Effect of Resurfacing on Highway Safety

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Critical reviews of the available literature and some original analyses dealing with the safety effects of road resurfacing projects were conducted and are summarized in this paper.

It is essential that the pavement surface retain its shape and structural integrity under its design loads and traffic if effective, safe, and economic highway transportation is to result. Considering the importance and expense of road resurfacing in maintaining high levels of service on the U.S. highway system, there have been few studies that directly address the issue of how accident frequency and severity change following resurfacing. These few studies indicate a response pattern that needs to be strengthened with additional studies using state-of-the-art experimental and analytic methodologies.

In the meantime, there is substantial safety information available on two aspects of pavement condition directly linked to resurfacing: pavement roughness and skid resistance. Pavement roughness is related to resurfacing because resurfacing improves surface smoothness. Skid resistance is often, although not necessarily, improved as a part of resurfacing projects. These pavement condition elements are closely related in their effects because both are important in vehicle control. Accordingly, studies of safety experience related to these factors should be consistent with and provide additional assistance and insight in estimating and bounding the safety response to resurfacing.

This analysis is concerned with resurfacing entire road sections rather than short lengths usually installed for improved skid resistance at curves or intersections.

FINDINGS

Rural resurfacing projects selected because of their pavement structural or riding condition have a small, immediate increase in overall accident experience, averaging 2 percent, and probably less than 5 percent. This is made up of a 10 percent increase in dry pavement accidents and a similar decrease in wet pavement accidents.

Rural projects resurfaced because of a large number of wet pavement accidents; for example, more than 25 percent of the total, have an immediate reduction in wet pavement accidents of from 15 to 70 percent, probably averaging 20 percent over the life of the project. In the first year, dry pavement accidents will increase up to 15 percent and total accident experience will drop as much as 5 percent.

The estimate of safety effects in the first and last years, and over the average life of the project are given in the following table:

Type of Accident	*First Year After Resurfacing*	*Final Year (%)*	*Project Average (%)*
Wet road	Down 15	0	Down 7
Dry road	Up 10	0	Up 6
All accidents	Up 5	0	Up 3

Following resurfacing, urban resurfacing projects should have an average accident reduction of about 25 percent over the life of the resurfaced pavement. There will be a small increase in overall accident severity on rural two-lane roads following resurfacing, probably on the order of 10 percent more injuries and fatalities per accident. Severity on urban streets will decrease about 25 percent.

Rationale

These findings are based on studies and opinions that suggest that resurfacing improves both road smoothness and skid resistance, which in turn ease vehicle control problems, particularly on wet pavements. Drivers respond by increasing speed and driving less carefully, leading to increased accident experience when the surface condition is not important to the safety of the road (usually the case on dry roads). Where there has been a significant wet pavement accident problem, important improvements in safety are realized after resurfacing. Over time these improvements dissipate—those dependent on improved friction more than those dependent on surface smoothness. The effects of resurfacing on accident severity are mixed, with higher speeds leading to more severe accidents and better surfaces making stopping distances shorter and thus reducing accident severity.

ANALYSIS

The remainder of this paper includes a summary of and comments on published research findings used in arriving at the foregoing conclusions. The relation of surface and road condition to vehicle and driver characteristics is discussed first, followed by a discussion of the results of studies of overall rural accident experience before and after resurfacing. Before-and-after resurfacing studies of wet pavement accidents are reported, and the changes in severity after resurfacing are considered. Safety relationships for skid resistance and road roughness are reviewed followed by a discussion of the safety interaction of resurfacing with roadside hazards and geometric design. Methodological issues in this type of analysis are discussed last.

SURFACE CONDITION AND VEHICLE AND DRIVER INTERACTION

Several characteristics of the driver-vehicle-road system contribute to the operational and safety aspects of resurfacing and interact in ways that are complex and poorly understood. The complexity of these interactions leads to safety effects that vary widely, resulting in substantial improvements under some conditions and worse accident experience in other situations.

