Rural—0.95 Urban—0.00	Divided—0.09 Undivided—0.86	Min—8 Max—10 Mean—8.33
	Freeway	40.96	AC—40.96 PCC—0.00	Min—24 Max—54 Mean—32.69	4—34.47 6—5.88 8—0.61	Rural—30.89 Urban—10.07	Divided—40.96 Undivided—0.00	Min—10 Max—15.5 Mean—11.87
Slurry Seal	Two-Lane	5.08	AC—5.08 PCC—0.00	Min—20 Max—44 Mean—25.32	2—5.08	Rural—5.08 Urban—0.00	Divided—0.00 Undivided—5.08	Min—0 Max—7 Mean—4.52

Treatment	Site Type	Total Length (mi)	Pavement Type (mi)	Surface Width (ft)	No. of Lanes (mi)	Area Type (mi)	Divided/Undivided (mi)	Avgshldwid (ft)
Thin HMA	Two-Lane	2,865.59	AC—2,865.59 PCC—0.00	Min—10 Max—100 Mean—23.24	2 -2,865.50	Rural—2,332.59 Urban—533.00	Divided—8.82 Undivided—2,856.77	Min—0 Max—17 Mean—5.44
	Multilane	201.34	AC—201.34 PCC—0.00	Min—12 Max—92 Mean—39.65	3—5.77 4—183.32 6—12.03 8—0.23	Rural—73.54 Urban—127.81	Divided—136.32 Undivided—65.02	Min—0 Max—18 Mean—4.76
	Freeway	87.15	AC—87.15 PCC—0.0.0	Min—23 Max—50 Mean—31.56	4—60.74 6—16.78 8—9.64	Rural—41.48 Urban—45.67	Divided—87.15 Undivided—0.00	Min—0 Max—17 Mean—10.66
UTBWC	Two-Lane	19.42	AC—19.42 PCC—0.00	Min—22 Max—35 Mean—23.15	2—19.42	Rural—15.55 Urban—3.87	Divided—0.00 Undivided—19.42	Min—4 Max—9 Mean—5.99
	Multilane	4.67	AC—4.67 PCC—0.00	Min—24 Max—66 Mean—47.22	4—1.18 6—3.49	Rural—0.00 Urban—4.67	Divided—1.61 Undivided—3.06	Min—0 Max—10 Mean—0.63
	Freeway	44.36	AC—44.36 PCC—0.00	Min—22 Max—70 Mean—33.13	4 –33.00 6—6.72 8—4.65	Rural—17.82 Urban—26.54	Divided—44.36 Undivided—0.00	Min—0 Max—15.5 Mean—11.96
UTBWC on PCC	Two-Lane	1.56	AC—0.00 PCC—1.56	Min—22 Max—22 Mean—22	2—1.56	Rural—0.00 Urban—1.56	Divided—0.00 Undivided—1.56	Min—4 Max—4.5 Mean—4.21
	Freeway	24.29	AC—0.00 PCC—24.29	Min—24 Max—70 Mean—36.69	4—15.54 6—5.65 8—3.10	Rural—14.50 Urban—9.79	Divided—24.29 Undivided—0.00	Min—5 Max—14 Mean—11.53

Avgshldwid = Average of left and right shoulder width
AC = Asphalt
PCC = Portland cement concrete
Max = Maximum
Min = Minimum
OGFC = Open graded friction course
HMA = Hot mix asphalt
UTBWC = Ultrathin bonded wearing course

Table 11. Summary statistics for North Carolina treatment site AADT and crashes.

ELCSI Treatment Type	Site Type		AADT Before	AADT After	Years Before	Years After	totrateb	totratea	injrateb	injratea	rorrateb	rorratea	wetrateb	wetratea	wetrorrateb	wetrorratea
Chip Seal	Multilane	Min	10,995	11,500	6.00	3.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Chip Seal	Multilane	Max	35,173	33,333	7.00	4.00	127.41	125.00	46.33	41.67	3.57	9.26	19.31	18.02	0.00	9.26
Chip Seal	Multilane	Mean	26,689	25,797	6.93	3.07	20.41	32.02	6.91	10.18	0.54	0.81	3.20	4.31	0.00	0.66
Chip Seal	Two-Lane	Min	500	500	2.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Chip Seal	Two-Lane	Max	24,368	32,000	8.00	8.00	41.85	100.00	31.25	50.00	31.25	7.58	17.54	22.73	9.62	2.40
Chip Seal	Two-Lane	Mean	1,980	1,947	5.74	4.26	0.83	0.97	0.41	0.40	0.10	0.04	0.17	0.15	0.02	0.00
Diamond Grinding on PCC	Freeway	Min	31,889	33,000	9.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Diamond Grinding on PCC	Freeway	Max	53,889	74,000	9.00	1.00	411.11	100.00	77.78	19.23	11.11	19.23	55.56	19.23	8.55	19.23
Diamond Grinding on PCC	Freeway	Mean	42,701	44,581	9.00	1.00	17.19	9.17	4.31	1.79	0.63	0.56	2.89	1.35	0.27	0.47
Microsurfacing	Freeway	Min	20,206	23,676	7.00	2.00	1.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Microsurfacing	Freeway	Max	30,314	32,000	8.00	3.00	95.24	15.15	12.99	6.33	10.42	4.44	10.42	15.15	3.00	0.00
Microsurfacing	Freeway	Mean	26,779	27,168	7.40	2.60	21.71	5.78	3.04	2.00	2.91	0.44	2.88	2.05	0.32	0.00
Microsurfacing	Multilane	Min	4,242	4,500	8.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Microsurfacing	Multilane	Max	8,032	8,200	8.00	2.00	1.48	1.69	0.62	0.93	0.00	0.00	0.45	0.74	0.00	0.00
Microsurfacing	Multilane	Mean	6,708	6,967	8.00	2.00	0.76	0.60	0.20	0.28	0.00	0.00	0.23	0.12	0.00	0.00
Microsurfacing	Two-Lane	Min	628	620	7.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Microsurfacing	Two-Lane	Max	9,539	12,667	8.00	3.00	8.24	250.00	4.46	10.10	4.76	3.70	6.49	5.56	2.86	3.70
Microsurfacing	Two-Lane	Mean	4,912	4,751	7.30	2.70	1.09	3.18	0.53	0.44	0.20	0.05	0.27	0.14	0.06	0.04
OGFC	Freeway	Min	17,563	17,000	2.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

ELCSI Treatment Type	Site Type		AADT Before	AADT After	Years Before	Years After	totrateb	totratea	injrateb	injratea	rorrateb	rorratea	wetrateb	wetratea	wetrorrateb	wetrorratea
OGFC	Freeway	Max	158,656	160,333	8.00	8.00	465.61	345.68	116.40	98.77	25.97	30.30	125.00	66.67	13.51	30.30
OGFC	Freeway	Mean	66,006	69,228	5.95	4.05	39.74	40.91	12.16	10.34	2.21	1.20	9.97	7.29	1.03	0.79
OGFC	Multilane	Min	14,961	13,313	2.00	3.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OGFC	Multilane	Max	31,371	29,000	7.00	8.00	7.94	11.11	4.76	3.79	0.00	0.28	1.13	0.00	0.00	0.00
OGFC	Multilane	Mean	17,696	16,094	2.83	7.17	1.70	3.32	0.98	1.14	0.00	0.05	0.19	0.00	0.00	0.00
Slurry Seal	Two-Lane	Min	1,396	1,500	8.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Slurry Seal	Two-Lane	Max	3,771	3,400	8.00	2.00	9.62	12.50	9.62	0.89	0.00	0.00	0.27	0.00	0.00	0.00
Slurry Seal	Two-Lane	Mean	2,370	2,536	8.00	2.00	1.04	0.81	0.82	0.08	0.00	0.00	0.01	0.00	0.00	0.00
Thin HMA	Freeway	Min	6,270	6,200	2.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thin HMA	Freeway	Max	117,500	124,500	8.00	8.00	1083.33	958.33	333.33	208.33	100.00	68.63	421.88	187.50	50.00	41.67
Thin HMA	Freeway	Mean	52,143	55,330	5.44	4.56	27.75	29.25	9.09	8.19	2.56	2.80	6.56	7.12	0.85	0.86
Thin HMA	Multilane	Min	984	2,200	2.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thin HMA	Multilane	Max	61,962	63,000	8.00	8.00	1657.14	1500.00	557.14	333.33	333.33	74.07	328.57	333.33	14.29	40.00
Thin HMA	Multilane	Mean	19,323	19,588	5.04	4.96	18.15	20.70	6.26	6.03	0.92	0.96	3.20	3.37	0.15	0.29
Thin HMA	Two-Lane	Min	500	520	2.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thin HMA	Two-Lane	Max	27,767	31,354	8.00	8.00	500.00	388.89	100.00	125.00	41.67	83.33	66.67	100.00	8.33	41.67
Thin HMA	Two-Lane	Mean	4,927	5,058	5.14	4.86	2.25	3.03	0.90	1.08	0.15	0.22	0.42	0.53	0.03	0.04
UTBWC	Freeway	Min	10,325	11,000	2.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
UTBWC	Freeway	Max	153,167	162,000	8.00	8.00	1033.33	2150.00	333.33	400.00	83.33	100.00	150.00	400.00	17.54	100.00
UTBWC	Freeway	Mean	69,054	74,410	6.65	3.35	43.51	63.15	13.13	13.06	2.46	3.53	7.70	13.53	0.84	1.85
UTBWC	Multilane	Min	4,932	12,000	4.00	3.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
UTBWC	Multilane	Max	41,833	51,667	7.00	6.00	155.88	94.55	61.76	35.26	10.00	7.49	26.47	22.99	1.61	2.58
UTBWC	Multilane	Mean	22,717	23,799	6.16	3.84	38.07	25.72	14.94	9.72	1.63	0.66	5.51	3.96	0.14	0.10
UTBWC	Two-Lane	Min	2,704	2,000	6.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

ELCSI Treatment Type	Site Type		AADT Before	AADT After	Years Before	Years After	totrateb	totratea	injrateb	injratea	rorrateb	rorratea	wetrateb	wetratea	wetrorrateb	wetrorratea
UTBWC	Two-Lane	Max	11,216	7,873	8.00	4.00	47.62	142.86	23.81	71.43	1.85	1.23	23.81	7.25	0.54	0.00
UTBWC	Two-Lane	Mean	5,730	4,536	7.05	2.95	3.10	3.47	1.80	1.80	0.06	0.02	0.75	0.39	0.01	0.00
UTBWC on PCC	Freeway	Min	22,625	23,000	8.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
UTBWC on PCC	Freeway	Max	107,250	113,000	9.00	2.00	701.09	2150.00	138.59	400.00	25.00	100.00	111.41	400.00	12.50	100.00
UTBWC on PCC	Freeway	Mean	66,031	67,988	8.27	1.73	37.67	72.15	9.19	12.58	2.87	5.54	6.92	12.11	1.09	2.60
UTBWC on PCC	Two-Lane	Min	6,420	5,325	6.00	4.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
UTBWC on PCC	Two-Lane	Max	6,938	8,000	6.00	4.00	5.85	41.67	2.92	41.67	0.00	0.00	2.78	0.54	0.00	0.00
UTBWC on PCC	Two-Lane	Mean	6,530	6,582	6.00	4.00	1.19	4.08	0.31	3.63	0.00	0.00	0.28	0.04	0.00	0.00

ELCSI = Evaluation of Low-Cost Safety Improvements
AADT = Average annual daily traffic
totrate = total crash rate per mi-year
injrate = injury crash rate per mi-year
wetrate = wet-road crash rate per mi-year;
rorrate = ROR crash rate per mi-year
wetrorrate = wet-road ROR crash rate per mi-year)
totrateb = total crash rate per mi-yr in before period
totratea = total crash rate per mi-yr in after period
injrate, wetrate, rorrate, wetrorrate = injury, wet-road, ROR, and wet-road ROR crash rates per mi-year, respectively
MAX = maximum
MIN = minimum
PCC = Portland cement concrete
OGFC = Open graded friction course
HMA = Hot mix asphalt
UTBWC = Ultrathin bonded wearing course

Table 12. Summary statistics for North Carolina reference sites.

Site Type	Total Length (mi)	Pavement Type (mi)	Surface Width (ft)	No. of Lanes (mi)	Area Type (mi)	Divided/ Undivided (mi)	Avgshldwid (ft)	AADT	Years	totrate	injrate	rorrate	wetrate	wetrorrate
Two-Lane	3,773.27	AC—3,764.57 PCC—8.70	Min—12 Max—131 Min—24.48	2—3,773.27	Rural—2,909.00 Urban—864.26	Divided—0.00 Undivided—3,773.27	Min—0 Max—38.5 Min—5.53	508 58,013 5,564	11 11 11	1.56	0.65	0.11	0.30	0.03
Multilane	384.04	AC—382.98 PCC –1.06	Min—12 Max—125 Min—.35	3—8.44 4—354.03 6—6.80 8—14.65 12—0.12	Rural—137.79 Urban—246.25	Divided—259.57 Undivided—124.47	Min—0 Max—30 Min—3.17	974 58,013 14,717	11 11 11	9.85	3.22	0.36	1.71	0.08
Freeway	6.80	AC—5.16 PCC—1.64	Min—24 Max—120 Min—53.14	2—0.46 4—1.97 6—0.07 8—3.92 16—0.38	Rural—4.00 Urban—2.80	Divided—6.80 Undivided—0.00	Min—0 Max—21.5 Min—8.39	2,713 105,400 38,706	11 11 11	11.71	3.62	1.10	2.77	0.49

Avgshldwid = Average of left and right shoulder width
AADT = Average annual daily traffic
totrate = total crash rate per mi-year
injrate = injury crash rate per mi-year
wetrate = wet-road crash rate per mi-year;
rorrate = ROR crash rate per mi-year
wetrorrate = wet-road ROR crash rate per mi-year)
AC = Asphalt concrete
PCC = Portland cement concrete
Max = maximum
Min = minimum

California

Data for California were provided by the California Department of Transportation (Caltrans) and HSIS. The data provided by Caltrans included a list of potential treatment sites based on pavement maintenance and preservation projects from 2004 through 2007. The data provided by HSIS included geometric, traffic, and crash data. The data are linked together using the District Number, County Number, Route Number, and milepost variables.

Geometric Data

Geometric data were obtained from HSIS and included the following variables:

- Number of lanes.
- Median type.
- Median width.
- Access control.
- Terrain.
- Design speed.
- Rural versus urban environment.
- Surface type.
- Shoulder width.
- Paved width.
- Surface width.
- Lane width.
- Divided versus undivided.
- Roadway class.

Traffic Data

Traffic data in the form of AADT were obtained from HSIS from 2000 to 2009.

Crash Data

The crash data were provided by HSIS for 2000 to 2009. The compiled crash data contain many variables related to the location, time, and characteristics of each crash. The following notes relate to the exclusion or inclusion of crash data and definition of crash types:

- Exclude intersection-related mainline crashes (if int_rmp = “ramp intersection”, “mid-ramp”, “ramp entry”, “ramp area/intersection street”, “in intersection”, or “outside intersection (non-state route) within 250 ft.”).

- Excluded crashes where veh_invl = “animal”.

- Excluded crashes where rdsurf = “snowy, icy”.

- Injury crashes defined as those where severity = fatal, A class, B class, or C class injury.

- ROR crashes defined as those where miscact1 for any involved vehicle = “ran-off-road”.

- Wet crashes defined as those where rdsurf=“wet”.

Construction Data

Construction history data were provided by Caltrans for 2000 to 2009 as a statewide list of capital improvement projects. This list includes resurfacing and other projects to verify that no other construction had been completed at the treatment site locations.

Treatment Sites

Sites on the initial list of treatment sites eligible for the study were removed if they underwent other significant construction during the study period. Other sites were moved when the roadway was a divided road but the treatment was only applied in one direction. In an attempt to eliminate any re-mileposted locations, those segments for which the post mile prefix variable “psmilprf” changed during the study period were removed. The “psmilprf” variable indicates that a segment has been reposted, realigned, or overlaps with another segment.

Reference Sites

Reference sites were identified by first identifying road segments in the same district and with the same route number as the treated sites. Then the various geometric and traffic variables were compared to ensure that the range of values for these variables were consistent. The construction data were linked to these data, and any segments that were resurfaced or had other construction works between 2000 and 2009 were removed. Similar to the treated sites, potential reference sites were excluded if the post mile prefix variable “psmilprf” changed during the study period.

Table 13 through table 15 provide summary statistics for the treatment and reference site data in California.

Table 13. Summary statistics for California treatment site geometry.

Treatment	Site Type	Total Length (mi)	Pavement Type (mi)	Surface Width (ft)	No. of Lanes (mi)	Area Type (mi)	Divided/Undivided (mi)	Avgshldwid (ft)
Chip Seal	Two-Lane	863.15	AC—863.15 PCC –0.00	Min—12 Max—50 Mean—23.91	2—863.15	Rural—849.05 Urban—14.10	Divided—11.16 Undivided—851.99	Min—0 Max—32 Mean—4.83
	Multilane	70.33	AC—70.33 PCC—0.00	Min—12 Max—60 Mean—30.17	3—10.92 4—59.29 5—0.12	Rural—67.45 Urban—2.88	Divided—55.28 Undivided—15.05	Min—0 Max—12 Mean—5.93
	Freeway	14.77	AC—14.77 PCC—0.00	Min—24 Max—39 Mean—26.22	4—14.77	Rural—12.86 Urban—1.91	Divided—14.77 Undivided—0.00	Min—24 Max—39 Mean—26.22
Diamond Grinding	Two-Lane	0.64	AC—0.00 PCC—0.64	Min—24 Max—26 Mean—25	2—0.64	Rural—0.00 Urban—0.64	Divided—0.12 Undivided—0.52	Min—0 Max—10 Mean—6
	Multilane	8.07	AC—0.00 PCC—8.07	Min—20 Max—36 Mean—26.15	4—7.01 6—1.06	Rural—6.15 Urban—1.92	Divided—8.07 Undivided—0.00	Min—4 Max—10 Mean—.4
	Freeway	76.26	AC—0.00 PCC—76.26	Min—24 Max—84 Mean—46.03	4—4.54 5—0.34 6—28.44 >6—42.94	Rural—12.68 Urban—63.58	Divided—76.26 Undivided—0.00	Min—0 Max—14 Mean—7.68
Grooved	Freeway	5.00	AC—0.00 PCC—5.00	Min—24 Max—24 Mean—24	4—5.00	Rural—5.00 Urban—0.00	Divided—5.00 Undivided—0.00	Min—7 Max—7.5 Mean—7.46
Microsurfacing	Two-Lane	45.58	AC—45.58 PCC—0.00	Min—12 Max—42 Mean—24.47	2—45.58	Rural—44.23 Urban—1.35	Divided—0.90 Undivided—44.68	Min—0 Max—8 Mean—3.69
	Multilane	23.45	AC—23.45 PCC—0.00	Min—12 Max—48 Mean—26.20	3—0.45 4—22.53 5—0.33 6—0.15	Rural—15.94 Urban—7.52	Divided—23.00 Undivided—0.45	Min—0 Max—8 Mean—5.90
	Freeway	3.27	AC—3.27 PCC—0.00	Min—24 Max—48 28.47	4—3.27	Rural—1.06 Urban—2.21	Divided—3.27 Undivided—0.00	Min—0 Max—6.5 Mean—5.2
OGFC	Two-Lane	232.00	AC—232.00 PCC—0.00	Min—12 Max—40 Mean—23.33	2—232.00	Rural—208.65 Urban—23.35	Divided—7.32 Undivided—224.68	Min—0 Max—14 Mean—5.65

Treatment	Site Type	Total Length (mi)	Pavement Type (mi)	Surface Width (ft)	No. of Lanes (mi)	Area Type (mi)	Divided/Undivided (mi)	Avgshldwid (ft)
	Multilane	59.66	AC—59.66 PCC—0.00	Min—12 Max—60 Mean—28.30	3—1.75 4—54.79 5—2.57 6—0.56	Rural—16.60 Urban—43.07	Divided—51.81 Undivided—7.85	Min—0 Max—20 Mean—5.40
	Freeway	124.37	AC—112.23 PCC –12.14	Min—20 Max—72 Mean—35.72	2—1.36 3—0.10 4—85.83 5—2.10 6—7.63 >6—15.21	Rural—59.69 Urban—52.54	Divided—124.37 Undivided—0.00	Min—0 Max—15 Mean—7.23
Slurry Seal	Two-Lane	100.24	AC—100.24 PCC—0.00	Min—12 Max—56 Mean—24.35	2 - 100.24	Rural—93.70 Urban—6.54	Divided—0.11 Undivided—100.13	Min—0 Max—12 Mean—6.15
	Multilane	15.45	AC—15.45 PCC—0.00	Min—12 Max—64 Mean—34.48	3—3.25 4—12.20	Rural—9.17 Urban—6.29	Divided—8.56 Undivided—6.90	Min—0 Max—11 Mean—6.11
	Freeway	18.56	AC—18.56 PCC—0.00	Min—24 Max—39 Mean—25.01	2—0.20 4—17.99 6—0.37	Rural—12.00 Urban—6.56	Divided—18.56 Undivided—0.00	Min—7 Max—9 Mean—8.57
Thin HMA	Two-Lane	347.63	AC—347.63 PCC—0.00	Min—11 Max—84 Mean—23.79	2—347.63	Rural—321.85 Urban—25.78	Divided—8.38 Undivided—339.25	Min—0 Max—22.5 Mean—5.02
	Multilane	71.87	AC—71.87 PCC—0.00	Min—12 Max—64 Mean—30.52	3—14.29 4—45.29 5—1.02 6—8.31 >6—2.96	Rural—29.80 Urban—42.07	Divided—50.98 Undivided—20.89	Min—0 Max—12 Mean—4.72
	Freeway	164.06	AC—161.25 PCC—2.81	Min—24 Max—105 Mean—45.12	3—0.51 4—75.78 5—25.18 6—18.80 >6—43.79	Rural—83.01 Urban—81.05	Divided—164.06 Undivided—0.00	Min—0 Max—15 Mean—7.43

Treatment	Site Type	Total Length (mi)	Pavement Type (mi)	Surface Width (ft)	No. of Lanes (mi)	Area Type (mi)	Divided/Undivided (mi)	Avgshldwid (ft)
UTBWC	2 Lane	10.31	AC—10.31 PCC—0.00	Min—22 Max—24 Mean—23.78	2—10.31	Rural—6.29 Urban—4.03	Divided—0.00 Undivided—10.31	Min—4 Max—8 Mean—5.72
	Multilane	16.37	AC—16.37 PCC—0.00	Min—12 Max—60 Mean—27.31	3—2.17 4—13.24 6—0.96	Rural—2.66 Urban—13.71	Divided—13.86 Undivided—2.51	Min—0 Max—8 Mean—5.40
	Freeway	30.37	AC—30.37 PCC—0.00	Min—20 Max—70 Mean—29.19	2—0.74 4—24.07 5—1.98 6—2.35 >6—1.23	Rural—22.22 Urban—8.15	Divided—30.37 Undivided—0.00	Min—0 Max—13 Mean—7.03

Avgshldwid = Average of left and right shoulder width
AC = Asphalt
PCC = Portland cement concrete
Max = Maximum
Min = Minimum
OGFC = Open graded friction course
HMA = Hot mix asphalt
UTBWC = Ultrathin bonded wearing course

Table 14. Summary statistics for California treatment site AADT and crashes.

