Using High Friction Surface Treatments to Improve Safety at Horizontal Curves

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Highway safety research consistently shows that higher crash and fatality rates are observed on horizontal curves than on tangent segments (1, 2, *3*). Figure 1 shows the number of fatal crashes on horizontal curves by state in 2010. In that year, 8,763 fatal crashes occurred on horizontal curves. Many of these crashes are a result of insufficient pavement friction for the conditions at the time of the crash, due to excessive driving speed, wet weather, deteriorated pavement quality, or any combination of these or other circumstances.

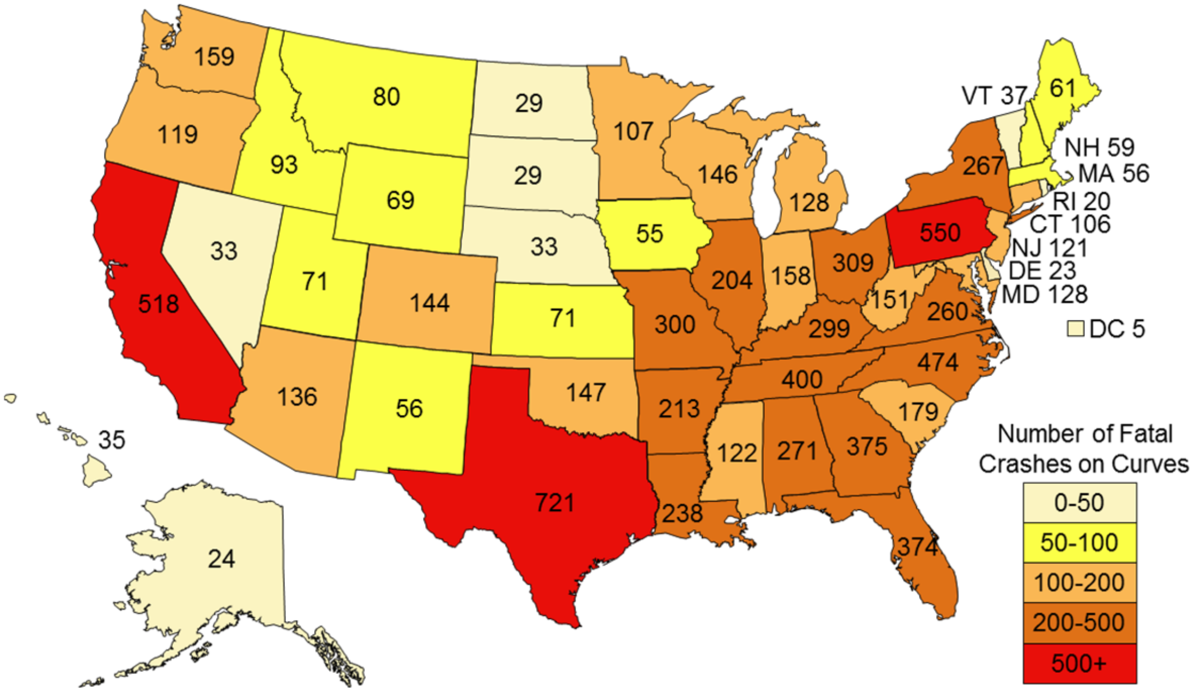

Figure 1: Fatal crashes on horizontal curves in 2010 (4).

Table 1 shows that in Texas, fatal crashes on curves have remained consistently above 700 per year since 2007, and comprising approximately 25 percent of all fatal crashes in Texas. Nationally, the number of fatal crashes occurring on curves has decreased to below 10,000 each year, but consistently remains above 27 percent of the total number of fatal crashes.

Table 1: Fatal Crashes on Curves for 2007-2010 (4)

	2006	2007	2008	2009	2010
Fatal crashes on curves in Texas	600	704	743	730	721
Fatal crashes on curves in Texas as a percent of total fatal crashes	19.2%	22.7%	23.8%	26.0%	24.7%
Fatal crashes on curves in the U.S.	10,342	10,463	9,517	8,534	8,763
Fatal crashes on curves in the U.S. as a percent of total fatal crashes	26.8%	27.9%	27.9%	27.7%	27.7%

The Texas Department of Transportation (TxDOT) has taken steps to proactively address the high crash and fatality rates on curves within the state. A 2011 report by the Texas Transportation Institute (TTI) determined the crash rates for injury and fatal crashes caused by roadway departures on curves and straight segments within TxDOT districts and grouped the rates as low, medium, and high. The data from the report is reproduced in Table 2 and Figure 2.