Among the system elements viewed as contributing most to this process and its complexity are the following:

1. The response of vehicles to emergency conditions encountered on the roadway is dynamically different, depending on both its smoothness and frictional capabilities. Both light automobiles and trucks handle differently from typical automobiles under these conditions *(1)*.
2. Environmental characteristics, particularly rain and standing or running water, affect the surface condition and, hence, the difficulty of vehicle control *(2)*.
3. Roadway geometric design elements such as curves, grades, cross sections, and intersections, as well as other traffic introduce the need for vehicle control at many locations.
4. Many other characteristics are important and originate with or operate through the driver and are interpreted by the driver. The most important of these in the resurfacing context is the selection of an operating speed, which depends on the driver's feeling about the road surface. Speeds are selected at which drivers believe they can control accelerations and turns safely for both existing and anticipated conditions. Accidents stemming from surface conditions occur when the roadway cannot provide the necessary traction or smoothness.

Given that an accident occurs, its severity depends on still another set of factors that includes speed, geometric design, roadside hazards and guardrails, and stopping and control capabilities of the road.

In general, improved highway safety has resulted when there have been changes in the road environment that make it easier for the driver to accomplish both customary and emergency driving tasks. An example related to resurfacing is the large accident reduction following short skid resistance treatments at locations where many decelerations are made, such as at high-speed approaches to signalized intersections *(3)*.

After resurfacing, there are lesser accumulations of water, splash and spray conditions are lessened, and the coefficient of friction is frequently increased *(4)*. Flat curves and grades and wider lanes with better shoulders are easier to drive and are more forgiving. Other RRR critical review studies show an improvement in overall safety under these conditions. However, there may be a counter response by drivers who react by driving with less effective control through inattentiveness or increasing speed. Under these conditions safety may be decreased following an improvement.

TOTAL RURAL ACCIDENT CHANGES AFTER RESURFACING

Several of the most recently published studies indicate small and statistically nonsignificant overall safety changes after resurfacing. Nevertheless, all indicate a small increase in overall accidents. In these studies raw accident experience is usually normalized for traffic and study section length exposure by using the accident rate, *AR* (accidents per million vehicle miles of travel), or the accident frequency, *AF* (accidents per mile of road per year). In some cases the actual numbers of accidents on a section for one or more years before and after resurfacing are compared.

All of these before-after comparisons are valid only when "controlled" by contrasting them with accident experience changes at identical nonimproved sites. This better isolates the effect of the improvement from other influences on safety that may be occurring at the same time. Because resurfacing programs are based on engineering considerations and are selected to achieve an immediate highway agency objective, when that objective is safety, high-accident locations are usually selected for action. Before-after accident comparisons made when sites have been selected in this manner must be carefully reviewed to avoid the "regression-to-the-mean" effect that frequently overstates the effectiveness of the resurfacing because many of these locations are in the high-accident groups due only to chance and will experience fewer accidents "next year," regardless of resurfacing.

Midwest Research Institute (MRI) studied the effectiveness of skid prevention for the Federal Highway Administration (FHWA) *(5)*. The research team obtained information on 428 locations, 142 of which had been resurfaced around 1974, the period of the oil crisis, which affected highway operations and safety significantly. The other sections were not changed and were intended to be used as controls for comparison. The sections used in the MRI data set are from roads with poorer cross sections. Only 20 percent of the rural sections had paved shoulders; 40 percent had shoulder widths of 6 ft or more, and 60 percent had 12-ft-wide lanes.

The sites had been selected for resurfacing because of physical pavement condition, not for safety reasons. Therefore, there was little possibility of a regression-to-the-mean effect in this data set. MRI concluded that there was no significant overall effect of the resurfacing on the *AR* although the average change was a 2 percent increase.

The FHWA separately analyzed 59 rural two-lane sections not matched with control sections from eight states from the MRI data set and found a 2.2 percent increase in the *AR*, from 2.39 to 2.45 accidents per million vehicle miles following resurfacing *(6–8)*. The *AR* increased at 36 of the 59 sites. These changes were far from being statistically significant. In a recent reanalysis of these data where matched control sites were identified and the sections weighted by length and average daily traffic (ADT), the increases at both types of sites were identical and hence, resurfacing had no effect.