ELCSI Treatment Type	Site Type		AADT Before	AADT After	Years Before	Years After	totrateb	totratea	injrateb	injratea	rorrateb	rorratea	wetrateb	wetratea	wetrorrateb	wetrorratea
Chip Seal	Freeway	Min	12,743	12,800	5.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Chip Seal	Freeway	Max	33,000	35,750	7.00	4.00	47.62	8.06	47.62	3.02	1.88	1.16	2.15	0.79	0.78	0.00
Chip Seal	Freeway	Mean	20,703	22,068	6.56	2.44	5.26	1.49	2.96	0.38	0.23	0.20	0.18	0.03	0.04	0.00
Chip Seal	Multilane	Min	1,280	1,175	4.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Chip Seal	Multilane	Max	22,600	25,075	7.00	5.00	31.61	39.47	20.83	9.62	20.83	39.47	6.67	8.62	2.19	0.93
Chip Seal	Multilane	Mean	7,357	7,711	4.73	4.27	2.03	1.97	0.75	0.64	0.58	0.51	0.21	0.14	0.03	0.01
Chip Seal	Two-Lane	Min	170	190	4.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Chip Seal	Two-Lane	Max	24,792	29,157	7.00	5.00	100.00	250.00	50.00	250.00	50.00	33.33	7.58	12.03	3.79	5.43
Chip Seal	Two-Lane	Mean	3,424	3,648	5.35	3.65	1.34	1.14	0.56	0.61	0.40	0.27	0.12	0.09	0.05	0.03
Diamond Grinding on PCC	Freeway	Min	14,283	12,800	4.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Diamond Grinding on PCC	Freeway	Max	278,200	273,000	7.00	5.00	530.36	298.70	169.64	118.42	45.45	20.00	83.33	51.72	45.45	8.70
Diamond Grinding on PCC	Freeway	Mean	138,133	147,383	4.86	4.14	45.33	42.30	15.06	14.16	1.67	0.67	4.24	3.23	0.32	0.10
Diamond Grinding on PCC	Multilane	Min	11,641	12,500	5.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Diamond Grinding on PCC	Multilane	Max	63,400	66,500	7.00	4.00	29.65	28.57	10.78	8.06	8.04	14.29	5.39	3.73	2.70	0.60
Diamond Grinding on PCC	Multilane	Mean	20,481	22,827	6.15	2.85	4.40	4.38	1.94	1.53	0.76	0.74	0.35	0.47	0.12	0.02
Diamond Grinding on PCC	Two-Lane	Min	38,751	48,000	7.00	2.00	0.00	2.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Diamond Grinding on PCC	Two-Lane	Max	39,303	48,000	7.00	2.00	4.39	7.81	1.88	4.17	0.31	0.00	1.25	4.17	0.00	0.00
Diamond Grinding on PCC	Two-Lane	Mean	39,081	48,000	7.00	2.00	1.46	4.72	0.63	1.39	0.10	0.00	0.42	1.75	0.00	0.00

ELCSI Treatment Type	Site Type		AADT Before	AADT After	Years Before	Years After	totrateb	totratea	injrateb	injratea	rorrateb	rorratea	wetrateb	wetratea	wetrorrateb	wetrorratea
Grooved on PCC	Freeway	Min	27,500	28,333	5.00	4.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Grooved on PCC	Freeway	Max	29,000	28,500	5.00	4.00	46.15	23.94	18.46	9.31	3.19	5.32	6.15	5.32	0.97	1.94
Grooved on PCC	Freeway	Mean	27,875	28,458	5.00	4.00	13.44	5.72	3.96	1.86	1.56	1.06	1.21	1.48	0.29	0.34
Microsurfacing	Freeway	Min	17,117	18,900	7.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Microsurfacing	Freeway	Max	24,588	28,300	7.00	2.00	11.90	23.81	3.23	2.62	2.76	2.65	11.90	23.81	0.00	0.00
Microsurfacing	Freeway	Mean	18,527	20,862	7.00	2.00	3.50	4.04	0.92	0.50	0.74	0.30	0.84	1.59	0.00	0.00
Microsurfacing	Multilane	Min	4,500	3,825	4.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Microsurfacing	Multilane	Max	48,838	51,500	7.00	5.00	46.78	46.78	32.16	40.00	9.43	2.88	5.56	7.89	4.72	0.96
Microsurfacing	Multilane	Mean	23,114	25,163	5.08	3.92	5.27	4.49	3.37	2.68	0.45	0.26	0.52	0.27	0.12	0.03
Microsurfacing	Two-Lane	Min	2,880	2,425	5.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Microsurfacing	Two-Lane	Max	37,452	40,173	7.00	4.00	41.67	77.78	41.67	66.67	13.89	16.67	8.33	14.29	8.33	1.15
Microsurfacing	Two-Lane	Mean	7,455	8,164	5.97	3.03	3.61	3.87	2.21	2.51	1.03	1.03	0.28	0.39	0.17	0.03
OGFC	Freeway	Min	13,620	13,525	4.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OGFC	Freeway	Max	191,750	217,000	7.00	5.00	333.33	500.00	142.86	166.67	28.57	41.67	46.61	166.67	8.16	6.06
OGFC	Freeway	Mean	70,918	80,723	5.80	3.20	18.38	19.31	6.48	6.24	2.24	1.28	1.97	2.29	0.41	0.11
OGFC	Multilane	Min	2,420	2,338	4.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OGFC	Multilane	Max	52,800	63,500	7.00	5.00	100.00	102.27	50.00	37.04	13.89	7.14	50.00	36.14	13.89	5.95
OGFC	Multilane	Mean	21,150	21,912	4.95	4.05	8.23	8.01	3.01	2.78	0.66	0.39	1.26	1.08	0.16	0.06
OGFC	Two-Lane	Min	324	308	4.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OGFC	Two-Lane	Max	37,122	40,870	7.00	5.00	58.27	119.05	25.00	45.45	25.00	11.73	38.46	19.16	18.52	3.83
OGFC	Two-Lane	Mean	8,261	8,756	5.44	3.56	3.43	3.65	1.24	1.43	0.72	0.50	0.68	0.35	0.16	0.08
OGFC on PCC	Freeway	Min	82,500	79,333	5.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OGFC on PCC	Freeway	Max	234,429	228,000	7.00	4.00	276.69	400.00	82.14	300.00	50.00	9.62	60.71	300.00	2.74	9.62
OGFC on PCC	Freeway	Mean	165,748	165,411	5.78	3.23	57.23	51.96	20.27	20.65	2.47	0.65	7.39	10.72	0.35	0.24
Slurry Seal	Freeway	Min	66,75	6,990	4.00	5.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

ELCSI Treatment Type	Site Type		AADT Before	AADT After	Years Before	Years After	totrateb	totratea	injrateb	injratea	rorrateb	rorratea	wetrateb	wetratea	wetrorrateb	wetrorratea
Slurry Seal	Freeway	Max	87,750	71,200	4.00	5.00	31.25	28.57	31.25	25.00	31.25	25.00	4.17	25.00	1.85	25.00
Slurry Seal	Freeway	Mean	24,661	26,202	4.00	5.00	2.43	3.60	1.36	1.14	1.05	0.97	0.27	0.53	0.10	0.43
Slurry Seal	Multilane	Min	2,156	2,650	4.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Slurry Seal	Multilane	Max	19,650	27,013	7.00	5.00	58.59	50.00	25.00	24.59	3.38	1.99	7.81	8.20	0.59	1.69
Slurry Seal	Multilane	Mean	11,682	12,952	5.03	3.97	5.71	7.16	2.09	2.28	0.23	0.10	0.48	0.32	0.01	0.05
Slurry Seal	Two-Lane	Min	321	324	4.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Slurry Seal	Two-Lane	Max	27,000	32,067	7.00	5.00	200.00	100.00	100.00	35.29	100.00	5.00	14.71	50.00	1.06	5.00
Slurry Seal	Two-Lane	Mean	7,772	8,100	5.29	3.71	4.73	3.64	1.96	1.24	0.85	0.21	0.25	0.44	0.03	0.04
Thin HMA	Freeway	Min	11,640	13,175	4.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thin HMA	Freeway	Max	322,000	332,000	7.00	5.00	600.00	642.86	266.67	200.00	45.45	100.00	95.24	83.33	18.18	6.67
Thin HMA	Freeway	Mean	130,126	135,859	5.29	3.71	44.76	42.16	11.66	12.27	0.83	0.67	3.24	2.21	0.13	0.05
Thin HMA	Multilane	Min	3,075	3,122	4.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thin HMA	Multilane	Max	96,333	120,667	7.00	5.00	500.00	457.14	125.00	228.57	7.94	13.33	35.71	42.42	3.33	5.46
Thin HMA	Multilane	Mean	31,308	33,006	5.36	3.64	18.06	19.08	6.68	7.75	0.52	0.44	1.34	1.28	0.07	0.04
Thin HMA	Two-Lane	Min	88	190	4.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thin HMA	Two-Lane	Max	48,943	48,875	7.00	5.00	159.09	78.95	41.67	55.56	8.57	14.71	41.67	20.00	2.16	8.33
Thin HMA	Two-Lane	Mean	7,142	7,774	5.27	3.73	3.76	3.82	1.48	1.52	0.43	0.58	0.38	0.35	0.04	0.08
Thin HMA on PCC	Freeway	Min	14,538	15,180	5.00	4.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thin HMA on PCC	Freeway	Max	140,250	147,600	5.00	4.00	97.78	83.33	35.56	35.71	9.37	4.55	20.00	16.67	3.13	1.28
Thin HMA on PCC	Freeway	Mean	108,858	114,462	5.00	4.00	31.63	27.75	10.00	9.17	2.58	0.66	5.79	2.90	0.45	0.15

ELCSI Treatment Type	Site Type		AADT Before	AADT After	Years Before	Years After	totrateb	totratea	injrateb	injratea	rorrateb	rorratea	wetrateb	wetratea	wetrorrateb	wetrorratea
UTBWC	Freeway	Min	7,600	6,725	5.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
UTBWC	Freeway	Max	137,000	158,000	7.00	4.00	153.85	100.00	46.15	35.71	22.22	33.33	11.27	12.66	5.13	2.38
UTBWC	Freeway	Mean	45,655	51,350	5.59	3.41	13.00	12.63	3.90	4.04	1.79	1.52	1.54	0.86	0.33	0.10
UTBWC	Multilane	Min	5,820	6,107	5.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
UTBWC	Multilane	Max	51,361	55,750	7.00	4.00	200.00	250.00	83.33	62.50	5.16	20.83	66.67	62.50	0.76	0.81
UTBWC	Multilane	Mean	31,378	35,065	5.76	3.24	23.38	18.53	8.77	6.36	0.54	0.54	2.54	2.09	0.03	0.02
UTBWC	Two-Lane	Min	5,820	6,112	5.00	3.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
UTBWC	Two-Lane	Max	29,444	30,379	6.00	4.00	15.96	25.86	9.72	6.94	3.57	4.46	3.98	4.46	0.48	4.46
UTBWC	Two-Lane	Mean	13,342	13,361	5.44	3.56	4.89	5.51	1.72	2.17	0.72	0.89	0.39	0.67	0.04	0.17

ELCSI = Evaluation of Low-Cost Safety Improvements
AADT = Average annual daily traffic
totrateb = total crash rate per mi-yr in before period
totratea = total crash rate per mi-yr in after period
injrate = injury rate
wetrate = wet-road rate
rorrate = ROR rate
wetrorrate = wet-road ROR crash rates per mi-yr
MAX = maximum
MIN = minimum
PCC = Portland cement concrete
OGFC = Open graded friction course
HMA = Hot mix asphalt
UTBWC = Ultrathin bonded wearing course

Table 15. Summary statistics for California reference sites.

Site Type	Total Length (mi)	Pavement Type (mi)	Surface Width (ft)	No. of Lanes (mi)	Area Type (mi)	Divided/ Undivided (mi)	Avgshldwid (ft)	AADT	Years	totrate	injrate	rorrate	wetrate	wetrorrate
Two-Lane	4,733.98	AC— 4,683.23 PCC— 50.745	Min—7 Max—32 Mean—11.79	2—4,733.98	Rural— 4,480.36 Urban— 253.61	Divided— 74.80 Undivided— 4,659.18	Min—0 Max—26 Mean—4.90	107 57,800 5,768	10 10 10	1.50	0.70	0.44	0.19	0.07
Multilane	445.50	AC— 416.53 PCC— 28.97	Min—10 Max—22 Mean—12.09	3—115.61 4—272.74 5—5.38 6—51.19 > 6—0.58	Rural— 104.62 Urban— 338.98	Divided— 292.64 Undivided— 150.96	Min—0 Max—10 Mean—4.29	4,447 102,444 33,701	10 10 10	9.89	3.96	0.45	0.97	0.05
Freeway	1,311.31	AC— 740.20 PCC— 571.10	Min—8 Max—24 Mean—12.04	2—27.95 3—17.96 4—881.64 5—30.41 6—172.06 > 6—181.29	Rural— 854.19 Urban— 457.12	Divided— 1,311.31 Undivided— 0.00	Min—0 Max—22 Mean—7.52	1,995 326,778 75,518	10 10 10	12.69	4.33	1.11	1.41	0.16

Avgshldwid = Average of left and right shoulder width
AADT = Average annual daily traffic
totrateb = total crash rate per mi-yr in before period
totratea = total crash rate per mi-yr in after period
injrate = injury rate
wetrate = wet-road rate
rorrate = ROR rate
wetrorrate = wet-road ROR crash rates per mi-yr
AC = Asphalt concrete
PCC = Portland cement concrete
Min = Minimum
Max = Maximum

Minnesota

Data for Minnesota were provided by the Minnesota Department of Transportation (MnDOT) and HSIS. The data provided by MnDOT included a list of potential treatment sites and data on recent paving projects. The data provided by HSIS included geometric, traffic, and crash data. The data are linked together using the District Number, Route Number, and milepost variables.

Geometric Data

Geometric data were obtained from HSIS and included the following variables:

- Shoulder width.
- Shoulder type.
- Surface width.
- Surface type.
- Median width.
- Median type.
- Surface type.
- Surface width.
- Number of lanes.
- Lane width.
- Roadway class.
- Rural versus urban environment.

Pavement Data

MnDOT provided resurfacing information during the period 2000 to 2010.

Traffic Data

Traffic data in the form of AADT and commercial vehicle AADT were obtained from HSIS for 2000 to 2010.

Crash Data

The crash data were provided by HSIS for 2000 to 2010. The compiled crash data contain many variables related to the location, time, and characteristics of each crash. The following notes relate to the exclusion or inclusion of crash data and definition of crash types:

- Include only nonintersection-related mainline crashes (if loc_type = 0, 1, 8, 9, 10, 11, 25, 90, 99 (various non-intersection categories)).

- Excluded crashes where acctype = “collision with deer” or “collision with other animal”.

- Excluded crashes where rdsurf = “snow”, “slush”, “ice/packed snow”, or “snow/slush”.

- Injury crashes defined as those where severity = fatal, A class, B class, or C class injury.
- ROR crashes defined as those where accdigm = "ran off road left side" or "ran off road right side".
- Wet crashes defined as those where rdsurf="wet".

Construction Data

MnDOT used the highway pavement management system to verify construction history for the treatment sites and reference sites and ensure that no other pavement treatment had occurred at these locations during the study period.

Treatment Sites

The list of treatment sites was provided by MnDOT.

Reference Sites

Reference sites were identified by first identifying road segments in the same county and with the same route number as the treated sites. Then the various geometric and traffic variables were compared to ensure that the range of values for these variables were consistent. The pavement data were linked to these data, and any segments that were resurfaced or had other construction works between 2000 and 2010 were removed.

Table 16 through table 18 provide summary statistics for the treatment and reference site data in Minnesota.

Table 16. Summary statistics for Minnesota treatment site geometry.

Treatment	Site Type	Total Length (mi)	Pavement Type (mi)	Width (ft)	No. of Lanes (mi)	Area Type (mi)	Divided/Undivided (mi)	Avgshldwid (ft)
Chip Seal	Two-Lane	251.17	AC—251.17 PCC – 0.00	Min—12 Max—24 Mean—12.78	2—251.17	Rural—249.60 Urban—1.57	Divided—7.60 Undivided—243.56	Min—0 Max—12 Mean—7.47
	Multilane	22.81	AC—22.81 PCC—0.00	Min—12 Max—16 Mean—12.08	3—3.36 4—19.44	Rural—19.78 Urban—3.03	Divided—18.51 Undivided—4.3	Min—0 Max—10 Mean—5.54
Diamond Grinding	Freeway	7.99	AC—0.00 PCC—7.99	Min—12 Max—13 Mean—12.07	4—3.92 5—2.49 6—1.39 8 - 0.19	Rural—0.81 Urban—7.19	Divided—7.99 Undivided—0.00	Min—5 Max—10 Mean—6.93
Microsurfacing	Two-Lane	27.37	AC—27.37 PCC—0.00	Min—12 Max—12 Mean—12	2—27.37	Rural—27.02 Urban—0.35	Divided—0.00 Undivided—27.37	Min—0 Max—12 Mean—7.01
	Multilane	29.68	AC—29.68 PCC—0.00	Min—12 Mean—18 12.41	4—29.68	Rural—11.06 Urban—18.63	Divided—29.68 Undivided—0.00	Min—0 Max—10 Mean—6.14
Microsurfacing on PCC	Two-Lane	15.63	AC—0.00 PCC—15.63	Min—12 Max—12 Mean—12	2—15.63	Rural—14.49 Urban—1.14	Divided—0.00 Undivided—15.63	Min—8 Max—8 Mean—8
	Multilane	0.32	AC—0.00 PCC—0.32	Min—13 Max—13 Mean—13	4—0.32	Rural—0.00 Urban—0.32	Divided—0.32 Undivided—0.00	Min—6.5 Mean—6.5 Mean—6.5
	Freeway	21.40	AC—0.00 PCC—21.40	Min—22 Max—22 Mean—22	4—20.16 5—0.36 6—0.89	Rural—10.00 Urban—11.401	Divided—21.40 Undivided—0.00	Min—6.5 Max—11 Mean—7.30

Treatment	Site Type	Total Length (mi)	Pavement Type (mi)	Width (ft)	No. of Lanes (mi)	Area Type (mi)	Divided/Undivided (mi)	Avgshldwid (ft)
Thin HMA	Two-Lane	198.05	AC—133.12 Chip Seal—64.93	Min—12 Max—14 Mean—12.01	2—198.05	Rural—194.08 Urban—3.97	Divided—0.00 Undivided—198.05	Min—0 Max—12 Mean—7.23
	Multilane	5.64	AC—5.42 Chip Seal—0.23	Min—12 Max—13 Mean—12.33	4—5.64	Rural—3.66 Urban—1.99	Divided—5.64 Undivided—0.00	Min—6.5 Max—10 Mean—8.22

Avgshldwid = Average of left and right shoulder width
AC = Asphalt concrete
PCC = Portland cement concrete
Min = minimum
Max = maximum
HMA = Hot mix asphalt

Table 17. Summary statistics for Minnesota treatment site AADT and crashes.