Table 2: Crash Rates for Injury and Fatality Roadway Departures (5)

TxDOT District	Injury and Fatality Rate for Roadway Departure Crashes per 100 MVMT					
	All Segments		Straight Segments		Horizontal Curves	
	Rate	Group	Rate	Group	Rate	Group
Paris	30.20	High	15.95	Medium	41.34	Medium
Fort Worth	36.95	High	19.28	Medium	50.42	High
Wichita Falls	27.02	Medium	23.62	High	33.20	Low
Amarillo	17.91	Low	12.59	Low	57.61	High
Lubbock	19.94	Low	17.88	Medium	21.11	Low
Odessa	27.42	Medium	26.46	High	28.63	Low
San Angelo	27.65	Medium	15.02	Low	42.07	Medium
Abilene	23.69	Low	22.72	High	39.15	Medium
Waco	27.19	Medium	17.21	Medium	39.45	Medium
Tyler	34.31	High	23.42	High	51.35	High
Lufkin	46.71	High	33.81	High	61.43	High
Houston	23.81	Medium	14.80	Low	49.16	High
Yoakum	25.29	Medium	22.14	High	33.89	Low
Austin	26.46	Medium	14.12	Low	37.03	Low
San Antonio	31.23	High	30.51	High	50.44	High
Corpus Christi	21.78	Low	15.30	Low	36.04	Low
Bryan	32.11	High	21.01	Medium	47.72	Medium
Dallas	29.14	Medium	22.58	High	42.82	Medium
Atlanta	30.35	High	21.24	Medium	43.48	Medium
Beaumont	23.34	Low	13.96	Low	32.24	Low
Pharr	26.11	Medium	14.57	Low	41.07	Medium
Laredo	14.77	Low	12.46	Low	51.10	High
Brownwood	30.84	High	15.31	Medium	45.05	Medium
El Paso	18.20	Low	20.07	Medium	48.87	High
Childress	15.84	Low	15.52	Medium	30.54	Low
State Average	26.73	-	19.26	-	42.21	-

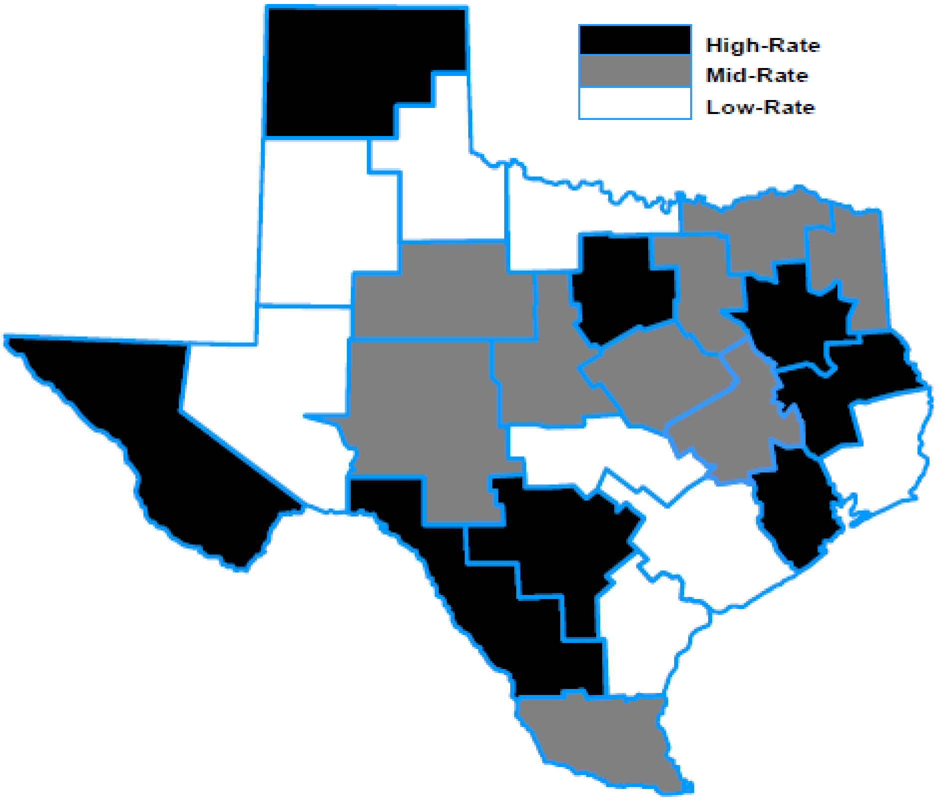

Figure 2: Fatal and injury roadway departure crash rate groups on horizontal curves in TxDOT districts (5).

Having identified areas where curves are in particular need of attention, the next step is to determine viable treatments to address the safety concerns. Increasing the friction at the pavement-tire interface can reduce crashes at locations where low levels of friction are observed or crashes during wet weather are common. One common procedure is called high friction surface treatments (HFSTs). Like a crash barrier or slip base for a sign, the purpose of an HFST is to make the road more forgiving to drivers by increasing the friction at locations where the demand for friction is great. Apart from applications on curves, HFSTs have been successful at other locations where the demand for friction may be great, such as on freeway ramps and intersection approaches. This report focuses on the benefits of HFSTs on conventional horizontal curves, including both the curvature and the approach to the curve where vehicles decelerate.