Another analysis of 40 of the rural MRI sites defined slightly differently revealed a 2.0 percent increase in the total number of accidents *(9)*. In this study 70 control sites recorded an increase of 6 percent over the same time period. Neither of these results was statistically significant.

The FHWA reported that studies of 48 mi of resurfacing at five sites in Arkansas indicated small and nonsignificant increases in average *AR (6, 7, 10)*. Dale reported that the *AR* dropped 24 percent, from 3.58 to 2.71 percent at 133 sites in several states and that this result was significant at the 95 percent confidence level *(11)*. However, no information on site selection or use of control sections was given for either of these studies.

Brown reported on the results of resurfacing 24 essentially tangent, controlled, two-lane rural sites in Alabama totaling 57 mi *(12)*. Information on site selection methodology was not given. The average increase in *AR* was 2.5 percent, a nonsignificant result.

The New York State Department of Transportation and FHWA reported on several resurfacing programs in that state *(13, 14)*, one of which is the Fast Track program designed to preserve the existing pavement and restore a smooth riding surface.

TABLE 1 Other Estimates of Resurfacing Effect on General and Rural Accident Experience

Road Width	Percent Improvement in Accident Experience: All	Property Damage Only	Injury	Fatal	Injury/ Fatality	Source	Year
General							
All sites	12	–	–	–	12	Jorgensen *(13)*	1966
	27	32	16	29	16	FHWA *(22)*	1982
	26	27	–	–	55	Creasy and Agent *(21)*	1985
	36	38	33	40	–	New Jersey *(25)*	1982
	58	58	57	–	–	FHWA *(22)*	1982
	55	73	24	–	24	Pennsylvania *(26)*	1981
	20	–	–	–	–	Creasy and Agent *(21)*	1985
Wet weather accident problem sites	63[a]	–	–	–	–	New Jersey *(25)*	1982
	58[a]	58	57	–	–	West Virginia *(27)*	1982
	57[a]	–	–	–	–	Pennsylvania *(26)*	1982
	40[a]	–	–	–	–	Creasy and Agent *(21)*	1985
	21[a]	–	–	–	–	Creasy and Agent *(21)*	1985
	64[a]	83	–	–	75	Creasy and Agent *(21)*	1985
Two-lane rural							
All sites	25	28	20	35	20	FHWA *(22)*	1982
	30	34	22	48	24	FHWA *(22)*	1982
	25[b]	–	–	–	–	Alabama *(28)*	1979
	21	–	–	–	16	Los Angeles *(28)*	1979
	21	–	16	+8	–	Dale *(9)*	1973
	22	–	–	–	–	FHWA *(22)*	1982
	15	–	–	–	–	*(17, 18)*	1981 1985
Site with wet weather accident problem	12	–	–	–	21	Jorgensen *(13)*	1966
	21	–	–	–	–	Texas *(28)*	1979
	46[a]	36	60	–	–	West Virginia *(26)*	1981
	42[a]	–	–	–	–	Texas *(27)*	1979
Four-lane	–	–	–	–	–		
Rural	–	–	–	–	–		
Other	44	–	–	–	59	Jorgensen *(13)*	1966
Four-lane	–	–	–	–	–		
Undivided	37	43	27	–	27	FHWA *(20)*	1982
Four-lane	–	–	–	–	–		
Divided	11	8	17	–	15	FHWA *(20)*	1982

NOTE: Dashes indicate not applicable.
[a]Improvement in wet pavement accidents.
[b]Skid resistant treatment.

Projects are selected on roads that do not need widening for safety or capacity. Roadsides are improved for clear zone safety only in response to a known safety hazard with high accident experience. All shoulders are paved as part of the resurfacing. At such locations, all accidents increased 4 percent, a nonsignificant change *(14)*. No significant change was found at 33 simple resurfacing projects on more than 182 mi of road with 2 years of before-and-after data. There was no change in the number of accidents on wet or dry roads, but ice and snow accidents increased by 32 percent. Under New York's more extensive Reconditioning and Preservation program, 47 projects were resurfaced, and all accidents increased by a significant 6 percent.