ELCSI Treatment Type	Site Type		AADT Before	AADT After	Years Before	Years After	totrateb	totratea	injrateb	injratea	rorrateb	rorratea	wetrateb	wetratea	wetrorrateb	wetrorratea
Chip Seal	Multilane	Min	961	924	8.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Chip Seal	Multilane	Max	28,219	35,658	8.00	2.00	125.00	100.00	37.50	50.00	2.60	8.93	5.32	50.00	1.32	8.93
Chip Seal	Multilane	Mean	12,111	14,029	8.00	2.00	4.35	6.54	1.52	1.91	0.22	0.30	0.39	2.01	0.04	0.13
Chip Seal	Two-Lane	Min	314	317	5.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Chip Seal	Two-Lane	Max	10,141	12,282	8.00	2.00	6.67	17.44	4.41	6.41	1.98	5.38	4.17	5.49	1.26	5.38
Chip Seal	Two-Lane	Mean	3,088	3,248	7.96	2.00	0.29	0.26	0.14	0.11	0.09	0.11	0.04	0.04	0.01	0.02
Diamond Grinding on PCC	Freeway	Min	23,752	27,000	6.00	3.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Diamond Grinding on PCC	Freeway	Max	74,139	72,785	7.00	4.00	60.44	64.10	19.23	32.05	19.23	12.82	19.23	12.82	8.24	1.46
Diamond Grinding on PCC	Freeway	Mean	54,539	54,179	6.66	3.34	6.53	5.01	1.71	2.09	1.44	1.04	1.09	1.16	0.33	0.22
Microsurfacing	Multilane	Min	14,422	12,272	7.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Microsurfacing	Multilane	Max	51,122	55,853	8.00	3.00	55.00	60.61	17.86	41.67	5.68	11.90	10.42	20.00	1.81	11.90
Microsurfacing	Multilane	Mean	33,585	33,870	7.58	2.42	6.11	6.53	2.09	2.44	0.64	0.62	1.14	0.89	0.11	0.17
Microsurfacing	Two-Lane	Min	1,926	1,826	8.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Microsurfacing	Two-Lane	Max	6,258	6,190	8.00	2.00	2.84	33.33	2.00	5.49	2.84	33.33	2.00	0.00	1.00	0.00
Microsurfacing	Two-Lane	Mean	3,647	3,523	8.00	2.00	0.32	0.62	0.14	0.18	0.19	0.59	0.06	0.00	0.04	0.00
Microsurfacing on PCC	Freeway	Min	36,036	40,122	1.00	4.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Microsurfacing on PCC	Freeway	Max	76,350	84,331	6.00	6.00	18.52	58.64	4.85	12.35	4.85	9.26	3.24	13.89	1.62	1.19
Microsurfacing on PCC	Freeway	Mean	54,854	60,194	4.32	5.27	3.48	7.30	0.93	1.80	0.56	1.30	0.38	1.77	0.13	0.19
Microsurfacing on PCC	Multilane	Min	32,896	35,536	8.00	2.00	2.34	1.56	0.39	0.00	1.17	0.00	0.00	0.00	0.00	0.00

ELCSI Treatment Type	Site Type		AADT Before	AADT After	Years Before	Years After	totrateb	totratea	injrateb	injratea	rorrateb	rorratea	wetrateb	wetratea	wetrorrateb	wetrorratea
Microsurfacing on PCC	Multilane	Max	32,896	35,536	8.00	2.00	2.34	1.56	0.39	0.00	1.17	0.00	0.00	0.00	0.00	0.00
Microsurfacing on PCC	Multilane	Mean	32,896	35,536	8.00	2.00	2.34	1.56	0.39	0.00	1.17	0.00	0.00	0.00	0.00	0.00
Microsurfacing on PCC	Two-Lane	Min	2,684	2,775	4.00	6.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Microsurfacing on PCC	Two-Lane	Max	3,342	3,628	4.00	6.00	0.22	0.99	0.22	0.66	0.08	0.33	0.08	0.03	0.04	0.00
Microsurfacing on PCC	Two-Lane	Mean	2,964	3,038	4.00	6.00	0.06	0.25	0.04	0.16	0.02	0.12	0.01	0.00	0.01	0.00
Thin HMA	Multilane	Min	5,026	6,228	8.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thin HMA	Multilane	Max	8,489	6,853	8.00	2.00	11.54	9.09	9.62	7.69	5.77	0.53	0.53	0.53	0.26	0.53
Thin HMA	Multilane	Mean	6,249	6,601	8.00	2.00	2.16	2.30	1.28	1.01	0.88	0.15	0.08	0.06	0.03	0.06
Thin HMA	Two-Lane	Min	69	61	7.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thin HMA	Two-Lane	Max	6,119	6,630	8.00	3.00	3.57	5.05	3.57	1.05	3.57	3.66	3.57	0.64	3.57	0.17
Thin HMA	Two-Lane	Mean	1,684	1,724	7.63	2.37	0.17	0.12	0.06	0.03	0.06	0.05	0.02	0.00	0.02	0.00

ELCSI = Evaluation of Low-Cost Safety Improvements
AADT = Average annual daily traffic
totrateb = total crash rate per mi-yr in before period
totratea = total crash rate per mi-yr in after period
injrate = injury rate
wetrate = wet-road rate
rorrate = ROR rate
wetrorrate = wet-road ROR crash rates per mi-yr
MAX = maximum
MIN = minimum
PCC = Portland cement concrete
HMA = Hot mix asphalt

Table 18. Summary statistics for Minnesota reference sites.

Site Type	Total Length (mi)	Pavement Type (mi)	Surface Width (ft)	No. of Lanes (mi)	Area Type (mi)	Divided/ Undivided (mi)	Avgshldwid (ft)	AADT	Years	totrate	injrate	rorrate	wetrate	wetrorrate
Two-Lane	922.86	AC—868.79 PCC—54.07	Min—10 Max—24 Mean—12.39	2—922.86	Rural—906.21 Urban—16.65	Divided—0.00 Undivided—922.86	Min—0 Max—12 Mean—7.04	59 12,823 3,292	11 11 11	0.18	0.09	0.08	0.02	0.01
Multilane	188.73	AC—158.35 PC—30.38	Min—8 Max—18 Mean—12.08	3—3.82 4—181.95 5—1.82 6—0.85 > 6—0.28	Rural—114.99 Urban—73.74	Divided—183.15 Undivided—5.58	Min—0 Max—10 Mean—2.86	688 55,074 22,515	11 11 11	2.36	0.88	0.47	0.39	0.10
Freeway	81.52	AC—58.55 PCC—22.97	Min—11 Max—14 Mean—12.21	3—0.15 4—66.26 5—3.75 6—8.48 > 6—2.88	Rural—57.37 Urban—24.15	Divided—81.52 Undivided—0.00	Min—0 Max—10 Mean—4.56	17,597 104,188 49,061	11 11 11	2.59	0.85	0.89	0.48	0.19

Avgshldwid = Average of left and right shoulder width
AADT =Average annual daily traffic
totrateb = total crash rate per mi-yr in before period
totratea = total crash rate per mi-yr in after period
injrate = injury rate
wetrate = wet-road rate
rorrate = ROR rate
wetrorrate = wet-road ROR crash rates per mi-yr
AC = Asphalt concrete
PCC = Portland cement concrete

CHAPTER 5. ANALYSIS

ANALYSIS OBJECTIVES

As discussed, the objective of this analysis was to estimate the effect of various low-cost pavement treatments on crashes using treatments from several States. These treatments were installed primarily for pavement preservation and not necessarily for safety improvement. As presented in chapter 3, the following treatments were evaluated:

- Chip seal (single, double, and triple layer).
- Diamond grinding (concrete pavement only).
- Grooved concrete pavement.
- Microsurfacing (asphalt and concrete pavement).
- OGFC (asphalt and concrete pavement).
- Slurry seal (asphalt pavement).
- Thin HMA (asphalt and concrete pavement).
- UTBWC (asphalt and concrete pavement).

The basic objective of the crash data analysis was to estimate the change in target crashes. Only nonintersection, nonanimal related crashes and crashes not involving snow or ice were considered. Crash types examined included the following:

- Total.
- Injury.
- ROR.
- Wet-Road.
- Dry-Road.
- Wet-Road ROR.

Further questions of interest examined included the following:

- Do effects vary by level of traffic volumes?
- Do effects vary by underlying pavement type?
- Do effects vary by posted speed limit or by urban-rural environments?
- Do effects vary by the site-specific expected crash frequency prior to treatment?
- Do effects vary by State and road class?
- What is the overall effect, measured by the economic costs of crashes, by crash type and severity?

Meeting these objectives placed some special requirements on the data collection and analysis tasks, including the need to do the following:

- Select a large enough sample size to detect, with statistical significance, what may be small changes in safety for some crash types.

- Carefully select reference sites to properly account for changes in safety not due to the treatments, including regression-to-the-mean, traffic volume changes, and time trends.

- Properly account for traffic volume changes.

- Pool data from multiple jurisdictions to improve the reliability of the results and facilitate broader applicability of the research products.

As discussed in chapter 4, roadway, pavement data, traffic volume, and crash data were acquired for sites in Pennsylvania, Minnesota, North Carolina, and California to facilitate the analysis. The States also provided information related to the installation of the pavement improvement (i.e., location and date).

ANALYSIS METHODOLOGY

The general analysis methodology applied is the EB before–after approach. The methodology is well documented by Hauer.(43) The advantages of the EB method include the following:

- Properly accounting for regression-to-the-mean.

- Overcoming the difficulties of using crash rates in normalizing for volume differences between the before and after periods.

- Reducing the level of uncertainty in the estimates of safety effect.

- Providing a foundation for developing guidelines for estimating the likely safety consequences of contemplated installations.

- Properly accounting for differences in crash experience and reporting practice in amalgamating data and results from diverse jurisdictions.

The approach comprises three basic steps:

- Step 1: Predict what safety would have been in the "after" period had the status-quo been maintained.

- Step 2: Estimate what the actual safety was in the "after" period.

- Step 3: Compare the two.

The EB procedure requires the calibration of SPFs, as outlined in the next section, relating crashes of different types and severities to traffic flow and other relevant factors for each jurisdiction for locations without the treatment, with appropriate adjustments for temporal effects. This will enable the simultaneous accounting for temporal and possible regression-to-the-mean effects, as well as those related to changes in traffic volume.

DEVELOPMENT OF SAFETY PERFORMANCE FUNCTIONS

Fundamental to the EB approach is the use of the SPFs to represent the conditions before installation. Where sufficient data are available for a reference population of sites similar to those treated, it is desirable to calibrate these functions directly for the jurisdiction and analysis period of interest.

Data required for SPF development are: crash, traffic, and geometric data for a sample of reference sites that are similar to those for which the SPF would be applied. The data are required for each year of the analysis period (i.e., the period of before and after at the treatment sites).

The direct calibration of SPFs was accomplished with generalized linear modeling (GLM) using the R software package. This procedure allows the specification of a negative binomial error structure, which is now recognized as more appropriate for crash counts than the normal distribution that is assumed in conventional regression modeling. The GLM procedure also estimates the overdispersion parameter k of the negative binomial distribution that is used in the EB estimation. Crash counts at locations in the reference group are used as estimates of the dependent variable, which is the expected number of crashes per year by type and severity, while corresponding road characteristics and traffic data are used as estimates of the independent variables.

SPECIFICS OF THE EMPIRICAL BAYES BEFORE-AFTER EVALUATION

Overall Safety Effects

In the EB evaluation of the effect of a treatment, the change in safety for a given crash type at a treated site is given by the equation in figure 17:

$$\mathrm{B} - \mathrm{A}$$

Figure 17. Equation. Change in safety for a given crash type at a treated site.

Where:

B = expected number of crashes that would have occurred in the after period without the treatment
A = number of reported crashes in the after period.

Because of changes in safety that may result from changes in traffic volume, from regression-to-the-mean, and from trends in crash reporting and other factors, the count of crashes before a treatment by itself is not a good estimate of B—a reality that has now gained common acceptance.(43) Instead, B is estimated from an EB procedure in which a safety performance function is used to first estimate the number of crashes that would be expected in each year of the before period at locations with traffic volumes and other characteristics similar to a treatment site being analyzed.(43) The sum of these annual SPF estimates (P) is then combined with the count of crashes (x) in the before period at the treatment site to obtain an estimate of the expected number of crashes (m) before the treatment. This estimate of m is shown in figure 18:

$$\mathrm{m} = \mathrm{w(P)} + (1 - \mathrm{w})(\mathrm{x})$$

Figure 18. Equation. Estimate of the expected number of crashes before treatment.

The weight *w* is estimated using the equation in figure 19:

$$\mathrm{w} = 1/(1 + \mathrm{kP})$$

Figure 19. Equation. Estimate of weight.

Where:

k = overdispersion parameter of the negative binomial distribution that is assumed for the crash counts used in estimating the SPF. The value of *k* is estimated from the SPF calibration process with the use of a maximum likelihood procedure.

A factor is then applied to *m* from the equation in figure 18 to account for the length of the after period, differences in traffic volumes between the before and after periods, and other unknown differences between these two periods accounted for by using the yearly factors of the SPF. This factor is the sum of the annual SPF predictions for the after period divided by *P*, the sum of these predictions for the before period. The result, after applying this factor, is an estimate of *B*. The procedure also produces an estimate of the variance of *B*, the expected number of crashes that would have occurred in the after period without the treatment.

The estimate of B is then summed over all sites in a treatment group of interest (to obtain B_{sum}) and compared with the count of crashes during the after period in that group (A_{sum}). The variance of *B* is also summed over all sites in the group of interest.

The index of safety effectiveness (θ) is estimated using the equation in figure 20:

$$\theta = (\mathrm{A_{sum}}/\mathrm{B_{sum}})/\{1 + [\mathrm{Var}(\mathrm{B_{sum}})/\mathrm{B_{Sum}}^2]\}$$

Figure 20. Equation. Estimate of the index of safety effectiveness.

The standard deviation of θ is given by the equation in figure 21:

$$\mathrm{Stddev}(\theta) = [\theta^2\{[\mathrm{Var}(\mathrm{A_{sum}})/\mathrm{A_{sum}}^2] + [\mathrm{Var}(\mathrm{B_{sum}})/\mathrm{B_{sum}}^2]\} / [1 + \mathrm{Var}(\mathrm{B_{sum}})/\mathrm{B_{sum}}^2]^2]^{0.5}$$

Figure 21. Equation. Standard deviation of the estimated index of safety effectiveness.

The percent change in crashes is in fact $100(1-\theta)$; thus, a value of $\theta = 0.70$ with a standard deviation of 0.12 indicates a 30-percent reduction in crashes with a standard deviation of 12 percent.

Effects on Different Severity and Impact Types

The methodology is essentially the same as outlined earlier. The difference is that crashes of interest are used along with SPFs specific to these crash types.

Effects of Design, Traffic, Operational, and Safety Characteristics

Where samples were large enough, the study sought to isolate sites with certain levels of a given variable and to estimate the separate effects for each level by road class. In the case of continuous variables, such as traffic volume, aggregation was attempted over specified ranges of that variable, and regression models were estimated to relate the safety effect to the value of that variable. These include the effects of the following:

- Annual precipitation levels.
- Level of safety before installation measured as the expected crash frequency.
- Traffic volume levels.

Differential Effects Over Time

The EB procedure facilitated the estimation of differential effects over time for certain treatment types. This was important given the belief that the effects of some treatments deteriorate over time. A minor adjustment to the procedure allowed the investigation of effects for each year starting immediately after installation as opposed to calendar years. This refinement was necessary to examine the effects over time, for example at 1, 2, and 3 years after installation, to the extent that the small sample sizes facilitated this investigation.

SAFETY PERFORMANCE FUNCTIONS

This section presents the SPFs developed. The SPFs are used in the EB methodology to estimate the expected number of crashes in the after period without treatment.

GLM was used to estimate model coefficients and assumed a negative binomial error distribution, which is consistent with the state of research in developing these models. Alternative models were evaluated by comparing the magnitude and statistical significance of the variables included as well as the value of the overdispersion parameter, which in itself, is a reliable goodness-of-fit measure, with a smaller overdispersion parameter indicating a model that better captures the overdispersion in the data.

Separate SPFs were developed for each State and for different site and crash types. SPFs were not estimated for dry-road crashes because logically the EB estimates for these crashes could be derived as the difference between the estimates for total and wet-road crashes.

Pennsylvania

The model form for the Pennsylvania SPFs is shown in figure 22:

$$\text{Crashes/mile-year} = \exp(\ln(\alpha)+\beta 2\text{Urbrur}+\beta 3\text{Shldwid})(\text{AADT})^{\beta_1}$$

Figure 22. Equation. Model form for Pennsylvania SPFs.

Where:

AADT = Average Annual Daily Traffic
Urbrur = 1 if rural environment; 0 if urban
Shldwid = average shoulder width in ft

α, the βs, and the overdispersion parameter, k, are parameters estimated in the modeling process.

Table 19 provides the parameter estimates and standard errors.

Table 19. SPF parameter estimates and standard errors for Pennsylvania treatment sites.

Site Type	Crash Type	ln(α) (s.e.)	β1 (s.e.)	β2 (s.e.)	β3 (s.e.)	Overdispersion Parameter, k (s.e.)
Controlled Access	Total	-9.2972 (0.4158)	1.0147 (0.0391)	-0.3707 (0.0548)	-0.0865 (0.0094)	0.4626 (0.0261)
Uncontrolled Access		-6.4756 (0.0701)	0.8174 (0.0078)	-0.1116 (0.0157)	-0.0589 (0.0027)	0.5155 (0.0092)
Controlled Access	Injury	-9.4717 (0.4935)	0.9569 (0.0462)	-0.3968 (0.0650)	-0.0810 (0.0110)	0.4787 (0.0373)
Uncontrolled Access		-7.2450 (0.0841)	0.8252 (0.0094)	-0.0495 (0.0181)	-0.0465 (0.0031)	0.5024 (0.0120)
Controlled Access	ROR	-5.1206 (1.1354)	0.2664 (0.1068)	-0.2769 (0.1362)	n/a	1.3620 (0.2820)
Uncontrolled Access		-5.4010 (0.1325)	0.4927 (0.0150)	-0.3326 (0.0298)	-0.0831 (0.0055)	1.1056 (0.0377)
Controlled Access	Wet-Road	-9.0427 (0.7568)	0.8363 (0.0710)	-0.3389 (0.0981)	-0.0860 (0.0168)	1.0787 (0.0968)
Uncontrolled Access		-7.0113 (0.1265)	0.7174 (0.0142)	-0.1386 (0.0279)	-0.0753 (0.0049)	1.2829 (0.0323)
Controlled Access	Wet-Road ROR	Apply model for Wet-Road with a factor of 7 percent				
Uncontrolled Access		-6.1144 (0.2440)	0.4433 (0.0278)	-0.4028 (0.0549)	-0.1064 (0.0106)	3.7394 (0.1846)

s.e. = Standard error
ROR = Run-off road

North Carolina

The model form for the North Carolina SPFs is shown in figure 23:

$$\text{Crashes/mile-year} = \exp(\ln(\alpha)+\beta 2\text{Urbrur})(\text{AADT})^{\beta 1}$$

Figure 23. Equation. Model form for North Carolina SPFs.

Where:

AADT = Average Annual Daily Traffic
Urbrur = 0 if rural environment; 1 if urban

α, the βs, and the overdispersion parameter, k, are parameters estimated in the modeling process.

Table 20 provides the parameter estimates and standard errors.

Table 20. SPF parameter estimates and standard errors for North Carolina treatment sites.