The purpose of this report is to quantify the potential benefits of applying HFSTs on curves using research findings that have shown their effectiveness at reducing crashes. This paper provides a background on the historical and modern use of HFSTs, shows how federal programs support them, and presents the physical components of a common application. The value of HFST treatments is also derived based on a review of studies on their effectiveness. The results are used to project the benefit of applying an HFST under various scenarios considering product cost and expected life. Finally, recommendations for placement are provided.

BACKGROUND

Lateral acceleration (or centripetal acceleration) is the component that moves vehicles in a circular direction around curves. The lateral force that supports this movement is determined by the speed and mass of the vehicle and the radius of the curve, and can be provided by superelevating the curve or relying on the side friction of the tires against the pavement. There is less demand for side friction when superelevation is provided, and the AASHTO Green Book (6) identifies five methods of supplying the necessary lateral force through various combinations of superelevation and side friction. When the amount of side friction required (called the side friction demand) is greater than the side friction supplied by the road, vehicles skid, often leading to lane departures and run-off-the-road (ROR) crashes that cause injuries and fatalities from overturning or colliding with fixed objects or opposing vehicles. These types of crashes account for the majority of crashes occurring on curves.

The Green Book provides the following guidance regarding side friction in the design of curves:

> *"Where practical, the maximum side friction factors used in design should be conservative for dry pavements and should provide an ample margin of safety against skidding on pavements that are wet as well as ice or snow covered. The need to provide skid-resistant pavement surfacing for these conditions cannot be overemphasized because superimposed on the frictional demands resulting from roadway geometry are those that result from driving maneuvers such as braking, sudden lane changes, and minor changes in direction within a lane. In these short-term maneuvers, high friction demand can exist but the discomfort threshold may not be perceived in time for the driver to take corrective action."(6)*

The guidelines for curve design are conservative enough that lane departures or ROR crashes should not be so prevalent. Unfortunately, there are a number of factors that may be present simultaneously, whose compounding effects cannot be considered in the design process. Some of them are: distracted driving, driver misjudgments, poor tire tread or insufficient vehicle maintenance, wet pavement conditions, and deteriorated pavement texture from aggregate polishing. On curve approaches, some drivers may not properly respond to the warning signs in advance of a curve. The sudden deceleration just before the curve may require more friction than supplied by the road, particularly during inclement weather. By increasing the friction of the pavement through a surfacing treatment, agencies can provide sufficient friction for these situations that lead to crashes (7).

Historical Use

HFSTs were first applied in the United Kingdom during the 1960's. The British government had begun to proactively address skidding crashes occurring at "black spots" and had found that the aggregate in the pavement at these locations had become polished (8). Research showed that small calcined bauxite chips were very resistant to polishing and could be applied to the surface of an existing pavement using an epoxy resin binder. The success of a trial period near London led to using the treatment to reduce crashes at black spots located on curves, roundabouts, and intersections. As a result of successful safety programs in the UK, with HFSTs playing a significant part, traffic fatalities have substantially and consistently decreased since the 1960's. HFSTs are now mandatory at certain curves, roundabouts, and intersection approaches.

Modern Use

After success in the UK, HFSTs began to be applied abroad. Hatherly and Young may have been the first in the United States to report on the benefits of calcined bauxite aggregate with epoxy resin in 1976, having found a 31% decrease in crashes at intersections where the HFST was applied (9). With more widespread use of the treatment in recent years, a number of applications have been documented as summarized below.

- Near Fort Lauderdale, Florida, the DOT applied an HFST in 2006 on a 300-ft section of an interstate loop ramp that had experienced twelve ROR crashes in a 3-year period (an average of four per year). In the following year after application only two ROR crashes were reported at that location. (8)
- In Bellevue, Washington, an HFST was applied in 2004 at a signalized intersection where one of the approaches is on a steep downgrade and a sharp curve. During a 5-year before period 21 crashes were observed; during the following 4 years only two crashes were observed. (8)
- The Pennsylvania DOT applied an HFST in 2007 on a rural road with a sharp curve with narrow lanes and no shoulders. The curve has a cliff on one side and a canal on the other, making such a segment even more problematic. Because of the success of the HFST at that location after only one year, the DOT made plans to install more HFSTs at sharp horizontal curves in its state. (8)
- In New Zealand, an HFST was applied in 1997 to a curve where 173 crashes had been observed over a 7-year period. During the following 7-year period only 11 crashes were observed (a 94-percent reduction). (*10*)
- In Kentucky, a program to improve safety through upgrading traffic control devices or applying HFSTs was initiated at 30 curves throughout the state. The DOT found HFSTs to be the more cost-effective of the two methods. (*11*)
- In Wisconsin, the DOT applied HFSTs at multiple sites, and found a reduction in crashes from 28 during a 3-year before period to two crashes in a 3-year after period (93 percent reduction). During those 6 years, only one crash occurred outside of the November to February winter months and occurred during wet weather. (*12*)