Studies have been summarized in several publications, but insufficient details have been provided to enable the study methodology to be evaluated. In other cases, engineers have used their judgment to estimate the safety response immediately after resurfacing *(11, 15–23)*. A summary of the values from these studies is given in Table 1. The first such study by Jorgensen summarized results from five states, and the differences among the states were found to be great, with increases recorded at some sites and decreases at others following resurfacing *(15)*. Jorgensen's final conclusions were based on Ohio data.

Many of the results given in Table 1 are from the FHWA, which determined these estimates of accident reduction levels from data provided by the states and FHWA research *(22, 24)*. The findings are based on data from after the mid-1970s and (a) use before-after comparisons corrected for traffic exposure, (b) control sites if possible, and (c) are reported only when the total accident frequency at all treated sites is large. Eighty percent Poisson confidence limits are used; however, no information on site selection is presented.

Skid resistance is at its peak immediately following treatment and declines rapidly at a decreasing rate; roughness also increases with traffic and time at an increasing rate, and the average change over the life of a project as the pavement wears out should be about 40 to 50 percent of that recorded immediately after the resurfacing.

Considering all of the preceding information, it is concluded that the overall effect of rural resurfacing is a small immediate increase of 2 percent in total accident experience. Averaged over the life of the pavement this should be less—about 1 percent.

WET WEATHER RURAL ACCIDENT STUDIES

Although dry pavement accidents usually increase after resurfacing, large reductions in wet pavement accident experience have often been found as can be observed from Table 1. The reductions occurred particularly where wet pavement accident experience was high and made up a large fraction of all accidents before the resurfacing. This conclusion was reached before 1970 by both British investigators and Jorgensen using Ohio data *(15, 29)*. Ohio policy was to resurface such sites when the number of wet pavement accidents (WPA) exceeded 25 percent of the total and where four or more were recorded in a 3-year period *(15)*. Both Ontario and New York classify sections based on a 30 percent wet pavement accident criterion *(3, 13)*. A reasonable explanation for this result can be developed from considering the improved skid, drainage, and roughness characteristics of the wet resurfaced road *(2)*.

For large safety improvements, it appears that there has been a "need" for improved surface characteristics before the resurfacing as evidenced by "high-accident" frequencies on the wet surfaces with respect to the dry pavement rate. This is an indication of an important differential between dry and wet pavement conditions at these sites when compared with safer places on the system. Such locations are usually those where "unusual" driver control is required, such as on curves, at intersection approaches, and other places where traffic conflicts are frequent. Rizenbergs et al. reported that the wet-to-dry accident ratio was only 0.23 on tangent sections and rose to 0.55 on curves where ratios as high as 0.75 were found *(30)*. Wet pavement accidents are much more clustered than other accidents and are found where unusual driving maneuvers are more common *(28)*. These intersections, curves, and downgrades occur in different mixes and numbers on a road and hence, the wet pavement safety effect would be expected to be highly variable. Also, when resurfacing projects are not initiated to remedy skidding accident problems, safety responses are less and more variable.

Under the best conditions, the wet pavement accident rate (WAR) (wet accidents per million vehicle miles of operation on wet pavements or often per million vehicle miles of travel under all surface conditions) approaches 133 to 150 percent of the dry pavement accident rate (DAR) *(29, 31)*. Of course, wet pavement accident criteria depend on local weather conditions.

The wet pavement accident experience in the MRI data set was reviewed. MRI found a nonsignificant WAR reduction of 8 percent (from 3.39 to 3.06) for about 140 resurfaced sections and a (DAR) increase of about 4 percent *(5)*. When wet and dry pavement accidents are combined, the previously mentioned total increase of 2 percent results. The control sections recorded a nonsignificant 1 percent decrease in the WAR.