Site Type	Crash Type	ln(α) (s.e.)	β1 (s.e.)	β2 (s.e.)	Overdispersion Parameter, k (s.e.)
Freeway	Total	-8.9291 (1.7994)	1.1483 (0.1749)	n/a	1.4036 (0.2603)
Two-Lane		-6.4036 (0.1230)	0.8662 (0.0136)	-0.4370 (0.0237)	0.8155 (0.0158)
Multilane Divided		-12.2644 (0.7668)	1.5219 (0.0779)	-0.8490 (0.0763)	1.3674 (0.0546)
Multilane Undivided		-10.4562 (0.8357)	1.3715 (0.0872)	-1.1596 (0.1126)	1.3972 (0.0711)
Freeway	Injury	-12.6732 (4.0381)	1.3625 (0.3622)	0.5611 (0.6506)	1.6429 (0.3745)
Two-Lane		-6.6692 (0.1344)	0.7780 (0.0149)	-0.2506 (0.0254)	0.6535 (0.0181)
Multilane Divided		-13.7169 (0.8460)	1.5502 (0.0857)	-0.5474 (0.0817)	1.1284 (0.0581)
Multilane Undivided		-12.4483 (0.9165)	1.4516 (0.0953)	-0.9979 (0.1283)	1.1527 (0.0776)
Freeway	ROR	-18.6447 (7.8055)	1.7776 (0.6959)	-0.5034 (1.1830)	3.1947 (1.2079)
Two-Lane		-6.1174 (0.2650)	0.5272 (0.0296)	-0.6736 (0.0496)	1.7266 (0.0828)
Multilane Divided		-11.7038 (1.3211)	1.1004 (0.1332)	-0.2530 (0.1276)	1.1807 (0.1455)
Multilane Undivided		-10.1531 (1.3697)	0.9828 (0.1421)	-0.6875 (0.1960)	1.0338 (0.1615)
Freeway	Wet-Road	-12.8639 (2.4304)	1.3526 (0.2293)	n/a	1.2069 (0.3233)
Two-Lane		-7.6283 (0.1773)	0.8035 (0.0196)	-0.3784 (0.0328)	0.8486 (0.0306)
Multilane Divided		-16.3897 (1.0357)	1.7516 (0.1047)	-0.6639 (0.0991)	1.3400 (0.0836)
Multilane Undivided		-14.7279 (1.1002)	1.6208 (0.1142)	-1.5177 (0.1696)	1.3161 (0.1053)
Freeway	Wet-Road ROR	Apply model for Wet-Road with a factor of 18 percent			
Two-Lane		Apply model for Wet-Road with a factor of 9 percent			
Multilane Divided		Apply model for Wet-Road with a factor of 5 percent			
Multilane Undivided		Apply model for Wet-Road with a factor of 4 percent			

s.e. = Standard error
ROR = Run-off road

California

The model form for the California SPFs is shown in figure 24:

$$\text{Crashes/mile-year} = \exp(\ln(\alpha)+\beta 2\text{Urbrur}+\beta 3\text{Surftype}+\beta 4\text{Medwid}+\beta 5\text{Avgshldwid}+\beta 6\text{Lanewid}+\beta 7\text{Terrain}+\beta 8\text{Divided})(\text{AADT})^{\beta_1}$$

Figure 24. Equation. Model form for California SPFs.

Where:

AADT = Average Annual Daily Traffic
Urbrur = 0 if rural environment; 1 if urban
Surftype = 1 if asphalt; 0 if concrete
Medwid = median width in ft
Avgshldwid = average of left and right shoulder width in ft
Lanewid = lane width in ft
Terrain = flat, rolling, or mountainous
Divided = 0 if undivided; 1 if divided

α, the βs, and the overdispersion parameter, k, are parameters estimated in the modeling process.

Table 21 provides the parameter estimates and standard errors.

Table 21. SPF parameter estimates and standard errors for California treatment sites.

Site Type	Crash Type	ln(α) (s.e.)	β1 (s.e.)	β2 (s.e.)	β3 (s.e.)	β4 (s.e.)	β5 (s.e.)	β6 (s.e.)	β7 (s.e.)	β8 (s.e.)	Over-dispersion Parameter, k (s.e.)
Freeway	Total	-9.1423 (0.2374)	1.1329 (0.0202)	-0.3610 (0.0362)	-0.1118 (0.0277)	-0.0034 (0.0005)	-0.0290 (0.0026)	n/a	n/a	n/a	0.3514 (0.0115)
Two-Lane		-6.0686 (0.1417)	0.9022 (0.0132)	-0.5306 (0.0394)	n/a	n/a	-0.0278 (0.0022)	-0.0240 (0.0075)	Flat: -0.0613 (0.0319) Rolling: 0 Mountainous: 0.2955 (0.0297)	n/a	0.6501 (0.0154)
Multilane		-8.5596 (0.3578)	1.0851 (0.0331)	-0.4479 (0.0547)	0.3783 (0.0897)	-0.0083 (0.0011)	-0.0188 (0.0043)	n/a	n/a	n/a	0.8087 (0.0288)
Freeway	Injury	-9.0776 (0.2467)	1.0198 (0.0209)	-0.3414 (0.0367)	-0.0972 (0.0274)	-0.0032 (0.0005)	-0.0215 (0.0026)	n/a	n/a	n/a	0.2895 (0.0112)
Two-Lane		-6.0802 (0.1581)	0.8215 (0.0143)	-0.3919 (0.0418)	n/a	n/a	-0.0298 (0.0024)	-0.0404 (0.0089)	Flat: -0.1469 (0.0341) Rolling: 0 Mountainous: 0.3413 (0.0316)	n/a	0.6049 (0.0177)
Multilane		-9.1947 (0.3745)	1.0635 (0.0348)	-0.3623 (0.0560)	0.3041 (0.0898)	-0.0083 (0.0011)	-0.0213 (0.0043)	n/a	n/a	n/a	0.7209 (0.0301)
Freeway	ROR	-3.1731 (0.3680)	0.2930 (0.0317)	-0.0818 (0.0527)	0.3059 (0.0434)	0.0030 (0.0009)	-0.0080 (0.0049)	n/a	n/a	n/a	0.6752 (0.0305)
Two-Lane		-4.3617 (0.2191)	0.5560 (0.0166)	0.2162 (0.0531)	0.1872 (0.1100)	n/a	-0.0448 (0.0029)	-0.0852 (0.0117)	Flat: -0.3181 (0.0408) Rolling: 0 Mountainous: 0.3464 (0.0356)	n/a	0.7667 (0.0246)
Multilane		-6.7850 (0.4649)	0.5544 (0.0447)	1.1378 (0.0682)	0.3380 (0.1181)	n/a	n/a	n/a	n/a	-0.1608 (0.0776)	0.8680 (0.0536)

Site Type	**Crash Type**	**ln(α) (s.e.)**	**β1 (s.e.)**	**β2 (s.e.)**	**β3 (s.e.)**	**β4 (s.e.)**	**β5 (s.e.)**	**β6 (s.e.)**	**β7 (s.e.)**	**β8 (s.e.)**	**Over-dispersion Parameter, k (s.e.)**
Freeway	Wet-Road	-9.1377 (0.4243)	0.9896 (0.0365)	-0.3465 (0.0623)	-0.1355 (0.0176)	-0.0106 (0.0009)	-0.0437 (0.0042)	n/a	n/a	n/a	0.8761 (0.0336)
Two-Lane		-8.9863 (0.2988)	1.0546 (0.0276)	-0.3104 (0.0716)	n/a	n/a	-0.0544 (0.0043)	-0.0616 (0.0161)	Flat: -0.2713 (0.0616) Rolling: 0 Mountainous: 0.6234 (0.0539)	n/a	1.5428 (0.0558)
Multilane		-11.6521 (0.5810)	1.1771 (0.0545)	0.2091 (0.0858)	0.4193 (0.1421)	-0.0158 (0.0019)	-0.0338 (0.0069)	n/a	n/a	n/a	1.5155 (0.0743)
Freeway	Wet-Road ROR	-4.3927 (0.6470)	0.2670 (0.0542)	-0.2842 (0.0976)	0.2958 (0.0767)	-0.0053 (0.0015)	n/a	n/a	n/a	n/a	1.3068 (0.1055)
Two-Lane		-7.4394 (0.4285)	0.7843 (0.0372)	0.2588 (0.1105)	n/a	n/a	-0.0809 (0.0064)	-0.1126 (0.0262)	Flat: -0.7034 (0.0921) Rolling: 0 Mountainous: 0.6254 (0.0710)	n/a	2.1307 (0.1161)
Multilane		-9.2772 (0.9370)	0.6312 (0.0858)	1.8060 (0.1584)	0.4104 (0.2662)	-0.0108 (0.0029)	-0.0420 (0.0136)	n/a	n/a	n/a	2.7556 (0.2820)

s.e. = Standard error
ROR = Run-off road

Minnesota

The model form for the Minnesota SPFs is:

$$\text{Crashes/mile-year} = \exp(\ln(\alpha) + \beta 2\text{Pavetype} + \beta 3\text{Lanes} + \beta 4\text{Urbrur} + \beta 5\text{Lanewid})(\text{AADT})^{\beta_1}$$

Figure 25. Equation. Model form for Minnesota SPFs.

Where:

AADT = Average Annual Daily Traffic
Pavetype = 1 if asphalt; 0 if PCC
Lanes = 0 if 4 or fewer lanes; 1 if greater than 4
Urbrur = 0 if rural; 1 if urban
Lanewid = lane width in ft

α, the βs, and the overdispersion parameter, k, are parameters estimated in the modeling process.

Table 22 provides the parameter estimates and standard errors.

Table 22. SPF parameter estimates and standard errors for Minnesota treatment sites.

Site Type	Crash Type	ln(α) (s.e.)	β1 (s.e.)	β2 (s.e.)	β3 (s.e.)	β4 (s.e.)	β5 (s.e.)	Overdispersion Parameter, k (s.e.)
Freeway	Total	-11.4349 (1.5748)	1.2288 (0.1446)	-0.4417 (0.1619)	n/a	n/a	n/a	0.5158 (0.0847)
Two-Lane		-7.8919 (0.5019)	0.9612 (0.0502)	0.2932 (0.1460)	n/a	-0.4795 (0.1612)	-0.0701 (0.0207)	0.6425 (0.0709)
Multilane		-5.4122 (0.8177)	0.7111 (0.0799)	n/a	n/a	-1.2037 (0.0841)	n/a	0.9496 (0.0575)
Freeway	Injury	-12.3445 (1.4706)	1.1764 (0.1372)	n/a	n/a	n/a	n/a	0.3526 (0.0835)
Two-Lane		-8.7986 (0.6043)	0.8716 (0.0602)	0.7464 (0.2139)	n/a	-0.4302 (0.1932)	-0.0473 (0.0240)	0.4903 (0.0931)
Multilane		-8.4136 (0.9822)	0.8947 (0.0955)	n/a	n/a	-0.9435 (0.0987)	n/a	0.8067 (0.0746)
Freeway	ROR	-8.3215 (3.1955)	0.7673 (0.2850)	n/a	0.5970 (0.3234)	n/a	n/a	0.5619 (0.1314)
Two-Lane		-9.1717 (0.6691)	0.7388 (0.0609)	0.9637 (0.2400)	n/a	0.6745 (0.2985)	-0.0432 (0.0261)	0.5535 (0.1028)
Multilane		-8.2183 (0.9628)	0.7435 (0.0934)	n/a	n/a	0.1862 (0.0994)	n/a	0.3542 (0.0722)
Freeway	Wet-Road	-15.1559 (1.9839)	1.3883 (0.1853)	n/a	n/a	n/a	n/a	0.5955 (0.1448)
Two-Lane		-12.8744 (0.9323)	1.1757 (0.1033)	0.7831 (0.3736)	n/a	n/a	-0.0606 (0.0379)	0.3202 (0.2029)
Multilane		-7.8879 (1.3467)	0.7692 (0.1310)	n/a	n/a	-1.2985 (0.1388)	n/a	1.1754 (0.1408)
Freeway	Wet-Road ROR	-6.9575 (2.7605)	0.5212 (0.2604)	n/a	n/a	n/a	n/a	0.7913 (0.2660)
Two-Lane		Use model for Wet-road with factor of 55 percent						
Multilane		-9.8883 (1.4965)	0.7710 (0.1492)	n/a	n/a	n/a	n/a	0.4314 (0.2233)

s.e. = Standard error
ROR = Run-off road
n/a = Not applicable

USE OF CLIMATE DATA

Objective

In the study work plan, climatic data were identified as of interest for the study. The hypothesis was that climate conditions are likely related to the risk of crashes that may be treatable through improved pavement friction conditions.

The study design for developing CMFs is applying the EB before–after methodology. In this approach, factors that may affect expected crash frequencies but that are not related to the treatment of interest are accounted for through the use of SPFs. This is done is by calibrating the SPFs using a reference group and determining yearly factors that represent time trends in crashes owing to demographics, reporting trends, weather, etc. These SPFs also include as many geometric-related variables and traffic exposure variables as possible so that changes in traffic are accounted for and predictions are as site-specific as possible.

To directly include weather-related measurements in the EB analysis, these variables would need to be used in the SPFs. This would in fact be attractive because site-specific differences between the before and after periods in temperature and/or precipitation could be accounted for when predicting expected crashes without treatment.

The climate data of interest included average monthly temperatures and average monthly precipitation. When using any data that change over time, there is a need to aggregate up to a reasonable level of analysis while leaving the data as disaggregated as possible so that variation is still observed. It was felt that using monthly data provided a reasonable balance between these two needs.

The feasibility of including average temperatures and precipitation was explored using the reference group from North Carolina.

Source of Data

As mentioned above, the two variables that were identified for treatment site climate data were temperature and precipitation. Temperature data consisted of average monthly temperatures for each month during the before and after analysis period for each site. Precipitation data consisted of actual monthly precipitation during the analysis period for each site.

The project team initially examined the feasibility of collecting climate data for each individual treatment site by selecting an appropriate weather station for each site. Considering the thousands of treatment sites and reference sites, this would have required a tremendous amount of effort to first identify viable weather stations, and then link each treatment site to a station. A second option was to collect climate data by county, because the county in which each treatment site is located is known. This did not prove to be a feasible option either because there are no known sources for climate data by county.

The most viable option identified by the team was to collect weather data by National Climatic Data Center (NCDC) divisions. Each State is broken down into several divisions (up to 10 per State) encompassing several counties each, with the borders of the divisions generally (but not always) following county boundaries. The NCDC uses an algorithm to compile and summarize climate data by division using the various weather stations within the division. This helps to eliminate uncertainty associated with the reliability of individual weather stations in the NCDC network.

Therefore, in compiling climate data for this effort, the project team established the NCDC division for each treatment or reference site based on the county in which each site is located. The monthly temperature and precipitation data for each division during the before and after analysis time period are then obtained from NCDC using the Land-Based Station Data.

Methodology and Results

The pilot test of climate data involved reestimating the SPFs using the reference group from North Carolina and comparing with the previously estimated SPFs. The difference now is that the unit of analysis is the monthly crash count rather than the sum of the observed crashes over the study period. The modeling applied the General Estimating Equations regression approach, which is required to account for temporal correlations that arise because each site is in the data as a separate observation for each month.

The evaluation of the new SPFs included a comparison with the earlier SPFs, the magnitude and significance of the estimated parameters, and a comparison of the estimated overdispersion parameters with and without the climate data.

The development of SPFs was attempted for total, injury, and ROR crashes. These were attempted for freeway, two-lane, multilane divided, and multilane undivided roads. Table 23 shows which SPFs were successful and which were not for the monthly data. Of the 12 SPFs attempted, no SPF was successfully calibrated for 7 categories. For the five categories for which an SPF was possible using the monthly data there was no improvement in the goodness of fit of the model for three. For the remaining two the improvement in goodness of fit was only slight.

Table 23. Summary of pilot test results of including climatic data.

Crash Type	Freeway	Two-Lane	Multilane Divided	Multilane Undivided
Total	Slight improvement using climate data	No SPF calibrated	No improvement using climate data	No improvement using climate data
Injury	Slight improvement using climate data	No SPF calibrated	No improvement using climate data	No SPF calibrated
ROR	No SPF calibrated	No SPF calibrated	No SPF calibrated	No SPF calibrated

ROR = Run-off road
SPF = Safety performance function

Conclusions on the Use of Climate Data

The use of monthly data makes the estimation of SPFs difficult because of the preponderance of zero counts. It was found that when using monthly data, SPFs could not be estimated for 7 of 12 site type/crash groups.

For the SPFs estimated with monthly data, the difference in model fit as measured by the overdispersion parameter between those SPFs with and without the climate data variables is negligible.

Considering the difficulty in estimating SPFs using monthly data and the negligible improvement in model fit using climate data where those SPFs were possible, it is was not recommended to further consider climate data in the reference group SPFs.

An additional concern with the monthly data is that the effects of climate are likely correlated to traffic volumes. The volume variable available is the average for the entire year. Fluctuations in volume throughout the year would be expected (e.g. the summer driving season), and these are likely correlated to average temperatures and precipitation. Unfortunately, average daily traffic volumes by month are not available.

CHAPTER 6. BEFORE–AFTER ANALYSIS

AGGREGATE RESULTS

Table 24 through table 31 provide the estimated CMFs and standard errors for the various treatments, broken down by crash type, State, and road class. A general discussion follows the presentation of all of the aggregate results.

Chip Seal Results

The results are shown in table 24. For multilane roads, there are significant benefits overall for wet-road crashes, due largely to reductions in California. There was an estimated increase in dry-road crashes on these roads, which contributed to a significant (5-percent level) increase in total crashes.

Table 24. Estimates of CMFs for chip seal treatment.

			Estimated CMF (standard error)					
Group	**Mi**	**Crashes After**	**Total Crashes**	**Injury Crashes**	**ROR Crashes**	**Wet-Road Crashes**	**Dry-Road Crashes**	**Wet-Road ROR Crashes**
California	948	3,272	0.908 (0.020)	0.892 (0.028)	0.870 (0.032)	0.830 (0.053)	0.918 (0.022)	0.709 (0.074)
Minnesota	274	179	1.255 (0.103)	1.005 (0.134)	1.271 (0.173)	1.604 (0.312)	1.201 (0.108)	0.862 (0.355)
North Carolina	765	2,149	1.011 (0.029)	1.011 (0.039)	0.655 (0.066)	0.937 (0.055)	1.027 (0.033)	0.682 (0.141)
Pennsylvania	570	1,271	0.949 (0.031)	0.959 (0.041)	1.053 (0.069)	0.999 (0.062)	1.256 (0.044)	1.004 (0.125)
All Freeway	15	94	0.832 (0.102)	0.570 (0.119)	0.638 (0.202)	Too few crashes	0.948 (0.122)	Too few crashes
All Multilane	95	619	1.147 (0.059)	1.105 (0.085)	0.959 (0.094)	0.775 (0.116)	1.206 (0.066)	0.373 (0.157)
Multilane California	70	425	1.046 (0.065)	1.039 (0.093)	0.935 (0.098)	0.423 (0.096)	1.141 (0.075)	0.222 (0.130)
Multilane Minnesota	23	94	1.519 (0.178)	1.067 (0.221)	1.214 (0.342)	Too few crashes	1.412 (0.186)	0.997 (0.705)
Multilane North Carolina	1	100	1.385 (0.172)	1.656 (0.327)	1.004 (0.708)	Too few crashes	1.390 (0.188)	Too few crashes
All Two-Lane	2448	6,158	0.939 (0.015)	0.934 (0.020)	0.883 (0.028)	0.950 (0.035)	0.937 (0.017)	0.829 (0.062)
Two-Lane California	863	2,753	0.892 (0.022)	0.884 (0.030)	0.865 (0.034)	0.927 (0.063)	0.888 (0.023)	0.775 (0.083)
Two-Lane Minnesota	251	85	1.050 (0.121)	0.960 (0.166)	1.285 (0.199)	1.092 (0.349)	1.045 (0.129)	Too few crashes
Two-Lane North Carolina	764	2,049	0.997 (0.029)	0.995 (0.040)	0.650 (0.066)	0.650 (0.066)	1.014 (0.034)	0.666 (0.141)
Two-Lane Pennsylvania	570	1,271	0.949 (0.031)	0.959 (0.041)	1.053 (0.069)	0.999 (0.062)	0.933 (0.036)	1.004 (0.124)

CMF = Crash modification factor
ROR = Run-off road

For chip seal on two-lane roads, there was a small benefit overall (significant at the 10-percent level) for wet-road crashes due mainly to reductions in California and North Carolina. For dry-road crashes, there was a small benefit overall (significant at the 5-percent level) due mainly to reductions in California and Pennsylvania. These benefits contribute to an overall benefit for all crashes and States combined for chip seal on two-lane roads.

There were too few crashes on freeways with this treatment to obtain a definitive result, although there are indications of an overall benefit for total crashes.

Diamond Grinding Results

For diamond grinding, the results in table 25 indicate that there was an overall benefit (significant at the 5-percent level) for both wet- and dry-road crashes, which resulted in a significant overall benefit for total crashes.

Table 25. Estimates of CMFs for diamond grinding treatment.

			Estimated CMF (standard error)					
Group	**Mi**	**Crashes After**	**Total Crashes**	**Injury Crashes**	**ROR Crashes**	**Wet-Road Crashes**	**Dry-Road Crashes**	**Wet-Road ROR Crashes**
California	85	12,267	0.950 (0.012)	0.973 (0.020)	0.606 (0.043)	0.866 (0.037)	0.957 (0.012)	0.703 (0.113)
Minnesota	8	119	0.899 (0.099)	1.127 (0.204)	1.221 (0.256)	Few crashes	0.792 (0.098)	Few crashes
North Carolina	24	139	0.641 (0.057)	0.525 (0.091)	Few crashes		0.576 (0.058)	
Pennsylvania	33	105	0.720 (0.081)	0.769 (0.115)	0.106 (0.106)	0.480 (0.136)	0.898 (0.104)	
All Freeway	141	12,518	0.943 (0.011)	0.967 (0.020)	0.642 (0.043)	0.869 (0.036)	0.950 (0.012)	0.869 (0.120)
Freeway California	76	12,155	0.951 (0.012)	0.975 (0.020)	0.595 (0.044)	0.862 (0.037)	0.959 (0.012)	0.700 (0.115)
All Multilane	8	108	Insufficient sites					
All Two-Lane	1	4	Insufficient sites					

CMF = Crash modification factor
ROR = Run-off road

Thin HMA Results

For thin HMA, the results in table 26 indicate that there were benefits (significant at the 5-percent level) for wet-road crashes for multilane roads and freeways, and no effect overall for dry-road crashes. (For the latter crash type, there was an increase in California and a decrease in North Carolina, both results significant at the 5-percent level.)