State HFST Programs

Kentucky was the first state to develop an HFST program to proactively address crashes on horizontal curves. To select sites for application, the crashes on rural roads are analyzed to identify locations where eight wet-weather, lane-departure crashes occurred within a 3,000-ft section. Further analysis is then completed to determine if the site will benefit from an increase in friction. These sites tend to have polished pavement or characteristics (like curves) that may have high levels of friction demand. A comprehensive crash analysis of the HFST applications has not yet been made, though the initial results show significant reductions in crash rates (*13*). Kentucky's program is primarily funded through the Highway Safety Improvement Program, with some specific locations funded by the state. Following Kentucky's initiative, West Virginia and Virginia have also recently developed an HFST program.

Federal Support

Since the Highway Safety Act of 1966, states have been tasked with proactively establishing programs to reduce crashes. McNeal (*14*) and Hall et al. (7) discuss four specific requirements of the Act: A system of recording crashes, investigations to determine the cause of a crash, proper design and maintenance of road facilities, and monitoring to detect and mitigate high-crash locations. After the Highway Safety Act of 1966 the Federal Highway Administration (FHWA) subsequently issued Highway Safety Program Standard 12 and Instructional Memorandum 21-2-73 titled "Skid-Accident Reduction" to instruct states to develop standards related to pavement design and construction and evaluate them within a safety framework to address locations subject to skidding (*14*, 7).

In 1980, FHWA provided more information on addressing problems with skid-accidents through *Technical Advisory T 5040.17*. FHWA emphasized identifying locations with high skid-accidents, ensuring that new pavements have adequate skid resistance, and using resources to address crash reductions in a cost-effective manner (7, *15*). In a Technical Advisory from 2005 (*16*), FHWA elaborated on the requirements of 23 CFR 626.3, called the FHWA pavement policy, explaining that a safe pavement design includes providing wet pavement friction, which is primarily governed by the pavement texture. In developing friction requirements within an individual agency, FHWA encourages states to give special attention to factors related to high-speed facilities, climate, and roadway geometry.

In 2008, AASHTO released a report *Driving Down Lane-Departure Crashes* (*17*) that focused attention on the problem of high crash and fatality rates associated with lane and roadway departures. Providing skid-resistant pavement is one of the treatments AASHTO recommends for situations when greater traction is needed. The report states that a water film 0.002 in. thick reduces tire pavement friction by 20 to 30 percent.

The Highway Safety Improvement Program (HSIP) was established to encourage agencies to address crashes that may be avoided through a program of monitoring safety and identifying potential improvements. 23 CFR 148(c)(1)(D) requires that DOTs identify the top 5 percent of crash locations within their states. They are given flexibility in producing the 5 Percent Reports, and the methods used in that process can be applied to identify areas where problems with friction may be addressed with an HFST. HSIP funds can be used for HFST applications, and the recently-passed surface transportation bill (MAP-21) increases HSIP funding and allows for a systemic approach in identifying treatment sites. In a systemic approach, crashes are not the primary determinant for treatment, but surrogate safety measures. One example would be to apply HFSTs based on in-field friction measurements, rather than observed crashes.

Components of a High Friction Surface Treatment

The amount of friction supplied at the tire-pavement interface is mainly determined by the vehicle's speed, condition of the tire treads, tire pressure, the presence or absence of water or ice and possible pollutants (such as motor oil), and the texture of the pavement (7). The texture of the pavement is the only factor that can be reasonably controlled by an agency and is primarily described by two terms: microtexture and macrotexture. Microtexture and macrotexture refer to deviations in the pavement from a true planar (flat) surface. Microtexture describes the roughness of the aggregate particles at a microscopic level, with small chips in a particle of aggregate less than 0.02 in. wide. Macrotexture describes the properties of the aggregate on a visible level, such as the gradation and spacing of gaps between particles 0.02–2 in. wide. Figure 3 visually represents these characteristics.

Both properties describing the pavement texture affect the friction provided to a vehicle's tires. Generally, good microtexture supports driving at low speeds and good macrotexture at high speeds (*19, 20*). Friction decreases with higher speed, but the gradient is lessened with greater amounts of macrotexture. This principle was shown by McLean and Foley (*21*) in Figure 4, demonstrating that friction is dependent on the running speed of the vehicle, but that higher measurements of microtexture and macrotexture result in more friction, regardless of the speed of the vehicle. Note that Figure 4a shows that the friction-speed gradient is less severe for surfaces with high macrotexture than surfaces with low macrotexture. This principle is also supported by research conducted for the UK Transport Research Laboratory (*22*).