The analysis closest to current study quality expectations was reported in 1979 by Sparks and Flowers *(32)* who analyzed before-after rural Texas accident data for 11 asphaltic concrete resurfacing (ACP) projects and 44 seal coated (SC) sites. These sites had been selected on the basis of high-accident frequency analysis, but it was concluded that regression-to-the-main effects would be minimal because the accident data used to make the overlay decision were not those used in the before-period analysis. Accident data, ADT, and precipitation values were developed for one-year, before-and-after periods between 1975 and 1978. The variability in precipitation between the two periods was large as revealed by 18 percent more rainy days at the SC sites after resurfacing. There were no satisfactory control sites available, and it was believed that the wet pavement change would be the sole result of the resurfacing and that resurfacing exhibited no effect on dry pavement accidents. Therefore, the dry pavement accident experience was used as the control to estimate the effect of other unknown, time-related factors.

Ignoring the effects of traffic and rain, total wet pavement accidents at ACP sites dropped almost 70 percent, from 341 to 105, whereas dry pavement accidents increased 14 percent, from 1,036 to 1,188 after resurfacing. Following the paving, wet weather accidents decreased at 90 percent of the locations. At the SC sites, dry pavement accidents increased 5 percent, and wet weather accident frequency was less by 60 percent. Wet pavement accidents decreased at 37 of the 44 sites.

A better estimate of the effect of resurfacing was made by using a multiplicative regression model that corrected for both the number of rainy days and the ADT. The dependent variable was the cross-product ratio (CPR), the fraction of wet pavement accidents after resurfacing compared with before, corrected for the change in dry accidents. For example, the CPR value of 0.31 obtained from the model for the ACP sites indicated a 69 percent reduction in wet pavement accidents compared with what would be expected considering the increase in dry pavement accidents. This value was significant at the 10 percent confidence level. There was also a highly significant 60 percent reduction for the 44 SC sites.

Because studies show that dry pavement accidents increase after resurfacing, it is concluded that the use of the dry pavement accident experience as the control overstates the effect of the wet accident improvement and that over the life of such improvements, a 25 percent reduction in the average wet pavement accident experience would be found for projects with high safety payoffs.

The wet pavement accident experience in the MRI rural two-lane data set was analyzed similarly as a part of this review *(8)*. MRI found an 8 percent wet accident reduction on the 142-site data set *(5)*. The FHWA did not report an analysis of the wet pavement accidents for this group of sites. There were 54 sites for which data on ADT and rain were available for an analysis similar to that conducted in Texas.

The model showed that a 22 percent decrease in accidents could be attributed to resurfacing. Because dry pavement accident experience was up 7 percent, a better estimate would be a 15 percent improvement in wet pavement accidents due only to resurfacing. There were 30 sites where wet pavement accidents exceeded 25 percent of the total, 21 sites where the wet pavement accident rate exceeded 1.0 accidents per mile per year, and 18 sites where both conditions were met. A 28 percent reduction in wet pavement accidents was reported at these sites accompanied by a 17 percent increase in dry pavement accidents.

The data were also analyzed by Persaud who used a method recently developed by Hauer *(33, 34)*. He corrected for traffic and rain condition exposure and concluded that an unbiased estimate of the reduction in accidents at 28 sites with high wet pavement accident experience was 18 percent. This reduction appears to be greater for roads with 2,500 to 5,000 vehicles per day.

New York analyzed projects of this type and the effect on wet weather accidents *(13)*. At 56 locations with higher wet pavement accident experience, there was substantial improvement following antiskid grooving treatment and the placement of overlays. On 37 roads that had been grooved, the wet accident rate was down 53 percent, and all accidents were down 21 percent; these results are significant. At 19 locations where high-friction overlays were applied, the wet accident rate dropped a significant 56 percent with similar results that were not statistically significant for all accidents. At 47 sites resurfaced with high-friction overlays but where wet pavement accident experience was low, accidents dropped a nonsignificant 4 percent.

Including ice and snow accidents in the MRI data file for the 27 sites recording these types of accidents, the total number of accidents increased by 15 percent following resurfacing. In New York, snow and ice accidents increased by a nonsignificant 12 percent after resurfacing, and other New York studies have always shown an increase in these types of accidents *(13)*.

The earlier studies described did not provide detailed information on the characteristics of the resurfacing material supplied, and because there are many differences among the possible coatings, the differences could be great as indicated in the New York studies *(14)*.