Table 26. Estimates of CMFs for thin HMA treatment.

			Estimated CMF (standard error)					
Group	Mi	Crashes After	Total Crashes	Injury Crashes	ROR Crashes	Wet-Road Crashes	Dry-Road Crashes	Wet-Road ROR Crashes
California	584	20,275	1.091 (0.010)	1.087 (0.017)	0.972 (0.034)	0.938 (0.032)	1.104 (0.011)	0.772 (0.075)
Minnesota	204	43	0.907 (0.148)	0.963 (0.220)	1.103 (0.243)	0.531 (0.310)	0.957 (0.163)	0.750 (0.533)
North Carolina	3,154	39,579	1.073 (0.009)	1.125 (0.014)	1.278 (0.033)	1.069 (0.018)	1.074 (0.010)	0.999 (0.047)
Pennsylvania	7	29	1.102 (0.252)	0.906 (0.294)	1.471 (0.931)	0.674 (0.367)	1.401 (0.335)	No crashes
All Freeway	259	18,323	1.021 (0.011)	0.986 (0.018)	0.973 (0.042)	0.910 (0.028)	1.039 (0.012)	0.797 (0.065)
Freeway California	164	13,326	1.043 (0.012)	1.019 (0.021)	0.666 (0.040)	0.903 (0.038)	1.054 (0.013)	0.551 (0.091)
Freeway North Carolina	87	5,068	0.967 (0.023)	0.908 (0.037)	1.405 (0.097)	0.914 (0.039)	0.990 (0.029)	0.871 (0.083)
Freeway Pennsylvania	7	29	Insufficient crashes					
All Multilane	279	15,776	0.988 (0.013)	1.021 (0.021)	1.420 (0.066)	0.865 (0.028)	1.010 (0.015)	1.149 (0.108)
Multilane California	72	4,241	1.188 (0.027)	1.191 (0.040)	1.051 (0.098)	0.955 (0.075)	1.209 (0.028)	0.680 (0.195)
Multilane Minnesota	6	7	Very few sites and crashes					
Multilane North Carolina	201	11,528	0.930 (0.015)	0.956 (0.025)	1.566 (0.086)	0.853 (0.031)	0.946 (0.017)	1.222 (0.122)
All Two-Lane	3,411	25,827	1.194 (0.011)	1.247 (0.016)	1.180 (0.031)	1.256 (0.023)	1.181 (0.013)	1.007 (0.054)
Two-Lane California	348	2,808	1.203 (0.031)	1.167 (0.043)	1.262 (0.062)	1.018 (0.083)	1.223 (0.033)	0.993 (0.137)
Two-Lane Minnesota	198	36	0.930 (0.165)	0.881 (0.222)	1.042 (0.244)	Too few crashes	Too few crashes	Too few crashes
Two-Lane North Carolina	2,866	22,983	1.193 (0.012)	1.258 (0.017)	1.146 (0.036)	1.273 (0.024)	1.175 (0.014)	1.013 (0.058)
Two-Lane Pennsylvania	0	0	No sites					

CMF = Crash modification factor
ROR = Run-off road

For two-lane roads, the thin HMA treatment was associated with highly significant increases overall in both wet- and dry-road crashes, a pattern that was consistent between California and North Carolina, the two States with large enough samples for a definitive result.

OGFC Results

For OGFC, the results in table 27 indicate a negligible effect on wet-road crashes for multilane and two-lane roads, but increases in dry-road crashes resulted in significant increases (5-percent level) in total crashes for these road types. By contrast, for freeways, there was a small but significant (5-percent level) decrease in total crashes, due in large part to highly significant and substantial reduction in wet-road crashes with no change in dry-road crashes for California and North Carolina combined.

Table 27. Estimates of CMFs for open OGFC treatment.

			Estimated CMF (standard error)					
Group	**Mi**	**Crashes After**	**Total Crashes**	**Injury Crashes**	**ROR Crashes**	**Wet-Road Crashes**	**Dry-Road Crashes**	**Wet-Road ROR Crashes**
California	416	9,525	1.060 (0.014)	1.032 (0.014)	0.974 (0.036)	0.997 (0.039)	1.068 (0.015)	0.807 (0.080)
North Carolina	42	2,231	0.748 (0.028)	0.743 (0.049)	0.485 (0.083)	0.506 (0.036)	0.875 (0.038)	0.306 (0.077)
All Freeway	165	8,571	0.945 (0.015)	0.934 (0.025)	0.816 (0.041)	0.685 (0.031)	1.008 (0.017)	0.482 (0.066)
Freeway California	124	6,354	1.041 (0.017)	1.004 (0.027)	0.873 (0.046)	0.920 (0.046)	1.055 (0.018)	0.643 (0.099)
Freeway North Carolina	41	2,217	0.747 (0.028)	0.746) (0.049)	0.481 (0.082)	0.508 (0.036)	0.873 (0.038)	0.307 (0.076)
All Multilane (almost all California)	61	1,734	1.092 (0.036)	0.959 (0.051)	1.028 (0.100)	0.981 (0.086)	1.108 (0.039)	1.114 (0.246)
All Two-Lane (California only)	232	1,451	1.109 (0.037)	1.128 (0.053)	1.107 (0.067)	1.038 (0.089)	1.120 (0.162)	0.878 (0.141)

CMF = Crash modification factor
ROR = Run-off road

Grooving Results

For grooving, there were two few sites to obtain a definitive result as indicated in table 28.

Table 28. Estimates of CMFs for grooving treatment.

			Estimated CMF (standard error)					
Group	**Mi**	**Crashes After**	**Total Crashes**	**Injury Crashes**	**ROR Crashes**	**Wet-Road Crashes**	**Dry-Road Crashes**	**Wet-Road ROR Crashes**
California (All Freeway)	5	119	0.776 (0.087)	0.746 (0.148)	0.674 (0.186)	2.034 (0.466) (Few crashes)	0.615 (0.079)	1.311 (0.696) (Few crashes)

CMF = Crash modification factor
ROR = Run-off road

Microsurfacing Results

The results are shown on table 29. For two-lane roads, there was a decrease in wet-road crashes and an increase in dry-road crashes overall (both results significant at the 5-percent level) resulting in a net increase in total crashes that was also significant at the 5-percent level. This trend was mainly due to results from Pennsylvania, which had the largest sample. For North

Carolina, the sample was small but there are weak indications of decreases on both wet- and dry-road crashes. For California, by contrast, the indication is that there was an increase in both wet- and dry-road crashes for microsurfacing on two-lane roads.

Table 29. Estimates of CMFs for microsurfacing treatment.

			Estimated CMF (standard error)					
Group	**Mi**	**Crashes After**	**Total Crashes**	**Injury Crashes**	**ROR Crashes**	**Wet-Road Crashes**	**Dry-Road Crashes**	**Wet-Road ROR Crashes**
California	72	766	1.078 (0.049)	1.120 (0.067)	1.016 (0.094)	1.061 (0.153)	1.079 (0.052)	0.712 (0.217)
Minnesota	94	626	1.108 (0.065)	1.026 (0.092)	1.226 (0.136)	0.944 (0.127)	1.140 (0.074)	1.105 (0.247)
North Carolina	39	89	0.765 (0.090)	0.958 (0.158)	0.440 (0.186)	0.604 (0.160)	0.810 (0.106)	0.505 (0.366)
Pennsylvania	164	865	1.067 (0.045)	1.123 (0.062)	1.077 (0.117)	0.775 (0.070)	1.419 (0.065)	1.173 (0.219)
All Freeway	40	518	1.075 (0.071)	1.036 (0.103)	1.169 (0.152)	0.963 (0.128)	1.101 (0.084)	1.178 (0.278)
All Multilane	58	580	1.006 (0.052)	0.972 (0.071)	0.925 (0.125)	0.785 (0.116)	1.039 (0.058)	Few crashes(12)
All Two-Lane	273	1,263	1.090 (0.038)	1.180 (0.053)	1.114 (0.082)	0.867 (0.071)	1.142 (0.044)	1.018 (0.171)
Two-Lane California	46	443	1.300 (0.076)	1.419 (0.110)	1.140 (0.122)	1.810 (0.314)	1.255 (0.077)	Few crashes(8)
Two-Lane Minnesota	43	23	Insufficient crashes					
Two-Lane North Carolina	32	60	0.718 (0.102)	0.838 (0.161)	Few crashes	0.516 (0.177)	0.769 (0.120)	Few crashes
Two-Lane Pennsylvania	152	737	1.040 (0.047)	1.099 (0.064)	1.088 (0.121)	0.761 (0.075)	1.129 (0.059)	1.122 (0.217)

CMF = Crash modification factor
ROR = Run-off road

For freeways, the results for microsurfacing were inclusive (i.e., there were no statistically significant effects), likely a result of the small sample size. For multilane roads, there was a decrease in wet-road crashes (significant at the 5-percent level) and a negligible effect on total and dry-road crashes.

Slurry Seal Results

For slurry seal, which was mostly on two-lane roads, almost all of which were in California, the results in table 30 indicate that there were benefits for wet-road crashes and weak (i.e., statistically insignificant) indications of a benefit for dry-road crashes.

Table 30. Estimates of CMFs for slurry seal treatment.

Group	Mi	Crashes After	Estimated CMF (standard error)					
			Total Crashes	Injury Crashes	ROR Crashes	Wet-Road Crashes	Dry-Road Crashes	Wet-Road ROR Crashes
California	134	1,084	0.936 (0.037)	0.888 (0.052)	0.669 (0.059)	0.736 (0.091)	0.959 (0.039)	0.621 (0.143)
North Carolina	5	5	0.843 (0.403)	0.710 (0.520)	Insufficient crashes			
All Freeway	19	200	Insufficient crashes					
All Multilane	15	192	Insufficient crashes					
All Two-Lane (almost all California)	105	697	0.931 (0.044)	0.972 (0.068)	0.578 (0.067)	0.802 (0.126)	0.943 (0.047)	Few crashes

CMF = Crash modification factor
ROR = Run-off road

UTBWC Results

The results are shown in table 31. For freeways, there was a small and marginally significant benefit overall for wet-weather crashes, due largely to the California treatments, which had a substantial and significant benefit. There was no effect for dry weather and for total crashes when this is considered.

On two-lane roads, there was a substantial and highly significant benefit for wet-road crashes and a smaller, but significant (10-percent level), benefit for dry-road crashes.

Table 31. Estimates of CMFs for UTBWC treatment.

Group	Mi	Crashes After	Estimated CMF (standard error)					
			Total Crashes	Injury Crashes	ROR Crashes	Wet-Road Crashes	Dry-Road Crashes	Wet-Road ROR Crashes
California	57	1,937	0.961 (0.027)	0.982 (0.046)	1.075 (0.098)	0.925 (0.083)	0.964 (0.029)	0.802 (0.208)
North Carolina	94	3,940	0.954 (0.019)	0.860 (0.032)	1.260 (0.093)	0.978 (0.043)	0.948 (0.021)	0.926 (0.109)
Pennsylvania	21	104	0.641 (0.073)	0.632 (0.100)	0.502 (0.198)	0.330 (0.082)	0.962 (0.118)	0.634 (0.381)
All Freeway	109	4,365	0.994 (0.019)	0.875 (0.031)	1.139 (0.070)	0.947 (0.041)	1.005 (0.021)	0.917 (0.102)
Freeway California	30	850	1.017 (0.044)	1.061 (0.078)	1.170 (0.129)	0.761 (0.102)	1.049 (0.048)	0.896 (0.274)
Freeway North Carolina	69	3,484	0.994 (0.021)	0.871 (0.036)	1.317 (0.100)	0.985 (0.046)	0.996 (0.024)	0.945 (0.113)
Freeway Pennsylvania	10	31	Insufficient crashes					
All Multilane	21	103	Insufficient crashes					
All Two-Lane	43	440	0.872 (0.051)	0.956 (0.081)	0.908 (0.169)	0.694 (0.103)	0.905 (0.058)	0.550 (0.254)

CMF = Crash modification factor
ROR = Run-off road

Summary of Aggregate Results

In summary, the combined results for all treatment types (except grooving, for which there were very few sites) suggest that the treatments resulted in benefits for wet-road crashes, with a few exceptions. The exceptions were for thin HMA on two-lane roads for both California and North Carolina, the two States with large enough samples for a definitive result, and for OGFC for two-lane and multilane roads, for which the effect was negligible.

For dry-road crashes, crashes increased for microsurfacing (except for North Carolina), thin HMA and OGFC on two-lane roads, and OGFC and chip seal on multilane roads. There were indications of a benefit for UTBWC, chip seal, and slurry seal on two-lane roads, and diamond grinding on freeways.

The estimated CMFs for treatments by road and crash type may be considered for use in the *Highway Safety Manual* and the CMF clearinghouse.

Disaggregate Results

Effect of Age of Treatment

For some of the pavement treatments, it was of interest to investigate the possible change in safety effects as the pavement ages. Traffic and weather play a significant role in wearing pavements down over time, generally leading to a reduction in pavement texture and reduction in friction.(28) The cause can be a complex interaction of factors but intuitively, we understand that aggregates abrade, polish, and are broken off of the pavement surface, bituminous binders can bleed to the surface of a pavement over time, ruts can form, and porous surfaces can become clogged. Although there have not been many studies to confirm this link between treatment age and safety, the project team wanted to evaluate whether there is any correlation in the data analyzed.

For the following identified treatments, the effect of age was investigated where the sample size allows for wet-road crashes:

- Chip seal on two-lane roads.
- Chip seal disaggregated by single versus double/triple seal.
- Diamond grinding on freeways.
- OGFC on two-lane roads.
- OGFC on freeways.

Table 32 presents the CMF estimates for all years of data and for years 1 to 3 for chip seal on two-lane roads. The results indicate that the positive safety effect of chip seal treatment on wet-weather crashes is greatest in the first year following treatment, with a declining benefit thereafter. This result is not entirely surprising for chip seal treatments. The two common "failure" mechanisms of chip seals are chip loss (raveling) and bleeding, both of which result in reduced surface texture and reduced friction, particularly in the wheelpaths where traffic has the most impact on the performance of the treatment. Figure 26 shows an example of an approximately 5-year-old chip seal on a heavily traveled roadway, with the loss of texture and friction apparent in the wheelpaths. Although it is not possible to say with certainty that this is the explanation of the results observed from this study (because each treatment site was not specifically investigated), the trend is consistent with observed performance of chip seals over time.

Table 32. Estimates of CMFs for chip seal treatment for wet-road crashes on two-lane roads by period after treatment.

Group	Estimated CMF (standard error) by period after treatment			
	All Years	Year 1	Year 2	Year 3
All Two-Lane	0.950 (0.035)	0.830 (0.055)	0.872 (0.060)	0.952 (0.067)

CMF = Crash modification function

Source: The Transtec Group, Inc.

Figure 26. Photo. Example of wear in wheelpaths over time for chip seal treatments, reducing surface texture and friction.

Table 33 provides the results for chip seal on all road types disaggregated by single versus double/triple seal applications. Data on single/double/triple seal were only available for North Carolina and Pennsylvania. For single applications, there is some indication that the safety benefit is greater in the first year after treatment than in later years; however, there is no such trend for double/triple seals.

Table 33. Estimates of CMFs for single and multi-layer chip seal treatment for wet-road crashes (NC and PA only) by period after treatment.

Chip Seal Type	Estimated CMF (standard error) by period after treatment			
	All Years	Year 1	Year 2	Year 3
Single	1.015 (0.063)	0.845 (0.098)	1.115 (0.119)	1.029 (0.113)
Double/Triple	0.924 (0.055)	0.882 (0.098)	0.890 (0.102)	0.680 (0.097)

CMF = Crash modification function

Table 34 provides the results for diamond grinding on freeways. There is no clear time trend to be seen for the first 4 years.

Table 34. Estimates of CMFs for diamond grinding treatment for wet-road crashes on freeways by period after treatment.

Group	Estimated CMF (standard error) by period after treatment				
	All Years	Year 1	Year 2	Year 3	Year 4
Freeways	0.869 (0.036)	0.916 (0.054)	0.779 (0.058)	0.923 (0.074)	0.940 (0.077)

CMF = Crash modification function

Table 35 provides the results for OGFC on freeways and two-lane roads. For freeways, there appears to be a trend of a decreasing CMF (increasing benefit) as the pavement age increases for the first 4 years. For two-lane roads, however, the trend is the opposite, and the benefits are seen to decline as the pavement ages.

Table 35. Estimates of CMFs for OGFC treatment for wet-road crashes on freeways and two-lane roads by period after treatment.

Group	Estimated CMF (standard error) by period after treatment				
	All Years	Year 1	Year 2	Year 3	Year 4
Freeway	0.685 (0.031)	0.846 (0.050)	0.810 (0.051)	0.618 (0.051)	0.573 (0.060)
Two-Lane	1.038 (0.089)	0.975 (0.130)	1.148 (0.150)	1.237 (0.188)	few crashes

CMF = Crash modification function

Effect of Other Factors

A thorough disaggregate analysis was undertaken in which multiple variable regression modeling was used to investigate the effects on the CMF of a number of factors, including AADT, precipitation, expected crash frequency before treatment, and environment (urban/rural). The primary objective was to investigate whether CMFunctions could be developed to capture the effects of these factors and more precisely estimate CMFs for prospective treatments.

In the end, the CMFunctions developed were not robust enough to recommend them. The direction of effect for attempted variables was not always consistent, and the statistical significance of estimated parameters tended to be poor. Nevertheless, there were useful insights that suggest that it would be worthwhile to pursue the development of robust CMFunctions in future research. These insights suggest that there appears to be a relationship between CMFs and AADT and sometimes precipitation, urban versus rural setting, and crash frequency. However, the direction of the effect varies by crash type and treatment, so the future research will need to reconcile (i.e., explain), these apparent inconsistencies.

Appendix A summarizes the approach to CMFunction development and presents some of the more promising results.

CHAPTER 7. HIGH FRICTION SURFACING TREATMENT

INTRODUCTION

The HFS treatment strategy was analyzed separately from the conventional pavements because of the nature of HFS treatments. Unlike the conventional treatments discussed in previous chapters, HFS is used almost exclusively for safety improvement (friction restoration or enhancement) purposes and not for pavement preservation or rehabilitation. In addition, with few exceptions, HFS treatments are used primarily for spot treatments of ramps or individual curves, rather than over longer sections of a roadway. As such, the data collection and analysis procedures differ somewhat from the conventional treatments.

DATA COLLECTION

HFS is a relatively new pavement treatment in the United States, at least in terms of systemic use. A limited number of States (including ELCSI-PFS States) have HFS treatments, and there are generally only a few treatments in those States.

States with HFS treatments were identified by the project team, FHWA, and PFS contacts, and also through related efforts such as the FHWA Surface Enhancements at Horizontal Curves (SEAHC) study. Data requested for HFS treatments were the same as that summarized in Table 4, previously. However, challenges with data collection for these sites included the following:

- *Obtaining traffic data for ramps*—Many States do not routinely collect traffic data on ramps, but rather just the mainline highway leading into or away from a ramp.
- *Obtaining accurate crash data for ramps*—Crash data for ramps can be difficult to obtain owing to inconsistencies in how the crash data are coded when recorded. They may be coded for the roadway (and associated milepoints) leading into the ramp or for the roadway leading away from the ramp.
- *HFS treatment information*—Knowing what material was used (specifically the aggregate type), the exact limits of the treatment, and the dates of installation is needed. Many HFS treatments were installed as demonstration or trial projects, and detailed records were not available. Some may have been removed prematurely or overlaid with another treatment.
- *Identifying reference sites*—HFS treatments are most commonly applied to curves or ramps with high crash rates that may be unique in geometry, location, traffic, etc. Finding similar sites to use as reference sites can be very difficult, if not impossible. Invariably, reference sites will likely have lower crash rates because the main criterion for selecting treatment locations was higher crash rates.
- *Collecting roadway data for HFS sites*—It was often necessary to use satellite imagery (Google Earth™) to verify the limits of an HFS treatment, lane and shoulder widths, and radius of curvature.

- *Friction data*—Before and after friction data were available for the SEAHC sites, including data from 1 and 3 years after installation. Unfortunately, friction data were not available for the remaining sites or for any of the reference sites, precluding the use of friction data in the analysis.

SUMMARY OF HFS TREATMENT DATA COLLECTION

Below are summaries of the data collection process for each of the volunteer States that provided candidate sites. The complete list of HFS treatment sites is provided in Appendix B.

Colorado

HFS treatment sites were on curves and were part of the FHWA SEAHC demonstration program. Treatment sites were originally selected by the Colorado Department of Transportation (CDOT) based on high crash rates at those curves. CDOT provided before and after crash data for the treatment sites. Roadway data (traffic volume, number of lanes, lane width, shoulder type and width, median type and width) were collected from the SEAHC project information and from an online CDOT roadway information database.

Reference sites were selected as segments of the roadway upstream and downstream from the treatment sites. Segments were selected based on similar traffic volume, number and width of through lanes, shoulder type and width, and median type. CDOT provided crash data for the same before and after periods as the treatment sites for these segments of roadway.