In addition to improved friction, higher macrotexture promotes channeling water under tires and thus reduces the risk of hydroplaning during wet conditions. Because the aggregate provides better friction and improved vehicle control under wet conditions, these treatments are ideal for locations with high proportions of skidding, wet-weather, and ROR crashes. A study completed in Europe shows a reduction in both wet- and dry-weather crashes due to increased macrotexture in the pavement (*22*).

The bauxite aggregate used in many HFST applications is very resistant to polishing that reduces both microtexture and macrotexture. Its good texture and resiliency are key to providing long-lasting skid resistance. ASTM D3319 is used to simulate the polishing that occurs on pavement aggregate under vehicle tires. The polished stone value (PSV) determined from the test indicates on a scale of 0 to 100 an aggregate's resistance to polishing. Bauxite has been shown to have a value near 70 (*24, 25*). In a study by TTI of six different aggregates used in pavements and excavated from Texas pits, their polish values were between 21 and 38 (*26*).

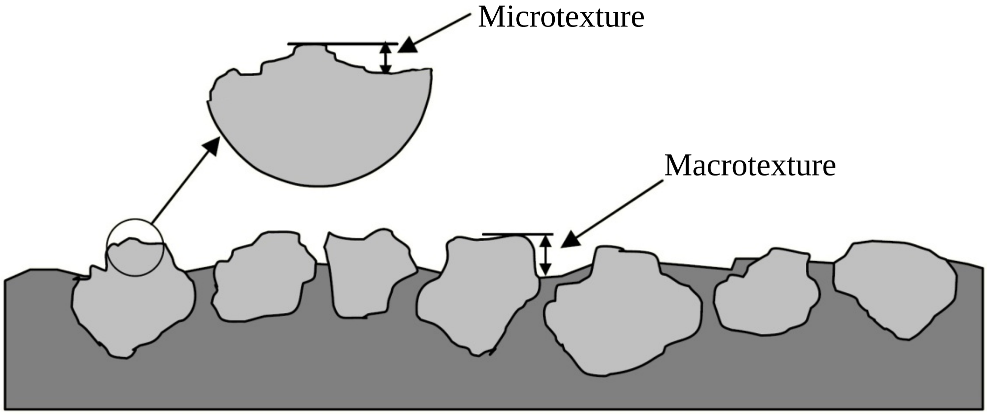

Figure 3: The relationship between different textures in pavement aggregate (*23*).