It is concluded that where wet pavement accident experience is high and also a large fraction of the total accident experience, wet pavement accidents can be reduced by 45 percent in the first year and an average of 20 percent over the life of the resurfacing. All accident experience should improve at these sites, generally up to 5 percent in the first year.

URBAN EXPERIENCE

Because of speed and many other differences between urban and rural areas safety responses to resurfacing may differ in cities. The results of other estimates are given in Table 2, and there is no recent detailed information that can be evaluated to modify these judgments. Reviewing these values, urban resurfacing should result in an average 25 percent reduction in accidents over the life of the pavement.

ACCIDENT SEVERITY

Considerable information is available on the difference in severity of accidents occurring before and after resurfacing. In this section changes in fatal and injury accidents after resurfacing are expressed as the percent change in the average percent that such accidents are of the total—severity ratio. A severity ratio of 30 percent means that 3 out of 10 accidents involve a fatality or personal injury. A 10 percent increase in the severity ratio would change that value to 33 percent.

The early Jorgensen study indicated widely varying severities for rural two-lane roads *(15)*. As shown in Table 1, accident severity was reduced following resurfacing, with values ranging from 5 to 15 percent better than the reduction in accidents at rural locations where the high wet pavement accident experience conditions are met.

Larsen reported a 16 percent increase in severity per accident for 33 New York State resurfacing projects *(14)*. Accident severity also increased at 37 grooved road sites *(13)*. Severity was reviewed for 47 projects that were resurfaced in 1981 and 1982 to obtain better friction where no other improvements were made. Almost 3 years of before-and-after accident data on these projects were available. There was a 3 percent increase in fatal and injury accident severity per accident for these projects. This 3 percent increase was not significant.

Brown reported on 57 mi of improvements at 24 controlled sites in Alabama *(12)* and concluded that accident severity was reduced after the improvement, with the personal injury and fatal accident severity improving by 14 percent, whereas the property-damage-only accidents remained unchanged.

A French study indicated a 10 percent greater reduction in individual accident severity than the impressive 59 percent reduction in overall accident experience *(35)*. However, this study appears to suffer from regression-to-the-mean effects.

The FHWA safety program evaluation estimated a 10 percent reduction in fatal and injury accidents against an overall accident reduction of 22 percent, an indication of a 15 percent expected increase in severity *(22)*. The FHWA reported small increases in severity of approximately 5 percent per accident *(22)* for three states.

McFarland and Rollins recently estimated that improving a road surface would produce a small, perhaps 5 percent reduction in severity *(19)*. On the other hand, Smith concluded that resurfacing highway sections would increase severity by between 5 and 10 percent *(20)*. Smith found no change in severity with ADT on Virginia secondary roads as well as no difference in severity between wet and dry conditions.

Beatty reported a 1.3 percent increase in the severity ratio—the percent of accidents involving an injury or fatality—for each 1-mph increase in speed *(36)*.

It is concluded that severity on rural resurfacing projects is about 10 percent greater, although changes of as much as 15 percent have been recently recorded.

TABLE 2 Estimates of the Effect of Resurfacing on Urban Accident Experience

	Percent Improvement in Accident Experience						
Road Width	All	Property Damage Only	Injury	Fatal	Injury/ Fatality	Source	Year
All	42	–	46	–	–	Jorgensen *(15)*	1966
	61[a]	64	56	–	–	West Virginia *(52)*	1982
Two lanes	25	27	19	–	19	FHWA *(24)*	1982
Four lanes	20	28	–	–	–	FHWA *(24)*	1982
Undivided	52	53	48	–	47	FHWA *(24)*	1982
Four lanes Divided	17	20	10		10	FHWA *(24)*	1982
Over four lanes Undivided	52	53	48	–	47	FHWA *(24)*	1982
Over four lanes Divided	32	39	16		16	FHWA *(24)*	1982

NOTE: Dashes indicate not applicable.

[a]Improvement in wet pavement accidents.

SURFACE CONDITION AND ACCIDENT STUDIES

Skid Resistance Studies

Skid resistance is often improved on resurfacing projects. The 1976 National Highway Safety Needs Report estimated that improved skid resistance was the ninth most effective highway safety countermeasure with a potential for saving almost 3,500 lives over a 10-year period *(37)*.