Kansas

HFS treatment sites were part of the FHWA SEAHC demonstration program and included two curves and two ramps. Treatment sites were originally selected by the Kansas Department of Transportation (KDOT) based on high crash rates at those locations. KDOT provided before and after crash data for the treatment sites and traffic information. Roadway information (pavement type, number and width of lanes, shoulder type and width) was collected from the SEAHC demonstration project information.

Reference sites were identified by KDOT based on similar roadway characteristics to the treatment sites (traffic and roadway geometry). KDOT provided crash data for the reference sites for the same before and after periods as the treatment sites.

Kentucky

HFS treatment site data were provided by the Kentucky Transportation Cabinet (KTC). KTC provided the list of treatment locations and summary before and after crash data. Roadway information (traffic volumes, number and width of lanes, shoulder type and width, and median information) were collected from KTC's online Highway Information System (HIS) database, and crash data were obtained from the Kentucky State Police Collision Analysis online database.

Reference sites were identified using roadway data from the HIS database. For treatments on curves, segments of the roadway upstream and downstream from the treatment sites with similar characteristics (traffic volume, number and width of through lanes, shoulder type and width, and median type) were identified as reference sites. For treatments on ramps, ramps with similar geometry in the vicinity of the treatment sites were selected. Crash data were collected through the Kentucky State Police Collision Analysis database.

Michigan

HFS treatment sites were part of the FHWA SEAHC demonstration program and from various safety improvement projects by the Michigan Department of Transportation (MDOT). Treatment sites were originally selected by MDOT based on high crash rates at the curve and ramp locations identified. MDOT provided before and after crash data for the treatment sites as well as roadway information (traffic volume, underlying pavement type, and treatment length). Additional information for lane and shoulder widths was estimated using satellite imagery (Google Earth™).

Reference sites were identified by MDOT based on similarity in roadway characteristics to the treatment sites. MDOT provided before and after crash data for the reference sites for the same time periods as the treatment sites.

Montana

HFS treatment sites were part of the FHWA SEAHC demonstration program. Treatment sites were originally selected by Montana Department of Transportation (MDT) based on high crash rates at the two locations. MDT provided before and after crash data for the treatment sites, while roadway data (traffic volume, number of lanes, lane width, shoulder type and width, median type and width) were collected from the SEAHC demonstration project information.

Reference sites were identified by MDT based on similar roadway characteristics to the treatment sites. MDT provided crash data for the reference sites for the same before and after periods as the treatment sites.

South Carolina

HFS treatment sites were provided by the South Carolina Department of Transportation (SCDOT) from various safety improvement projects using HFS treatments. SCDOT provided the treatment site locations, before and after crash data, traffic, and underlying pavement information.

Reference sites were identified by SCDOT based on similar roadway characteristics to the treatment sites. SCDOT provided reference site locations and before and after crash data for the selected reference sites.

Tennessee

HFS treatment sites were identified by Tennessee Department of Transportation (TDOT) from safety improvement projects completed by TDOT. Six treatment locations were originally provided, but two were intersection approaches and not considered in the analysis. TDOT provided the treatment locations, and roadway information (traffic volumes, lane width, shoulder type and width, and median information) was collected from the online Tennessee Roadway

Information Management System (TRIMS) maintained by TDOT. Detailed before and after crash data were also obtained from the TRIMS database.

Reference sites were identified using the roadway data from the TRIMS database. Segments of the same highway upstream and downstream from each of the treatment sites with similar characteristics (traffic volume, number and width of through lanes, shoulder type and width, and median type) were identified as reference sites. Before and after crash data were collected through the TRIMS database.

Wisconsin

One HFS treatment installed under the FHWA SEAHC demonstration program in 2011 was provided by the Wisconsin Department of Transportation (WisDOT). WisDOT provided before and after crash data for the treatment site, and roadway data (traffic volume, number of lanes, lane width, shoulder type and width, median type and width) were collected from the SEAHC demonstration project information.

Other States

Various other HFS treatments were provided by several States, but were not included in the final analysis because of insufficient crash data, information on the treatment site itself, or a lack of reference sites.

California—Caltrans provided a list of 48 completed and planned HFS treatments in the State. Of those, seven were selected as potential candidates for analysis. Unfortunately, a lack of crash data for each of these sites (due in part to most being less than 2 years old) and a lack of reference sites precluded their use in the analysis.

Iowa—Four sites that were installed as part of safety improvement projects in 2012 by the Iowa Department of Transportation were identified. A lack of raw crash data for these sites and reference sites for the analysis precluded their use.

Louisiana—One HFS site, installed as a safety improvement project in 2010, was provided by the Louisiana Department of Transportation. Crash data were provided for the site, as well as traffic and roadway information. However, because the treatment location was an elevated structure (bridge deck), and reference sites could not be identified, it was not included in the analysis.

Mississippi—One HFS site, installed as a safety improvement project in 2008, was identified by the Mississippi Department of Transportation, and before and after crash data were provided. However, a lack of reference sites (due to the unique characteristics of the treatment site) precluded its inclusion in the analysis.

Texas—Two HFS sites installed as safety improvement projects, and tested under the FHWA SEAHC program, were identified for Texas. A lack of crash data and reference sites precluded the use of these sites in the analysis.

West Virginia—West Virginia Department of Transportation provided a list of 24 horizontal curve HFS treatment sites installed as safety improvement projects. Before and after crash data and reference sites could not be obtained for these sites, and many of them were just over 1 year old, precluding their use in the analysis.

SUMMARY OF HFS TREATMENT SITES

Table 36 and table 37 provide a summary of the treatment and reference site data that were collected and used in the study.

Table 36. Summary statistics of HFS treatment site data collected.

Site Type	Sites by State	Sites by Road Classification	Sites by Pavement Type	Crashes per Site-Year Before	Crashes per Site-Year After	Wet-Road Crashes per Site-Year Before	Wet-Road Crashes per Site-Year After
Ramps	Kansas—2 Kentucky—2 Michigan—6 Montana—1 South Carolina—6 Wisconsin—1	Urban—17 Rural—1	Asphalt—12 PCC—5 Chip Seal—1	Min—0.00 Max—28.68 Mean—6.10	Min—0.00 Max—10.50 Mean—2.77	Min—0.00 Max—12.25 Mean—3.32	Min—0.00 Max—3.00 Mean—0.57
Curves	Colorado—2 Kansas—2 Kentucky—28 Michigan—1 Montana—1 South Carolina—1 Tennessee—4	Urban—4 Rural—35	Asphalt—38 Chip Seal—1	Min—0.25 Max—17.00 Mean—2.93	Min—0.00 Max—16.00 Mean—1.90	Min—0.00 Max—14.00 Mean—1.62	Min—0.00 Max—4.00 Mean—0.49

PCC = Portland cement concrete

Table 37. Summary statistics of HFS comparison site data collected.

Site Type	Sites by State	Sites by Road Classification	Sites by Pavement Type
Ramps	KS—14 MI—39 MT—8 SC—38	Urban—36 Rural—6 Unknown—49	Asphalt—23 PCC—36 Unknown—32
Curves	CO—8 KS—17 KY—117 MI—13 MT—13 SC—11 TN—27	unknown	unknown

PCC = Portland cement concrete

ANALYSIS OBJECTIVES

Similar to the conventional treatments, the objective of this analysis was to estimate CMFs for the safety effect of HFS treatments using data from the States listed above. Treatment sites identified were either freeway ramps or individual curves. The treatments were generally applied because of a perceived problem with friction-related crashes.

The basic objective of the crash data analysis was to estimate the change in target crashes. Only nonintersection, nonanimal related crashes, and crashes not involving snow or ice were considered. Crash types examined total and wet-road crashes. Because of the limited sample sizes, other crash types were not investigated. Even for wet-road crashes, the sample size becomes small, but because these constituted the primary target crash type, they were analyzed separately. It should be noted that because HFS treatments are installed in a shorter period of time than conventional treatments, only the month in which the treatment was applied was masked off from the before and after periods, rather than the entire year.

ANALYSIS METHODOLOGY

The data collection for HFS treatments proved more difficult than for conventional treatments, particularly for treatments on ramps. For States that could provide untreated reference site data, the number of such sites was often limited, and, in many cases, traffic (i.e., AADT) information was missing. For South Carolina, fewer years of crash data were provided for reference sites than for treatment sites.

The lack of available data prohibited the application of the robust EB before–after methodology at this time. In the interim, both naïve before–after and comparison group (C-G) before–after studies were conducted with the limited data available, and guarded conclusions made on the basis of the results, given the methodological issues with these studies. Even so, not all of the treatment sites with before and after data had comparison sites for a C-G study. Below is a description of the methodology for the naïve and C-G studies, taken from Gross et al.(44)

Naïve Study Approach

The simple before–after study, also referred to as the naïve before–after study, is a comparison of the number of crashes before and after treatment. The CMF for a given crash type at a treated site is estimated by first summing the observed crashes for the treatment site for the two time periods (assumed equal). The notation for these summations is summarized as follows:

K = the observed number of crashes in the before period for the treatment group.
L = the observed number of crashes in the after period for the treatment group.

The expected number of crashes for the treatment group that would have occurred in the after period without treatment is estimated using the equation in figure 27:

$$\mathrm{B} = \mathrm{K}(\mathrm{Years\ After}/\mathrm{Years\ Before})$$

Figure 27. Equation. Estimated number of crashes that would have occurred in the after period with no treatment in the naïve study.

The variance of B is estimated using the equation in figure 28:

$$\mathrm{Var(B)} = \mathrm{K(Years\ After/Years\ Before)}^2$$

Figure 28. Equation. Estimated variance of B in the naïve study.

The CMF and its variance are estimated using the equations in figure 29 and figure 30.

$$\mathrm{CMF} = (\mathrm{L/B})/\{1 + [\mathrm{Var(B)/B}^2]\}$$

Figure 29. Equation. Estimated CMF in the naïve study.

$$\mathrm{Variance}\{\mathrm{CMF}\} = [\mathrm{CMF}^2\{[1/\mathrm{L}] + [\mathrm{Var(B)/B}^2]\}/[1 + \mathrm{Var(B)/B}^2]^2]$$

Figure 30. Equation. Estimated CMF variance in the naïve study.

This method assumes that the number of crashes before the treatment is a good estimate of the expected crashes that would have occurred without the treatment. This assumption is in fact problematic because it does not take into account any other factors that can affect this estimate, such as changes in traffic volume and external causal factors. Most critically, sites that receive treatments such as HFS are typically selected on the basis of a high crash count, which introduces a regression to the mean (RTM) error whereby, without any treatment, the total number of crashes would have naturally declined in the after period. Thus, the results of a naïve before–after study can be biased toward overestimating the benefit of HFS treatment (i.e., underestimating the CMF).

C-G Study Approach

The before-and-after study using the C-G method is similar to the simple before-and-after study. It uses a comparison group of untreated sites to compensate for the external causal factors that could affect the change in the number of collisions. It does this by assuming that the ratio of crashes between the before and after period of the untreated sites would have been the same for the treated sites. Therefore, any external changes that would have changed the number of crashes in the after period throughout the area would be accounted for.

The CMF for a given crash type at a treated site is estimated by first summing the observed crashes for both the treatment and comparison groups for the two time periods (assumed equal). The notation for these summations is summarized as follows:

K = the observed number of crashes in the before period for the treatment group.
L = the observed number of crashes in the after period for the treatment group.
M = the observed number of crashes in the before period in the comparison group.
N = the observed number of crashes in the after period in the comparison group.

The comparison ratio (N/M) indicates how crash counts are expected to change in the absence of treatment (i.e., owing to factors other than the treatment of interest). This is estimated from the comparison group as the number of crashes in the after period divided by the number of crashes in the before period. The expected number of crashes for the treatment group that would have occurred in the after period without treatment is estimated using the equation in figure 31:

$$B = K(N/M)$$

Figure 31. Equation. Estimated number of crashes that would have occurred in the after period with no treatment in the C-G study.

If the comparison group is ideal, the variance of B is estimated using the equation in figure 32:

$$\mathrm{Var}(B) = B^2(1/K + 1/M + 1/N)$$

Figure 32. Equation. Estimated variance of B in the C-G study.

The CMF and its variance are estimated as using the equations in figure 33 and figure 34:

$$\mathrm{CMF} = (L/B)/\{1 + [\mathrm{Var}(B)/B^2]\}$$

Figure 33. Equation. Estimated CMF in the C-G study.

$$\mathrm{Variance}\{\mathrm{CMF}\} = [\mathrm{CMF}^2\{[1/L] + [\mathrm{Var}(B)/B^2]\}/[1 + \mathrm{Var}(B)/B^2]^2]$$

Figure 34. Equation. Estimated CMF variance in the C-G study.

This method, like the naïve method, does not account for RTM because it does not account for the natural reduction in crashes in the after period that would occur for the sites with abnormally high numbers of crashes, which would characterize the sites typically selected for HFS treatments. Thus, again, the results would likely be biased toward overestimating the benefit of HFS treatment (i.e., underestimating the CMF).

RESULTS

Results are provided in table 38 and table 39 for both the naïve and C-G studies. As mentioned earlier, not all treatment sites could be analyzed using the C-G method because reference sites were either unavailable or lacked the required data.

As noted, the results from applying these two methods are likely biased toward underestimating the CMF, and thereby exaggerating crash reductions, because RTM is likely at play and is not accounted for. An approximate method for resolving this problem has been suggested in the process of developing CMFs for the *Highway Safety Manual*.(45) That report suggests (on page 7) that "for a large RTM bias, where only a few sites with the highest crash frequency were treated out of the total population and few years of before-crash data were included in the evaluation study," the biased CMF should be corrected by multiplying it by a factor of 1.25. That recommendation seems appropriate for this evaluation, so this correction of 1.25 was applied to the biased CMFs. The CMFs with this RTM correction are shown in addition to the biased ones in table 38 and table 39. These indicate that HFS treatments have a substantial beneficial impact on safety, especially for wet-road crashes.

Table 38. Results for the naïve before–after study based on all sites.

Group	No. of Sites	Crashes After	Wet-Road Crashes After	CMF (and standard error) for Total Crashes		CMF (and standard error) for Wet-Road Crashes	
				Biased	With HSM RTM Correction	Biased	With HSM RTM Correction
All Ramps	27	111	19	0.387 (0.041)	0.484	0.169 (0.041)	0.211
All Curves	43	104	45	0.502 (0.052)	0.628	0.298 (0.048)	0.373

CMF = Crash modification function
HSM = *Highway Safety Manual*
RTM = Regression to the mean

Table 39. Results for the before–after C-G study for treatment sites for which comparison sites were available.

Group	No. Sites	Crashes After	Wet-Road Crashes After	Total Crashes—C-G		Wet-Road Crashes—C-G	
				Biased	With HSM RTM Correction	Biased	With HSM RTM Correction
Ramps	12	77	8	0.522 (0.092)	0.653	0.111 (0.042)	0.139
Curves	35	104	45	0.607 (0.067)	0.759	0.385 (0.064)	0.481

CMF = Crash modification function
HSM = *Highway Safety Manual*
RTM = Regression to the mean

CONCLUSIONS FOR HFS TREATMENT

This analysis was limited because there were insufficient treatment and reference group data to conduct a state-of-the-art EB analysis. Naïve before–after study results for all treatment sites, and those of a C-G study of treatment sites for which comparison sites were available, were obtained. These results are likely biased because the HFS treatments sites were likely selected on the basis of high crash counts, resulting in RTM that was not accounted for with the less rigorous methods that could be applied. A correction based on a method used to obtain *Highway Safety Manual* CMFs from similarly biased studies was applied as an approximation. The corrected results suggest that HFS can be a highly effective safety treatment whose implementation should continue.

Deployment of HFS as a safety countermeasure for curves and ramps is continuing in many States. It is strongly recommended that additional data be collected to conduct a robust EB before study to derive a CMF that could be recommended to practitioners and for which a BC ratio could be confidently estimated. The future data collection should, where possible, focus on those States with available traffic counts in both the before and after periods and that can identify appropriate reference sites.

CHAPTER 8. BC ANALYSIS

METHODOLOGY

The BC analysis provides a method for a comparison of the various pavement treatment options. By considering the cost of each treatment, typically just the installation cost, and the benefit, quantified in terms of crash reduction and lifespan, agencies will be equipped to better justify selection of one treatment over another.

Separate analyses are provided for treatments and States for which the sample size was large enough and for which there was a statistically significant (5-percent level) benefit for total crashes. The annualized cost of the treatment is first computed using the equation in figure 35:

$$\text{Annual Cost} = \frac{\mathrm{C} \cdot \mathrm{R}}{1 - (1 + \mathrm{R})^{\mathrm{N}}}$$

Figure 35. Equation. Annualized cost pavement treatment.

Where:

C = Treatment cost.
R = Discount rate (as a decimal).
N = Expected service life (years).

Quantifying the actual treatment cost is one of the more difficult aspects of this analysis. Treatment costs vary widely from State to State and even within each State. Although statewide bid averages provide an estimate of the cost of the treatment itself, they do not account for any ancillary costs associated with the treatment (e.g., design, inspection, mobilization, maintenance of traffic). Therefore, calculated treatment costs were based on cost ranges published in a recent SHRP2 research report on pavement preservation treatments.(31) The SHRP2 report also provides a range for service lives of the various treatment types. For the purposes of this analysis, low-end to median values were used for service life based on a conservative assumption that rehabilitation cycle is longer than the period over which safety benefits are achieved. There is some support for this assumption in the results of the limited investigation of treatment effects over time.

Based on information from the Office of Management and Budget, the following real discount rates, based on the service life of a treatment, were used to determine the annual cost of the treatment.(46)

- Chip seal, HFS, and slurry seal: 5 years; -0.8 percent.
- Thin HMA, OGFC, and UTBWC: 6 years; -0.6 percent (interpolated).
- Diamond grinding: 8 years; -0.2 percent (interpolated).

The most recent FHWA mean comprehensive crash costs are based on 2001 dollar values.(47) As recommended in that report, if crash costs are required for another year, the recommended adjustment procedure is to multiply the human capital costs provided in the tables by a ratio of the Consumer Price Index (CPI)—all items—for the year of interest divided by the CPI for 2001.

Based on the appropriate CPI information from the U.S. Department of Labor, the ratio of the 2013 to the 2001 CPI is 230.08/175.1 = 1.314.(48) The 2001 unit costs for property damage only and fatal+injury crashes from the FHWA report were multiplied by this ratio and then weighted by the frequencies of these two crash types for a group in the after period to obtain and aggregate 2013 unit cost for total crashes.

The total crash reduction was calculated for each treatment/State group by subtracting the actual crashes in the after period from the expected crashes in the after period had the treatment not been implemented. The number of crashes saved per year was obtained by dividing the total crash reduction by the average number of after period years per site. The annual *benefit* (i.e., crash savings) is the product of the total crash reduction per year and the aggregate cost of a crash (all severities combined). The BC ratio is calculated as the ratio of the annual benefit to the annual cost.

CONVENTIONAL TREATMENTS

Table 40 summarizes the results of the economic analysis of the conventional pavement treatment strategies evaluated in this study with a robust EB analysis. As noted earlier, this analysis was done for treatments and States for which the sample size was large enough and for which there was a statistically significant (5-percent level) benefit for total crashes.

Table 40. Results of BC analysis for conventional treatment groups with statistically significant crash reductions.

Treatment (State)	Road Type	Cost/Lane-Mi	Sites	Mi	Crash Reduction per Year	Cost/ Crash	BC Ratio
Chip Seal (All)	Two-Lane	$12,320/layer (conventional) $21,120 (rubberized or polymer-modified)	5,770	2,448	107.16	$106,905	0.69
Chip Seal (California only)	Two-Lane		1,432	863	91.27	$107,687	2.06
Diamond Grinding (All)	Freeway	$25,570	691	141	206.67	$77,408	5.95
Thin HMA (North Carolina only)	Multilane	$31,680	1,411	201	174.60	$74,695	3.01
OGFC (All)	Freeway	$39,000	453	165	147.90	$74,633	2.10
OGFC (North Carolina only)			105	41	184.61	$64,173	9.15
Slurry Seal (All)	Two-Lane	$15,000*	248	105	14.41	$95,587	2.25
UTBWC (All)	Two-Lane	$35,200	187	43	18.78	$96,197	3.60

*Used the cost provided by California because almost all sites are from that State
BC = Benefit-cost
HMA = Hot mix asphalt
OGFC = Open grade friction course
UTBWC = Ultrathin Bonded Wearing Course

HFS TREATMENT

Although it was not possible to conduct a rigorous EB analysis for the HFS treatments, a cursory economic analysis was undertaken based on the results in table 39 for the ramps and curves for which a comparison group study was possible. The methodology used above for the other treatments was used, with the following conservative estimates:

- Service life: 5 years (typical range: 5–7 years).
- Installation cost: $35/square yd (typical range: $25–$35/square yd).
- Cost per crash: $64,173 (based on the lowest value in table 40).

The results suggest the following BC cost ratios for HFS treatments:

- 3.97 (curves).
- 11.88 (ramps).

CHAPTER 9. DISCUSSION AND CONCLUSIONS

The research was broad in scope, covering several treatments in several States, and with many variations in applications, but was nevertheless groundbreaking in that there is a dearth of definitive results on the safety effects of various pavement improvement treatments. It would be beneficial for the future research to now focus on individual treatments to isolate the application types and circumstances that are most cost-effective for safety. The results of this study will be useful in guiding such future efforts.