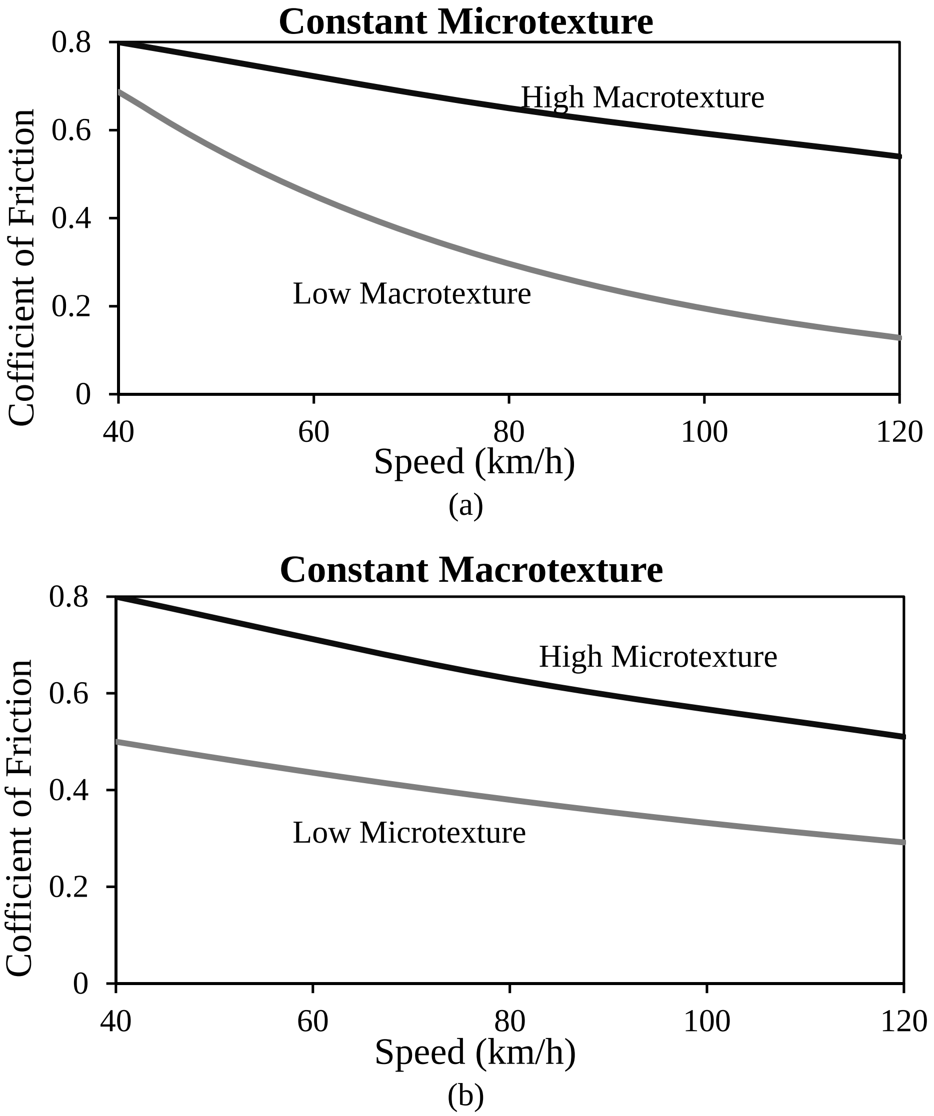

Figure 4: Friction gradients for speed under various conditions of pavement texture (*21*).

THE VALUE OF A HIGH FRICTION SURFACE TREATMENT

Vehicle crashes result in societal and economic costs from the lives that are lost, the pain and suffering felt by those injured or those associated with the injured or deceased, the property damage to vehicles and highway facilities, the demands on law enforcement and emergency response personnel, and other effects of crashes. The value of an HFST is rooted in economically quantifying the reductions in fatalities, injuries, and overall crashes that are a result of the applied treatment. To obtain this value, the following information must be known: the expected reduction in crashes as a percent of total crashes, the crash frequency expected at a specific location, and an assessed economic cost of crashes. Using the cost of a typical application and the expected life of the treatment, a true benefit-cost analysis can be completed to find the value of an HFST.

Crash Reductions from Studies of HFST Applications

The use of the HFST applications presented in the Background, though successful, have not received enough widespread use within a jurisdiction to develop statistically-sound estimates of their effectiveness. Fortunately, some studies have been completed whose results may be worthy of predicting crash reductions when applied at other locations. The following discussion presents some of the research findings that can be used to project possible benefits from applying HFSTs. Not all of the studies analyzed HFSTs of the same composition, but they were still able to link an improvement in safety with improved friction.

NCHRP report 617 (*27*) presents crash reductions for friction treatments developed from data first analyzed by Bray (*28*) based on New York's Skid Accident Reduction Program that targets locations within the state based on a high proportion of wet-road accidents and low friction numbers (SN less than 32). The treatments were generally a 1 ½-in. hot-mix asphalt resurfacing or a ½-in. microsurfacing of noncarbonated aggregates. A 24 percent reduction for all crashes and a 57 percent reduction in wet-weather crashes were identified.

A 1996 report by the Kentucky Transportation Center (*29*) compiled a number of accident reduction factors used by states during the planning and programming of projects. The average accident reduction for an applied skid resistant surface was 27 percent for all crashes and 45 percent for wet-weather crashes. The report also contained a literature review of research on friction treatments and found the average reduction for all crashes was 22 percent, with a 50 percent reduction in wet weather crashes.

A similar report was completed for the Florida DOT in 2005 (*30*) and includes reduction factors used by other state agencies. The following reductions are cited in the report:

- Reductions for resurfacing a curve with a skid-resistant overlay:
  - 10 percent for all crashes (California)
  - 24 percent for all crashes (Montana)
  - 51 percent for wet pavement crashes (Missouri)
- Reductions for overlay skid treatments:
  - 20 percent for all crashes on roads with ADT>5,000/lane (New York)
  - 13 percent for all crashes on roads with ADT<5,000/lane (New York)
  - 28 percent for run-off-road fatal and injury crashes (Minnesota)
  - 29 percent for run-off-road property damage only crashes (Minnesota)
  - 50 percent for wet-pavement crashes on roads with ADT>5,000/lane (New York)
  - 23 percent for wet-pavement crashes on roads with ADT<5,000/lane (New York)
  - 27 percent for all crashes (Iowa)
  - 42 percent for all crashes (Texas)
- Reductions for general resurfacing:
  - 7 percent for all crashes (Arizona)
  - 25 percent for all crashes (Kentucky)
  - 25 percent for all crashes (Missouri)
  - 25 percent for all crashes (Oklahoma)
  - 25 percent for all run-off-road crashes (Arizona)
  - 45 percent for all wet-pavement crashes (Kentucky)
  - 45 percent for all wet-pavement crashes (Missouri)

From these reductions applied by various state DOTs through individual experience and research, it appears that a 20-to 30-percent reduction in all crashes and a 50-percent reduction in wet-weather crashes is a reasonable expectation for general HFST applications. Based on the specific examples cited above, greater reductions may be observed for locations where friction treatments are in particular need.