Many studies have been conducted on the relationship between skid resistance and accident experience, including both cross-section studies and longitudinal studies of accident rates before-and-after skid treatments were implemented.

The MRI study measured a small decrease in the skid resistance for the resurfaced sites and, as described previously, no significant overall safety change was recorded *(5)*.

There are many studies that show a relationship between measures of skid resistance and accident experience. Jorgensen found such a result for skid resistance in data from Texas. Where the skid number (SN) (speed standardized friction coefficient expressed as a percent) was a very poor 10, the accident rate (AR) was 3.5; it decreased to 1.5 at locations where the SN was an excellent 60 *(15)*. Other studies in Texas and Arizona showed similar effects *(38, 39)*. The FHWA reported a West Virginia study of nine urban and rural projects in 1980–1981 where the SN was increased by 20 and the wet pavement accident rate decreased by 1.0 accidents per million vehicle miles *(40)*. The MRI cross-section study revealed that as the skid number increased by 10, the wet accident rate decreased by 0.5 accidents per million vehicle miles. However, the effect was less at sites where the SN was higher. This is consistent with Burchett's findings that a declining exponential function captures the relationship *(31)*.

In Germany Beckmann also found a similar relationship involving the percent of wet pavement accidents *(41)*. Rizenbergs found an exponential relation between the skid number and the percent of wet pavement accidents *(26)*. When the SN was 16, this percentage was 44 percent, and it declined exponentially to 18 percent when the SN was 58. German studies indicated that the percent of wet pavement accidents declined with increasing skid resistance, from 70 percent at $f = 0.18$ to 30 percent where $f = 43$ *(42)*.

Burchett also showed that the results were nonlinear with respect to ADT *(31)*. Using Texas data, McFarland found a much smaller decrease in wet accident rate (0.11) for the same SN change *(43)*. Levy explored the relationship between skid resistance and safety on 94 sections of Indiana highway involving 4,416 accidents between 1973 and 1975 and found that the wet-to-dry accident ratio stratified by road type related weakly to the SN *(44)*.

Rizenbergs and Burchett studied almost 8,500 accidents between 1969 and 1971, along with the friction of almost 1,500 mi of rural two-lane Kentucky highways and found a large scatter obscuring any relationship between skid number and any measure of accident experience *(26)*. However, of all the measures investigated, the results with the wet-dry accident ratio were the best. All investigators have noted that the skid number–wet accident rate relation is a very complex function of many conditions and that the variance explanation of their models was very poor, never more than 10 percent according to Sparks and Flowers *(32)*.

In an effort to take some of these differences into account, MRI related the wet accident rate to the dry accident rate and found that at sites with a high dry accident rate, the wet accident rate was more sensitive to the available SN *(5)*. The relationship was highly nonlinear. The interaction with the dry accident rate indicates the importance of the relative exposure to emergency control maneuvers and is a clear indication of the presence of other safety problems. Accordingly, this is a reasonable result for sites at which there is a need for additional friction to avoid accidents.

As speeds increase, there is a significant drop in the available skid resistance. This speed increase works against safety on resurfaced roads.

Road Roughness, Speed, and Accident Studies

The cited accident studies reveal a consistent increase in dry pavement accidents after resurfacing. The MRI found a significant 15 percent increase in the dry accident rate, from 2.35 to 2.70 *(5)*. Several researchers have concluded over many years that the increase in accident experience following resurfacing can only be attributed to driver response to the changed road and most likely to the selection of a higher speed *(5, 13, 15, 29)*. However, there is little information available to support this belief. One early British study showed a speed increase of almost 5 mph following resurfacing of a "very irregular" road *(29)*. Zegeer described the results of a Kentucky study in which the average speed before and after resurfacing of a "very rough" road increased by 8 mph *(45)*.

A possible explanation for the higher dry accident rate is that resurfacing usually makes relatively little change in the ability of the dry road to provide traction or substantial change in road roughness *(41)*. It would be expected that in cases where the desired speed is high, locations that do not have a safety problem at lower speeds would become more hazardous at higher speeds and a larger number of accidents would result.