SUMMARY

The objective of the study was to estimate the effect of various low-cost pavement treatments on crashes by evaluating a variety of treatments from several states. The state-of-the-art EB before–after methodology was applied to evaluate the effects on various crash types (total, injury, wet road, dry road, wet-road ROR, and all ROR) of the following treatments, based on data from California, North Carolina, Pennsylvania, and Minnesota:

- Chip Seal (single and double layer).
- Diamond Grinding (concrete pavement only).
- Grooved Concrete Pavement.
- Microsurfacing (asphalt and concrete pavement).
- OGFC (asphalt and concrete pavement).
- Slurry Seal (asphalt pavement).
- Thin HMA (asphalt and concrete pavement).
- UTBWC (asphalt and concrete pavement).

A preliminary, simple before–after evaluation was completed for HFS treatments based on limited data from several States. These data were insufficient to apply the EB method.

The combined results for all treatment types subjected to the rigorous EB evaluation (except grooving, for which there were very few sites) suggest that the treatments resulted in benefits for wet-road crashes, with the exception of thin HMA for two-lane roads for both California and North Carolina, the two states with large enough samples for a definitive result, and for OGFC for two-lane and multilane roads, for which the effect was negligible.

For dry-road crashes, crashes increased for microsurfacing on two-lane roads (except for North Carolina), thin HMA and OGFC on two-lane roads, and OGFC and chip seal on multilane roads; there were indications of a benefit for UTBWC, chip seal, and slurry seal on two-lane roads, and for diamond grinding on freeways.

The CMFs for treatments by road and crash type may be considered for use in the *Highway Safety Manual* and the CMF Clearinghouse.

A thorough disaggregate analysis of the before–after evaluation data was undertaken in which regression analysis was used to investigate the effects on the CMFs of a number of variables, including AADT, precipitation, expected crash frequency before treatment, environment (urban/rural), and treatment age. In the end, the CMFunctions developed were not robust enough to recommend them. Nevertheless, there were useful insights that suggest that it would be worthwhile to pursue the development of robust CMFunctions in future research. The results did suggest that there is a relationship between CMFs and AADT and sometimes precipitation, urban versus rural setting, and expected crash frequency. However, the direction of the effect is not always consistent, varying by crash type, site type, and treatment. Future research is needed to reconcile (i.e., explain) these apparent inconsistencies.

An economic analysis was conducted for treatments and States for which the sample size was large enough and for which there was a statistically significant (5-percent level) benefit for total crashes based on the EB evaluation. The results indicate that BC ratios larger than 2.0, considering impacts on safety only, are attainable for the following situations:

- Chip seal on two-lane roads (California only).
- Diamond grinding on freeways.
- Thin HMA on multilane roads (North Carolina only).
- OGFC on freeways.
- Slurry seal on two-lane roads.
- UTBWC on two-lane roads.

For other treatments/road classes/States, sample sizes were too small in some cases and, in other cases, overall safety benefits were not achieved or were statistically insignificant.

For HFS treatments, the results of the basic before–after analysis suggest that HFS can be a highly safety- and cost-effective treatment for which implementation should continue. It is strongly recommended that additional data be collected to conduct a robust EB before study to derive a CMF that could be recommended to practitioners and for which a BC ratio could be confidently estimated.

RELATING RESULTS TO PAVEMENT FACTORS

Several of the results from this analysis may not be intuitively obvious. Unfortunately, without very detailed information on the specific characteristics (friction, texture, pavement condition, etc.) of each particular pavement section included in this analysis, it is not possible to draw definitive conclusions for these observations. However, this section postulates some possible explanations for these results. It should be noted that these points of discussion are observations of the researchers and should not be construed as documented conclusions.

When looking at the impact of pavement treatments on crashes, potential changes in driver behavior or driver response must be considered in addition to the effects of the treatment on pavement surface characteristics (texture and friction). Some potential driver responses to these treatments include the following:

- Smoother and/or quieter pavement may lead to higher speeds, particularly for local drivers who are accustomed to the roadway and may have a sense that it is safer to drive faster with the new treatment in place.(27)

- Similarly, improvement to pavement condition (e.g., elimination of cracking, rutting, etc. and improvement in friction) when a pavement treatment is applied can potentially lead to higher speeds.

- Porous surfaces are known to reduce splash and spray, thereby improving visibility in wet weather, potentially leading to a reduction in wet-weather crashes.

In the following sections, the results reached in the study and described earlier in the report appear in indented blocks, followed by the possible explanations or observations by the researchers.

Chip Seals

> For multilane roads, there are significant benefits overall for wet-road crashes, due largely to reductions in California. There was an estimated increase in dry-road crashes on these roads, which contributed to a significant (5-percent level) increase in total crashes.
>
> For chip seal on two-lane roads, there was a small benefit overall (significant at the 10-percent level) for wet-road crashes due mainly to reductions in California and North Carolina. For dry-road crashes, there was a small benefit overall (significant at the 5-percent level) due mainly to reductions in California and Pennsylvania. These benefits contribute to an overall benefit for all crashes and States combined for chip seal on two-lane roads.

Given the aggressive nature of chip seals (good macrotexture and friction), a decrease in wet-road crashes is not surprising. However, the increase in dry-road crashes and the difference between multilane and two-lane roads is not readily explainable from a pavement perspective.

Diamond Grinding

> For diamond grinding, there was an overall benefit (significant at the 5-percent level) for both wet- and dry-road crashes, which resulted in a significant overall benefit for total crashes.

Concrete pavements are usually diamond ground later in their life, when the original pavement texture may be substantially worn or polished. Diamond grinding gives the pavement renewed texture and improved friction, and therefore could explain this benefit for crashes.

Thin HMA Overlay

> For thin HMA, there were benefits (significant at the 5-percent level) for wet-road crashes for multilane roads and freeways and no effect overall for dry-road crashes. (For the latter crash type, there was an increase in California and a decrease in North Carolina, both results significant at the 5-percent level).

A possible explanation for wet-road crash reduction is that the overlay may have eliminated rutting and/or flushing that existed in the old pavement. Ruts tend to hold water and can lead to more wet-weather crashes, while flushing can significantly reduce friction in the wheelpaths, particularly in wet weather. Multilane and freeways (with presumably higher AADT) would likely exhibit more rutting and flushing. This has not been formally documented in any previous research, however.

> For two-lane roads, the thin HMA treatment was associated with highly significant increases overall in both wet- and dry-road crashes, a pattern that was consistent between California and North Carolina, the two States with large enough samples for a definitive result.

A new asphalt overlay, which would likely improve smoothness, could possibly lead to higher speeds and possibly more crashes in wet or dry weather. This increase in speed with improvement in pavement condition has not been formally researched, but has been postulated elsewhere.(27,49) There is also the possibility that the cumulative effect of multiple thin overlays over time could lead to a nonrecoverable side-slope at the edge of the pavement, particularly on two-lane roads without paved shoulders. Again, however, this has not been formally documented in any previous research.

OGFC

> For OGFC, there was a negligible effect on wet-road crashes for multilane and two-lane roads, but increases in dry-road crashes resulted in significant increases (5-percent level) in total crashes for these road types. By contrast, for freeways, there was a small but significant (5-percent level) decrease in total crashes, due in large part to highly significant and substantial reduction in wet-road crashes with no change in dry-road crashes for California and North Carolina combined.

Similar to the thin HMA overlay treatment, a smoother (and presumably quieter) OGFC may lead to higher speeds and potentially more crashes for multilane and two-lane roads. For freeways, OGFC could also possibly reduce splash and spray on heavily traveled freeways, reducing wet-weather crashes due to poor visibility.

Microsurfacing

> For microsurfacing on two-lane roads, there was a decrease in wet-road crashes and an increase in dry-road crashes overall (both results significant at the 5-percent level) resulting in a net increase in total crashes that was also significant at the 5-percent level. This trend was mainly due to results from Pennsylvania, which had the largest sample. For North Carolina, the sample was small but there are weak indications of decreases on both wet- and dry-road crashes. For California, by contrast, the indication is that there was an increase in both wet- and dry-road crashes for microsurfacing on two-lane roads.
>
> For freeways, the results for microsurfacing were inclusive, (i.e., there were no statistically significant effects), likely a result of the small sample size. For multilane roads, there was a decrease in wet-road crashes (significant at the 5-percent level) and a negligible effect on total and dry-road crashes.

The decrease in wet-road crashes is not surprising because microsurfacing is known as a treatment to help improve skid resistance. There is no readily available explanation for the increase in dry-road crashes, however.

Slurry Seal

> For slurry seal, which was mostly on two-lane roads, almost all of which were in California, there were benefits for wet-road crashes and weak (i.e., statistically insignificant) indications of a benefit for dry-road crashes.

Similar to microsurfacing, slurry seal is known to help improve skid resistance and therefore would be expected to exhibit benefits for wet-road crashes.

UTBWC

> For UTBWC treatment on freeways, there was a small and marginally significant benefit overall for wet-weather crashes, due largely to the California treatments, which had a substantial and significant benefit. There was no effect for dry weather and for total crashes when this is considered.
>
> On two-lane roads, there was a substantial and highly significant benefit for wet-road crashes and a smaller, but significant (10-percent level) benefit for dry-road crashes.

A UTBWC is similar in nature to a thin HMA overlay, and therefore similar results might be expected. The difference in effect for two-lane roads and freeways, however, is not readily explainable.

HFS

> For HFS treatments, the results of the cursory before–after analysis suggest that HFS can be a highly safety- and cost-effective treatment.

The crash reduction observed for the HFS treatment sites is not surprising as this treatment is applied specifically as a safety treatment to problem locations with high crash rates, particularly ROR crashes. The higher crash reduction for wet-road crashes over total crashes is also not surprising as this treatment provides significant improvement to both microtexture and macrotexture of existing pavement, which is particularly important for wet-road friction.

Age of Treatment—Chip Seal

> CMF estimates for all years of data and for years 1 to 3 for chip seal on two-lane roads indicate that the positive safety effect of chip seal treatment on wet-weather crashes is greatest in the first year following treatment, with a declining benefit thereafter.

Although it is not possible to say with certainty that this is the explanation of the results observed from this study, as discussed previously, the trend is consistent with the performance of chip seals over time—reduced friction as the treatment ages due to bleeding and/or raveling.

> Data on single/double/triple seal were only available for North Carolina and Pennsylvania. For single applications, there is some indication that the safety benefit is greater in the first year after treatment than in later years; however, there is no such trend for double/triple seals.

This trend for double/triple seals could be the result of improved performance (e.g., reduced chip loss/bleeding over time) over a single chip seal, owing to the thickness of double/triple seals.

Age of Treatment—OGFC

> For freeways, there appears to be a trend of a decreasing CMF (increasing benefits) as the pavement age increases for the first 4 years. For two-lane roads, however, the trend is the opposite, and the benefits are seen to decline as the pavement ages.

The trend observed for two-lane roads is closer to what might be expected from OGFC because the treatment may clog over time, reducing its porosity and effectiveness in draining water from the surface. There is no clear explanation for the contrary effect on freeways.

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APPENDIX A—INVESTIGATION OF THE DEVELOPMENT OF CMFUNCTIONS

OBJECTIVES

A thorough disaggregate analysis of the before–after evaluation data was undertaken in which regression analysis was used to investigate the effects on the CMFs of a number of variables, including AADT, precipitation, expected crash frequency before treatment, and environment (urban/rural). The primary objective was to investigate whether CMFunctions could be developed to capture the effects of these factors and more precisely estimate CMFs for prospective treatments.

If successful, such CMFunctions would allow a user to apply a more accurate CMF that better reflects the specific site characteristics than an average value.

METHODOLOGY

The methodology investigated was a relatively new and innovative approach that models the values of the CMF using weighted linear regression.(50) Because of the preponderance of sites with zero crashes and short segment lengths, each individual segment could not be used as an observation. Rather, all segments were grouped together by ranges of the variables being modeled and then used to estimate a CMF and its variance for that group. Segments were not aggregated across States because applications may vary across States in unknown ways. Also, consistency in results across States would be indicative of the accuracy of the results.

For example, if the model were only to consider an urban versus rural environment, then all urban sites would be used to estimate a CMF and its variance, and the same would be done for rural sites. This would be done separately for each State. Then the weighted linear regression model would be estimated using these estimates of the CMF as the dependent variable and a categorical variable to represent urban versus rural settings as the independent variable. The regression weights are assigned as the inverse of the variance of the CMF estimate.

The variable definitions for those independent variables considered are described below. For those variables that are continuous in nature (i.e., AADT and precipitation), the weighted mean for each category was used as the independent variable. The weights applied are the mile-years of after period data for each segment. The cutoff points for defining categories for the continuous variables were determined in an iterative manner and considering the goodness-of-fit of the estimated models and the number of observations in each category. Following are the variable specifications so obtained.

RURURB

if URBAN then rururb = 1.
if RURAL then rururb = 0.

PTYPE

if concrete pavement then ptype = 1.
if asphalt pavement then ptype = 0.

AADT Categories for Freeways (after period AADT)

if AADT >= 0 and AADT < 20,000 then volcat *= 1.
if AADT >= 20,000 and AADT < 40,000 then volcat = 2.
if AADT >= 40,000 and AADT < 60,000 then volcat = 3.
if AADT >= 60,000 and AADT < 80,000 then volcat = 4.
if AADT >=80,000 and AADT < 100,000 then volcat = 5.
if AADT >= 100,000 then volcat = 6.

*Weighted mean AADT for each category is used as the independent variable.

AADT Categories for Multilane Roads

if AADT >= 0 and AADT < 10,000 then volcat *= 1.
if AADT >= 10,000 and AADT < 20,000 then volcat = 2.
if AADT >=20,000 and AADT < 30,000 then volcat = 3.
if AADT >= 30,000 and AADT < 40,000 then volcat = 4.
if AADT >= 40,000 and AADT <50,000 then volcat = 5.
if AADT >= 50000 then volcat = 6.

*Weighted mean AADT for each category is used as the independent variable

AADT Categories for Two-Lane Roads

if AADT >= 0 and AADT < 5,000 then volcat* = 1.
if AADT >= 5,000 and AADT < 10,000 then volcat = 2.
if AADT >= 10,000 and AADT < 15,000 then volcat = 3.
if AADT >= 15,000 then volcat=4.

*Weighted mean AADT for each category is used as the independent variable

Precipitation Categories (the 5-year average precipitation in after period)

if precip <= 30 then prec = 1.
if precip > 30 and __yr_precip <= 40 then prec* = 2.
if precip > 40 and __yr_precip <= 45 then prec = 3.
if precip > 45 and __yr_precip <= 50 then prec = 4.
if precip > 50 then prec = 5.

*Weighted mean precipitation for each category is used as the independent variable.

ACCRATE

accrate= sum of expected crashes after without treatment/sum of mile-years of after-period data.

RESULTS

Models were attempted separately for all crash types and all road types (freeway, multilane, and two-lane) with varying success. Given the data demands for even estimating a single average CMF, it is perhaps not surprising that estimating several CMFs for categorized subsets of the same data proved challenging.

Nevertheless, in general, the results did suggest that there is a relationship between CMFs and AADT and sometimes precipitation, urban versus rural setting, and expected crash frequency. However, the direction of the effect is not always consistent, varying by crash type, site type, and treatment. Future research will need to reconcile (i.e. explain) these apparent inconsistencies.

Some of the more promising results are provided below to illustrate the potential for developing CMFunctions for pavement treatments. It is not, however, recommended to use these models for estimating CMFs. Rather the aggregate CMFs in chapter 6 are recommended at the current time.

Thin HMA—Freeway—Total Crashes

For thin HMA treatments on freeways, the model in figure 36 was estimated for total crashes, and table 41 presents the results.

$$\mathrm{CMF} = a + b(\mathrm{AADT}/10000)$$

Figure 36. Equation. Model estimated for total crashes on thin HMA treatments on freeways.

Table 41. Results for model for total crashes on thin HMA treatments on freeways.

Parameter	Estimate (standard error)
a	0.6720 (0.0954)
b	0.0221 (0.0065)
R-squared	0.5133

The results indicate that the CMF value increases with increasing AADT, meaning that the treatment is more effective at locations with lower AADTs.

OGFC—Two-Lane—Total Crashes

For OGFC treatments on two-lane roads, the model in figure 37 was estimated for total crashes and table 42 presents the results.

$$\mathrm{CMF} = a + b(\mathrm{AADT}/10000) + c(\mathrm{precip})$$

Figure 37. Equation. Model estimated for total crashes on OGFC treatments on two-lane roads.

Table 42. Results for model for total crashes on OGFC treatments on two-lane roads.

Parameter	Estimate (standard error)
a	1.33347 (0.1869)
b	-0.0581 (0.0823)
c	-0.0100 (0.0078)
R-squared	0.4014

The results indicate that the CMF value decreases with increasing AADT, meaning that the treatment is more effective at locations with higher AADTs. The model also indicates that the CMF decreases at higher levels of precipitation, indicating that the treatment is more effective in areas with higher precipitation. The parameter estimates for the model, however, are of low statistical significance.

Diamond Grinding—Freeway—Total Crashes

For diamond grinding treatments on freeways, the model in figure 38 was estimated for total crashes, and table 43 presents the results.

$$\mathrm{CMF} = a + b(\mathrm{AADT}/10000) + c(\mathrm{precip})$$

Figure 38. Equation. Model estimated for total crashes on diamond grinding treatments on freeways.

Table 43. Results for model for total crashes on diamond grinding treatments on freeways.

Parameter	Estimate (standard error)
a	1.0800 (0.0415)
b	-84.0876 (36.53)
c	-0.0202 (0.2262)
R-squared	0.5514

The results indicate that the CMF value decreases with increasing AADT, meaning that the treatment is more effective at locations with higher AADTs. The model also indicates that the CMF decreases at higher levels of precipitation, indicating that the treatment is more effective in areas with higher precipitation. The parameter estimates for the precipitation variable is of low statistical significance however.

APPENDIX B—LIST OF HFS TREATMENT SITES PROVIDED BY STATE

Table 44. Treatment sites by State, part 1.