Average Crash Frequencies

The Highway Safety Manual (HSM) (*31*) contains safety performance functions (SPFs) that estimate the number of crashes expected to occur on a highway segment under various conditions. Equation 1 is the SPF for a two-lane rural highway segment, and Equation 2 is the crash modification factor (CMF) for horizontal curves. These equations are used to construct Table 3, which provides yearly crash frequencies that can be expected for curves of the given hypothetical conditions. Year-to-year fluctuations in observed crashes can be expected, but these predictions are averages based on a large and national dataset. The curves that experience crash frequencies consistently higher than these predictions should be examined for potential safety-related treatments. If a substantial portion of the crashes are due to skidding or wet weather, an HFST should be considered as a viable option.

$$N = AADT \times L \times 2.67 \times 10^{-4} \times CMF \qquad (1)$$

$$CMF = \frac{1.55 \times L + \frac{80.2}{R}}{1.55 \times L} \qquad (2)$$

Where *N* is the yearly crash frequency, *AADT* is the annual average daily traffic, *L* is the segment length (in miles), and *R* is the curve radius (in feet).

Table 3: Expected Yearly Crash Frequencies Using the Highway Safety Manual (*31*)

Radius (ft)	AADT (vpd)	Curve Length (ft)		
		300	500	700
250	4,000	0.28	0.32	0.36
250	8,000	0.56	0.64	0.73
500	4,000	0.17	0.21	0.25
500	8,000	0.34	0.42	0.50
1,000	4,000	0.12	0.16	0.20
1,000	8,000	0.23	0.31	0.39

Based on the crash frequencies shown in Table 3, it would not be unusual to expect many curves to experience less than one crash per year. This is not surprising, because Fitzpatrick et al. (1) studied crash frequencies on 5,287 curves and found that 94 percent of the curves experienced only one or no crash during a 3-year period. Depending on the actual conditions of the road, one or more crashes consistently occurring each year may be excessive for any conventional horizontal curve.

Economic Benefits

Agencies may benefit most from HFSTs applied to target curves within their jurisdictions that experience high crash rates. The following matrix presents scenarios to illustrate the potential value of an HFST application. The matrix investigates four possible yearly crash frequencies and three percentage reductions in total crashes for those sites. Using an FHWA study (*32*), an economic value of one crash is estimated at $158,177 based on the average “cost” of all classifications of fatal and injury crashes (K, A, B, or C on the KABCO scale). This amount excludes property-damage-only crashes, because the skidding crashes that are targets of HFSTs tend to cause injuries or fatalities. The cost of a fatal crash alone is considered to be over $4,000,000, resulting in even more savings when one is averted. Crash reductions and economic savings of “average” crashes over 1 year and 5 years are shown to illustrate the possible short- and long-term benefits of an HFST.

Table 4: Hypothetical Scenarios of Crash Reductions and Economic Benefits

Crash Frequency Before Treatment	Effective Crash Reduction, Economic Benefit					
	20% Reduction		30% Reduction		40% Reduction	
	1 Year	5 Years	1 Year	5 Years	1 Year	5 Years
1	0.2	1	0.3	1.5	0.4	2
	$31,635	$158,177	$47,453	$237,266	$63,271	$316,354
3	0.6	3	0.9	4.5	1.2	6
	$94,906	$474,531	$142,359	$711,797	$189,812	$949,062
5	1	5	1.5	7.5	2	10
	$158,177	$790,885	$237,266	$1,186,328	$316,354	$1,581,770
7	1.4	7	2.1	10.5	2.8	14
	$221,448	$1,107,239	$332,172	$1,660,859	$442,896	$2,214,478

Table 4 shows hypothetical crash reductions of 20, 30, and 40 percent based on reasonable reductions expected from the studies discussed above. From the table, even if the treatment provides only a 20-percent reduction in total crashes, an application that costs $30,000 may be considered cost-effective after only one year at a location that experiences an average of one crash per year. Naturally, 0.2 crashes is an impossible figure—but when applied at multiple locations, the 0.2 “average” reduction is one crash over five locations.

Cost for Application

Applications of HFSTs are inexpensive. New processes have significantly reduced the costs of labor, which once involved a long process of manually pouring the epoxy-resin binder, spreading it by hand with a squeegee, and then distributing the aggregate over the surface. Technological improvements have been made that allow this process to be completed automatically by a truck (see Figure 5), thus increasing the speed of application, eliminating some personnel, improving the material consistency, and reducing lane rental fees. The equipment on the truck applies the HFST with a single, continuous movement, from the start of the segment to the end. The significant benefit of applying HFSTs with an automatic process is the quick application and curing compared to a manual application. With this process the lanes can be opened quicker, resulting in fewer delays for road users, less demand for traffic control, and reducing or eliminating the need for extended lane rentals. It is not uncommon for application to occur during the night, with both lanes reopening for regular travel the next day. With this quick application, the cost of materials makes up the principal amount of application costs, which range from $25 to $35 per square yard.