State	County	Route	Dir	Milepost Begin	Milepost End	Site Type	Location Description	Area Type	Number Lanes	Radius of Curvature	Type of Curve	Friction Data (DFT 20 kph) Pre-HFS	Friction Data (DFT 20 kph) HFS 1-Year	Friction Data (DFT 20 kph) HFS 3-Year
KS	**Johnson**	**I-35**	NB	28.487	28.487	ramp	Ramp from NB I-35 to NB I-635	urban	1	410	simple	0.519	0.558	0.594
KS	**Leavenworth**	**K5**	Both	6.141	6.141	curve	Curve on K5	rural	2	215	simple	0.283	0.588	0.604
KS	**Sedgwick**	**K96**	EB	36	36	ramp	Ramp from EB K96 to EB US 54	urban	1	280	compound	0.422	0.641	0.648
KS	**Wabaunsee**	**K99**	Both	36.887	36.887	curve	Curve on K99	rural	2	1190	simple	0.381	0.688	-
CO	**Boulder**	**US36**	Both	10.92	11.09	curve	Curve on US 36	rural	2	330	simple	0.541	0.699	0.637
CO	**Boulder**	**CO119**	Both	30.48	30.63	curve	Curve on CO 119	rural	2	380	simple	0.73	0.617	0.467
MT	**Missoula**	**US93**	SB	85.8	86.2	curve	SB lanes for US 93	rural	2	910	simple	0.783	0.612	0.294
MT	**Silver Bow**	**I-15**	NB	121	121.5	ramp	Ramp from NB I-15 to WB I-90	rural	1	150	compound	0.698	0.746	0.688
MI	**Oakland**	**I-75**	NB	0	0.166	ramp	Ramp from NB I-75 to SB Baldwin Rd.	urban	1	220	simple	0.491	0.923	0.643
MI	**Oakland**	**I-75**	NB	0.168	0.21	ramp	Right and middle lane of curve along ramp from NB I-75 to Rochester Rd.	urban	2	215	simple	0.359	1.02	0.885
MI	**Genesee**	**I-69**	WB	0.194	0.497	ramp	Ramp from WB I-69 to SB I-75	urban	1	265	compound	0.403	0.636	0.546
MI	**Kent**	**I-96**	WB	0	0.127	ramp	Ramp from WB I-96 to NB US 131	urban	1	310	simple	0.466	0.737	0.569
MI	**Wayne**	**M39**	NB	0.013	0.037	ramp	First part of ramp from NB M-39 Ramp to EB US-12	urban	1	115	simple	—	—	—
MI	**Macomb**	**I-94**	EB	0.496	0.523	ramp	Portion of ram from EB I-94 ramp to NB Gratiot Ave	urban	1	675	simple	—	—	—
MI	**Delta**	**M35**	EB	0.606	0.701	curve	Downhill curve on M-35	urban	1	515	simple	—	—	—
KY	**Jefferson**	**KY-1142**	Both	0.343	0.408	curve	Single curve	urban	2	360	s-curve	—	—	—
KY	**Jefferson**	**KY-22**	WB	1.38	1.46	curve	Single curve	urban	1	515	simple	—	—	—
KY	**Jefferson**	**KY-22**	WB	2.893	2.971	curve	Single curve	urban	1	390 EB/ 340 WB	simple	—	—	—
KY	**Oldham**	**KY-22**	Both	4.385	4.47	curve	Single curve	rural	2	475	simple	—	—	—
KY	**Fayette**	**KY-922**	Both	7.815	7.876	curve	Single curve	rural	2	390	simple	—	—	—
KY	**Garrard**	**KY-1295**	Both	2.788	2.908	curve	Single curve	rural	2	675	simple	—	—	—
KY	**Garrard**	**KY-1295**	Both	2.933	3.062	curve	Single curve	rural	2	745	simple	—	—	—
KY	**Garrard**	**KY-1295**	Both	4.579	4.753	curve	Single curve	rural	2	560	simple	—	—	—
KY	**Garrard**	**KY-1295**	Both	4.773	5.073	curve	Single curve	rural	2	575	simple	—	—	—
KY	**Jessamine**	**KY-29**	Both	6.438	6.516	curve	Single curve	rural	2	1100	simple	—	—	—

State	County	Route	Dir	Milepost Begin	Milepost End	Site Type	Location Description	Area Type	Number Lanes	Radius of Curvature	Type of Curve	Friction Data (DFT 20 kph) Pre-HFS	Friction Data (DFT 20 kph) HFS 1-Year	Friction Data (DFT 20 kph) HFS 3-Year
KY	**Madison**	**KY-21**	Both	6.777	6.837	curve	Single curve	rural	2	255	simple	—	—	—
KY	**Madison**	**KY-21**	Both	6.861	6.912	curve	Single curve	rural	2	635	simple	—	—	—
KY	**Madison**	**KY-21**	Both	11.297	11.374	curve	Single curve	rural	2	405	simple	—	—	—
KY	**Madison**	**KY-21**	Both	12.308	12.428	curve	Single curve	rural	2	590	simple	—	—	—
KY	**Madison**	**KY-21**	Both	12.492	12.593	curve	Single curve	rural	2	860	simple	—	—	—
KY	**Madison**	**KY-21**	Both	12.807	12.922	curve	Single curve	rural	2	640	simple	—	—	—
KY	**Madison**	**KY-21**	Both	13.258	13.424	curve	Single curve	rural	2	470	simple	—	—	—
KY	**Madison**	**US-421**	Both	3.56	3.639	curve	Single curve	rural	2	390	simple	—	—	—
KY	**Madison**	**US-421**	Both	5.943	6.101	curve	Single curve	rural	2	225	simple	—	—	—
KY	**Madison**	**US-421**	Both	6.125	6.282	curve	S-curve	rural	2	255	s-curve	—	—	—
KY	**Madison**	**US-421**	Both	6.303	6.382	curve	Single curve	rural	2	570	simple	—	—	—
KY	**Scott**	**US-25**	Both	11.03	11.104	curve	Single curve	rural	2	725	simple	—	—	—
KY	**Scott**	**US-25**	Both	11.14	11.199	curve	Single curve	rural	2	540	simple	—	—	—
KY	**Bracken**	**KY-1159**	Both	1.771	1.971	curve	S-curve	rural	2	530	s-curve	—	—	—
KY	**Bracken**	**KY-1159**	Both	2.197	2.31	curve	Single curve	rural	2	215	simple	—	—	—
KY	**Greenup**	**KY-1458**	Both	1.31	1.369	curve	Single curve	rural	2	170	simple	—	—	—
KY	**Hardin**	**KY-9001**	EB	—	—	ramp	Ramp from WK Pkwy EB (KY 9001) to I-65 NB	urban	1	240	simple	—	—	—
KY	**Fayette**	**I-75**	NB	—	—	ramp	Ramp from I-75 NB to US 27	urban	1	155	compound	—	—	—
KY	**Mercer**	**US-68**	Both	5.112	5.312	curve	S-curve	rural	2	315	s-curve	—	—	—
KY	**Pike**	**US-460**	Both	23.08	23.12	curve	Single curve	rural	2	435	simple	—	—	—
SC	**Charleston**	**I-526 @ US 17**	NB	—	—	ramp	Ramp from NB US 17 to WB I-526—first half of ramp	urban	1	140	compound	—	—	—
SC	**Charleston**	**I-526 @ US 17**	EB	—	—	ramp	Ramp from SB US 17 to EB I-526—end of ramp	urban	1	140	simple	—	—	—
SC	**Cherokee**	**I-85 @ US 29**	NB	—	—	ramp	Offramp from NB I-85 to US 29—only first part of ramp treated	urban	1	140	simple	—	—	—
SC	**Greenville**	**US 25**	Both	52.19	53.22	curve	Multiple curves	rural	4	1430 (2)	multiple curves	—	—	—
SC	**Horry**	**SC 31 @ SC 9**	EB	—	—	ramp	Ramp from NB/EB SC 31 to NB SC 9—first part of ramp	urban	2	765	simple	—	—	—
SC	**Horry**	**SC 31 @ SC 9**	EB	—	—	ramp	Ramp from NB SC 9 to NB/WB SC 31—first part of ramp	urban	1	255	simple	—	—	—
SC	**Horry**	**SC 31 @ SC 544**	WB	—	—	ramp	Ramp from WB/SB SC 31 to SB SC 544—first part of ramp	urban	1	255	simple	—	—	—

State	County	Route	Dir	Milepost Begin	Milepost End	Site Type	Location Description	Area Type	Number Lanes	Radius of Curvature	Type of Curve	Friction Data (DFT 20 kph) Pre-HFS	Friction Data (DFT 20 kph) HFS 1-Year	Friction Data (DFT 20 kph) HFS 3-Year
SC	**Horry**	**SC 31 @ US 501**	WB	—	—	ramp	Ramp from WB/SB SC 31 to SB US 501—first half of ramp	urban	1	295	simple	—	—	—
SC	**Horry**	**SC 31 @ US 501**	EB	—	—	ramp	Ramp from NB/EB SC 31 to NB US 501—first part of ramp	urban	1	315	simple	—	—	—
SC	**Richland**	**I-126 @ US 21**	NB	—	—	ramp	Ramp from NB US 21 (Huger St.) to WB I-126	urban	2	315	simple	—	—	—
SC	**Richland**	**I-126 @ US 21**	SB	—	—	ramp	Offramp from EB I-126 to SB US 21 (Huger St.)	urban	2	700	simple	—	—	—
TN	**Houston**	**SR49**	Both	14.9	15.15	curve	Rural road curve	rural	2	975	simple	—	—	—
TN	**Carter**	**SR37**	Both	11.6	11.75	curve	Rural road curve	rural	3	405	simple	—	—	—
TN	**Rhea**	**SR30**	Both	6.84	7.14	curve	Rural road curve	rural	3	475	simple	—	—	—
TN	**Cumberland**	**SR68**	Both	8.1	8.33	curve	Rural road curve	rural	2	440	simple	—	—	—
WI	**Milwaukee**	**I-94**	EB	346.57	346.57	ramp	Ramp from EB I-94 to NB I-43	urban	2	505	compound	0.314	0.979	-
CA	**Humboldt**	**US 101**	NB	88.2	88.3	ramp	Ramp from NB US 101 to EB CA 299—first part of ramp	urban	1	290	simple	—	—	—
CA	**Nevada**	**CA 20**	Both	30.4	30.6	curve	Single curve	rural	2	300	simple	—	—	—
CA	**Sacramento**	**US 50**	WB	16.805	n/a	ramp	Ramp from Folsom Blvd to WB US 50—beginning of ramp	urban	3	205	simple	—	—	—
CA	**Sacramento**	**US 50**	WB	16.805	n/a	ramp	Ramp from Folsom Blvd to WB US 50—end of ramp	urban	1	870	simple	—	—	—
CA	**Sacramento**	**US 50**	WB	R0.595	n/a	ramp	Ramp from Stockton Blvd to WB US 50—end of ramp	urban	1	150	simple	—	—	—
CA	**Sacramento**	**US 50**	WB	R2.680	n/a	ramp	Ramp from NB 65th St. to WB US 50—end of ramp	urban	1	150	simple	—	—	—
CA	**Santa Cruz**	**CA17**	SB	9.37	9.65	curve	Curve on SB Highway 17	rural	2	470	simple	0.469	0.806	—
TX	**Williamson**	**I-35**	NB	—	—	ramp	Ramp for U-turn lane on NB I-35 frontage road at FM 2338	urban	1	60	simple	0.456	—	—
TX	**Williamson**	**US 183**	NB	—	—	curve	Curve at intersection of NB US 183 and US 183A	rural	2	115	simple	0.52	—	—

State	County	Route	Dir	Milepost Begin	Milepost End	Site Type	Location Description	Area Type	Number Lanes	Radius of Curvature	Type of Curve	Friction Data (DFT 20 kph) Pre-HFS	Friction Data (DFT 20 kph) HFS 1-Year	Friction Data (DFT 20 kph) HFS 3-Year
IA	**Polk**	**I-80**	EB	—	—	ramp	Ramp from EB I-80 to SB I-235	urban	1	510	simple	—	—	—
IA	**Polk**	**I-80**	EB	—	—	ramp	Ramp from EB I-80 to NB I-35	urban	1	770	simple	—	—	—
IA	**Polk**	**I-80**	WB	—	—	ramp	Ramp from WB I-80 to SB I-235	urban	1	770	simple	—	—	—
IA	**Linn**	**I-380**	Both	19.7	19.7	curve	Elevated roadway on I-380 just south of Cedar River	urban	6	1125	simple	0.53	—	—
LA	**Orleans**	**I-610**	WB	2.7	3.17	curve	Curve on bridge/ elevated roadway	urban	3	1300	simple	—	—	—

Sites listed in California, Texas, and Iowa were not included in the analysis.

— = for Milepost columns, indicates information not available. For Friction Data columns, indicates data not available.

Dir = Direction

DFT = Drift friction tester

HFS = High friction surface

EB = Eastbound

WB = Westbound

Table 45. Treatment site by State, part 2.

State	County	Route	Underlying Pavement Type	Lane Width (Avg)	Left Shoulder Width (Avg)	Right Shoulder Width (Avg)	Posted Speed Limit	Month-Year of Treatment	Length of Treatment (ft)	Single/ Double HFST	HFST Binder Type	HFST Agg Type
KS	**Johnson**	**I-35**	pcc	11	10	4	35	9-Aug	780	Single	Epoxy Binder	Flint
KS	**Leavenworth**	**K5**	asphalt	10.5	n/a	0	20	9-Aug	255	Single	Epoxy Binder	Flint
KS	**Sedgwick**	**K96**	pcc	15	4	8	30	9-Aug	850	Single	Epoxy Binder	Flint
KS	**Wabaunsee**	**K99**	asphalt	11	n/a	0	50	9-Aug	450	Single	Epoxy Binder	Flint
CO	**Boulder**	**US36**	asphalt	12	n/a	1	35	9-Sep	925	Single	Epoxy Binder	Flint
CO	**Boulder**	**CO119**	asphalt	12	n/a	2	40	9-Sep	600	Single	Epoxy Binder	Flint
MT	**Missoula**	**US93**	chip seal	12	4	8	55	9-Sep	1375	Single	Epoxy Binder	Flint
MT	**Silver Bow**	**I-15**	chip seal	13	6	6	25	9-Sep	1600	Single	Epoxy Binder	Flint
MI	**Oakland**	**I-75**	pcc	14	4	7	25	10-Sep	865	Single	Epoxy Binder	Bauxite
MI	**Oakland**	**I-75**	asphalt	12	n/a	8	35	10-Sep	275	Single	Epoxy Binder	Bauxite
MI	**Genesee**	**I-69**	pcc	14.5	3	6	25	10-Sep	1124	Single	Epoxy Binder	Flint
MI	**Kent**	**I-96**	pcc	14.5	6	8	25	10-Sep	730	Single	Epoxy Binder	Flint
MI	**Wayne**	**M39**	asphalt	13	2	2	15	?/2007	120	Single	Epoxy Binder	Bauxite
MI	**Macomb**	**I-94**	asphalt	11	15	12	45	?/2007	150	Single	Epoxy Binder	Bauxite
MI	**Delta**	**M35**	asphalt	12	n/a	12	40	9-Sep	500	Single	Epoxy Binder	Bauxite
KY	**Jefferson**	**KY-1142**	asphalt	10	n/a	2	35	10-Oct	343	Single	Epoxy Binder	Bauxite
KY	**Jefferson**	**KY-22**	asphalt	10	n/a	3	35	9-Jul	422	Single	Epoxy Binder	Bauxite
KY	**Jefferson**	**KY-22**	asphalt	11	n/a	3	35	10-Oct	412	Single	Epoxy Binder	Bauxite
KY	**Oldham**	**KY-22**	asphalt	10	n/a	3	45	9-Aug	449	Single	Epoxy Binder	Bauxite
KY	**Fayette**	**KY-922**	asphalt	9	n/a	4	55	10-Nov	322	Single	Epoxy Binder	Bauxite
KY	**Garrard**	**KY-1295**	asphalt	9	n/a	2	55	10-Nov	634	Single	Epoxy Binder	Bauxite
KY	**Garrard**	**KY-1295**	asphalt	9	n/a	2	55	10-Nov	681	Single	Epoxy Binder	Bauxite
KY	**Garrard**	**KY-1295**	asphalt	9	n/a	2	55	10-Nov	919	Single	Epoxy Binder	Bauxite
KY	**Garrard**	**KY-1295**	asphalt	9	n/a	2	55	10-Nov	1584	Single	Epoxy Binder	Bauxite
KY	**Jessamine**	**KY-29**	asphalt	10	n/a	4	55	10-Nov	412	Single	Epoxy Binder	Bauxite
KY	**Madison**	**KY-21**	asphalt	10	n/a	2	55	10-Nov	317	Single	Epoxy Binder	Bauxite
KY	**Madison**	**KY-21**	asphalt	10	n/a	2	55	10-Nov	269	Single	Epoxy Binder	Bauxite
KY	**Madison**	**KY-21**	asphalt	10	n/a	2	45	11-Apr	407	Single	Epoxy Binder	Bauxite
KY	**Madison**	**KY-21**	asphalt	10	n/a	2	55	11-Apr	634	Single	Epoxy Binder	Bauxite
KY	**Madison**	**KY-21**	asphalt	10	n/a	2	55	11-Apr	533	Single	Epoxy Binder	Bauxite
KY	**Madison**	**KY-21**	asphalt	10	n/a	2	55	11-Apr	607	Single	Epoxy Binder	Bauxite
KY	**Madison**	**KY-21**	asphalt	10	n/a	2	55	11-Apr	876	Single	Epoxy Binder	Bauxite
KY	**Madison**	**US-421**	asphalt	10	n/a	3	55	11-Apr	417	Single	Epoxy Binder	Bauxite

State	County	Route	Underlying Pavement Type	Lane Width (Avg)	Left Shoulder Width (Avg)	Right Shoulder Width (Avg)	Posted Speed Limit	Month-Year of Treatment	Length of Treatment (ft)	Single/ Double HFST	HFST Binder Type	HFST Agg Type
KY	**Madison**	**US-421**	asphalt	10	n/a	3	55	11-Apr	834	Single	Epoxy Binder	Bauxite
KY	**Madison**	**US-421**	asphalt	10	n/a	3	55	11-Apr	829	Single	Epoxy Binder	Bauxite
KY	**Madison**	**US-421**	asphalt	10	n/a	3	55	11-Apr	417	Single	Epoxy Binder	Bauxite
KY	**Scott**	**US-25**	asphalt	10	n/a	3	55	10-Nov	391	Single	Epoxy Binder	Bauxite
KY	**Scott**	**US-25**	asphalt	10	n/a	3	55	10-Nov	312	Single	Epoxy Binder	Bauxite
KY	**Bracken**	**KY-1159**	asphalt	10	n/a	2	55	11-Apr	1056	Single	Epoxy Binder	Bauxite
KY	**Bracken**	**KY-1159**	asphalt	10	n/a	2	55	11-Apr	597	Single	Epoxy Binder	Bauxite
KY	**Greenup**	**KY-1458**	asphalt	11	n/a	2	35	11-Apr	312	Single	Epoxy Binder	Bauxite
KY	**Hardin**	**KY-9001**	asphalt	14	6	6	20	10-Nov	990	Single	Epoxy Binder	Bauxite
KY	**Fayette**	**I-75**	asphalt	15	4	6	25	10-Nov	790	Single	Epoxy Binder	Bauxite
KY	**Mercer**	**US-68**	asphalt	10	n/a	2	55	11-Nov	1056	Single	Epoxy Binder	Bauxite
KY	**Pike**	**US-460**	asphalt	10	n/a	2	55	11-Nov	211	Single	Epoxy Binder	Bauxite
SC	**Charleston**	**I-526 @ US 17**	asphalt	18	4	1	35	10-Nov	450	Single	Epoxy Binder	Bauxite
SC	**Charleston**	**I-526 @ US 17**	asphalt	17	4	2	35	10-Nov	345	Single	Epoxy Binder	Bauxite
SC	**Cherokee**	**I-85 @ US 29**	asphalt	16	3	10	20	11-Jun	250	Single	Epoxy Binder	Bauxite
SC	**Greenville**	**US 25**	asphalt	11	3	10	45	8-Oct	5438	Single	Epoxy Binder	Bauxite
SC	**Horry**	**SC 31 @ SC 9**	asphalt	11	6	10	40	10-Apr	515	Single	Epoxy Binder	Bauxite
SC	**Horry**	**SC 31 @ SC 9**	asphalt	16	3	3	30	10-Apr	925	Single	Epoxy Binder	Bauxite
SC	**Horry**	**SC 31 @ SC 544**	asphalt	17	5	5	25	10-Apr	620	Single	Epoxy Binder	Bauxite
SC	**Horry**	**SC 31 @ US 501**	asphalt	16	8	6	30	10-Apr	670	Single	Epoxy Binder	Bauxite
SC	**Horry**	**SC 31 @ US 501**	asphalt	14	6	6	25	10-Apr	560	Single	Epoxy Binder	Bauxite
SC	**Richland**	**I-126 @ US 21**	asphalt	12	0	0	35	11-Jun	650	Single	Epoxy Binder	Bauxite
SC	**Richland**	**I-126 @ US 21**	asphalt	14	0	0	35	11-Jun	715	Single	Epoxy Binder	Bauxite
TN	**Houston**	**SR49**	asphalt	12	n/a	10	55	10-May	1100	Single	Epoxy Binder	Bauxite
TN	**Carter**	**SR37**	asphalt	11	n/a	6	55	9-Apr	800	Single	Epoxy Binder	Bauxite
TN	**Rhea**	**SR30**	asphalt	12	n/a	4	55	9-Apr	1600	Single	Epoxy Binder	Bauxite
TN	**Cumberland**	**SR68**	asphalt	11	1	1	55	9-Apr	1200	Single	Epoxy Binder	Bauxite
WI	**Milwaukee**	**I-94**	asphalt	12	4	14	40	11-Sep	1130	Single	Epoxy Binder	Bauxite
CA	**Humboldt**	**US 101**	asphalt	11	4	6	35	12-Oct	800	Single	Epoxy Binder	Bauxite
CA	**Nevada**	**CA 20**	asphalt	11.5	6	6	30	11-Jul	700	Single	Epoxy Binder	Bauxite
CA	**Sacramento**	**US 50**	asphalt	14	2	6	25	11-Jul	645	Single	Epoxy Binder	Bauxite

State	County	Route	Underlying Pavement Type	Lane Width (Avg)	Left Shoulder Width (Avg)	Right Shoulder Width (Avg)	Posted Speed Limit	Month-Year of Treatment	Length of Treatment (ft)	Single/ Double HFST	HFST Binder Type	HFST Agg Type
CA	**Sacramento**	**US 50**	asphalt	12	3	1	25	11-Jul	400	Single	Epoxy Binder	Bauxite
CA	**Sacramento**	**US 50**	asphalt	13	4	6	35	11-Jul	330	Single	Epoxy Binder	Bauxite
CA	**Sacramento**	**US 50**	asphalt	13	6	8	35	11-Jul	415	Single	Epoxy Binder	Bauxite
CA	**Santa Cruz**	**CA17**	asphalt	12	5	11	40	12-Jul	930	Double	Polyester Resin	Bauxite
TX	**Williamson**	**I-35**	asphalt	17.5	5	7	n/a	10-Jun	240	Single	Epoxy Binder	Bauxite
TX	**Williamson**	**US 183**	asphalt	11	n/a	4	20	10-Jun	355	Single	Epoxy Binder	Bauxite
IA	**Polk**	**I-80**	asphalt	14	4	6	40	12-Jun	890	Single	Epoxy Binder	Bauxite
IA	**Polk**	**I-80**	asphalt	14	6	4	45	12-Jun	1270	Single	Epoxy Binder	Bauxite
IA	**Polk**	**I-80**	asphalt	14	6	4	45	12-Jun	1000	Single	Epoxy Binder	Bauxite
IA	**Linn**	**I-380**	pcc	12	5	9	55	12-May	2240	Single	Epoxy Binder	Bauxite
LA	**Orleans**	**I-610**	pcc	12	10	12	60	10-Mar	1265	Single	Epoxy Binder	Bauxite

Sites listed in California, Texas, and Iowa were not included in the analysis.
Avg = Average
HFST = High friction surface treatment
Agg = aggregate

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