An application of a 26-ft. wide HFST on a 400-ft segment can be completed for approximately $35,000. Using the FHWA crash costs (*32*), the return on investment is almost five-fold if that one application prevents one "average" fatal or injury crash (valued at over $158,000). If a fatality is averted, the return is over 100 times the amount invested.

Figure 5: Application of an HFST by truck.

Expected Life

There are a number of factors that affect the deterioration of HFST applications, such as traffic volumes, climate, and quality of application. Because these factors change by location, it is difficult to identify an expected life of the product for every circumstance. Izeppi et al. state that a 10-year service life is an acceptable estimate (*24*), but Waters (*33*) has found many instances of premature failures, which primarily occur as a result of poor road construction and failures in the original pavement surface. Table 4 show crash reductions for up to 5 years as a conservative service life. Longer life-cycles will be observed in most cases, which will result in even more savings from reduced crashes.

PLACEMENT

In addition to increasing the side friction on horizontal curves, HFSTs may be applied on the approach tangent before curves to increase the friction provided for braking before the curve. Many crashes on curves are the result of insufficient friction for the last second(s) of braking that occurs when drivers need to apply hard braking because they underestimated the curve severity.

These crashes may be prevented by extending the HFST from the point of curvature (PC) back to the critical point where the deceleration must begin in advance of the curve. This is the segment where vehicles must decelerate before the point of curvature (PC) to reach a proper speed for navigating the curve. Most drivers decelerate well in advance of this critical point, but those who wait and firmly apply the brakes at the last moment require more friction and may skid or lose control if the pavement is polished or wet.

For this analysis, a deceleration rate of 10 ft/s^2 was used to determine the starting point of HFST application, prior to the PC of the curve (10 ft/s^2 was used as a conservative deceleration value based on driver comfort, but greater deceleration rates are possible on most pavements, even in wet weather (*34*)). In Table 5, the approach speed can be the speed limit or the operating speed, and the curve speed is the advisory speed. Note that a 10-mph speed reduction occurs over approximately 100 ft, depending on the speeds of the approach and curve. Greater reductions, which are needed on severe curves, require longer segments.

Research has shown that curves that employ superelevation may be at risk for hydroplaning due to water buildup from poor drainage when the cross slope is low in the transition area (*35*). In these instances, there is an advantage to extend the surface treatment beyond the approach distances shown in Table 5 to the end of the superelevation runoff because the high macrotexture of the bauxite aggregate improves drainage. Comparisons with superelevation runoff guidelines in the AASHTO Green Book (6) show that for many cases, the additional application distance will not be great.

Table 5: Recommended Distance Upstream of the PC to Begin HFST Application

Approach Speed (mph)	Curve Speed (mph)						
	30	35	40	45	50	55	60
35	35	-	-	-	-	-	-
40	76	41	-	-	-	-	-
45	122	86	46	-	-	-	-
50	173	138	97	51	-	-	-
55	230	194	154	108	57	-	-
60	292	257	216	170	119	62	-
65	359	324	284	238	186	130	68

CONCLUSION

Over 47,000 fatal crashes occurred on horizontal curves in the United States in the 5-year period from 2006 to 2010. Many of these are skidding and lane or roadway departure crashes that can be attributed to low friction between the vehicles' tires and the pavement due to polishing of the aggregate in the pavement, wet weather, speeding, and other factors. HFST applications have been proven to successfully reduce the prevalence of these crashes, leading to reduced crash and fatality rates.

A return of 100 times the original investment is possible from an HFST application that results in one reduced fatality during its lifespan. If even more lives are saved, not to mention fewer injuries and less damage to property and infrastructure, the return can be immense. It is difficult to identify the exact location where that one fatal crash will occur. Fortunately, there are methods available to predict where an HFST will provide the most benefit. For curves, such locations tend to have sharp curvature, low advisory speeds, and histories of wet-weather and skidding crashes. Predictive equations such as the SPFs in the Highway Safety Manual can also be used for comparisons with observed crash frequencies to identify problem spots.

The cited applications with over 90-percent crash reductions show that there are clearly some locations where surface treatments are the most effective method to address safety concerns. More reasonable expectations, however, may be found in the controlled studies with lower but consistent improvements in safety, especially in reducing the number of wet-weather crashes. A 50-percent reduction in wet-weather crashes and 30-percent reduction in total crashes from HFSTs seem to be reasonable expectations. With such reductions in crashes possible, HFSTs have the potential to save thousands of lives.

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