Accordingly, additional indirect evidence supporting such an effect was sought. Speed selection depends on many elements, including the driver's desired speed, the speed limit, vehicle capabilities, enforcement level, and constraints of other traffic. Most important within the context of this study is the effect of the perceived ease of travel related to road surface roughness.

A Swedish driver attitude and operational study conducted before and after the initial surfacing of a gravel curve showed that this improved ease of travel was easily detected by the subject drivers and that they increased their speed on the curve following its surfacing *(46)*.

Speed studies over many years show little difference between wet and dry conditions. In a recent study of Illinois data, speeds on wet roads were lower but the difference was usually well under 2 mph, and never as much as 5 mph *(25)*. MRI found an average speed difference between dry and wet conditions of less than 2 mph *(5)*.

Results of cross-section studies exploring the effects of surface roughness on speed were reviewed. The most widely accepted measure of road roughness is the Pavement Serviceability Index (PSI) (also called PSR). On most highway systems in the United States, PSI values range from 2 when the surface is in very poor condition to 5 when it meets the highest smoothness standards. Roads typically have a PSI of 4 immediately after resurfacing, which declines at an increasing rate with time and traffic until additional rehabilitation is necessary. Roads are considered ready for possible resurfacing when the PSI reaches a value of 3. About 10 percent of the U.S. rural mileage has a PSI value less than 2, and only 20 percent is greater than 4 *(20, 38)*. There are no longitudinal studies documenting speed changes over time as the PSI decreases at a location. Cross-section speed-PSI studies at locations with varying roughness show higher speed with higher PSI values *(26, 27)*. Studies of rural highways in Ontario revealed about a 0.7-mph decrease in average speed per unit of PSI drop *(26)*. McFarland estimated a 5-mph drop from a smooth road speed of 25 mph and a 12-mph drop from 60 mph as the PSI changes from 5 to 2 *(43)*. Hazen concluded that speed decreases noticeably as the PSI drops below 3 *(47)*. He estimated that the average speed at a PSI of 2 is about 91 percent of that at 5 and 93 percent of that at 4. Extending Hazen's analysis, Zaniewski recently reviewed research findings and concluded that a road operating at an average speed of 49 mph when the PSI is 5 would average 45 mph when it is 2 *(27)*. The overall effect on speed therefore appears to be an increase of about 5 mph following resurfacing of a road with a PSI of 2 and raising its smoothness to 4. Numerous cross-section studies have shown that surface smoothness and skid resistance affect accidents. In all but one study the increase in road roughness or decrease in skid resistance was associated with increased accident experience. Locations at which accident experience is worse on rougher roads have been found in Jamaica, Kentucky, Kenya, Great Britain, and Ontario *(3, 29, 31, 48)*. It should be noted that these results are contrary to the assertions previously described in this paper that improved smoothness increases accidents as was found in a recent study by Zaniewski *(27)*, who studied the relationships between PSI and 1976 accident experience for 1,800 rural, primary and secondary road sections in Texas totaling 8,300 mi. The study showed that accident frequency increased slightly but significantly with a smoother pavement surface on two-lane rural roads with ADT in the 1,000 to 8,000 range. His findings indicate an increase of about 0.6 accidents per million vehicle miles as the road condition varies from a PSI of 4 to 2.

Roughness and Skid Resistance

Zegeer studied records for 2,300 mi of two-lane rural Kentucky highway analyzed for resurfacing in the early 1970s *(44)*. Roughness and skid resistance were quantified separately and regressed against accident measures developed from 2 years of accident data. The roughness rating correlated strongly with road defect accidents and somewhat with the percentage of wet pavement accidents. Rougher roads had higher road defect accident experience and a decreasing fraction of wet pavement accidents. The skid resistance rating correlated well with the wet and dry pavement accident rate, and the wet pavement accident percent correlated with both of these measures, increasing with decreased skid resistance. Accidents involving road defects did not correlate with this measure.

Contrasting these two measures, skid resistance was strongly related to wet pavement accident experience whereas roughness was not. Accidents involving road defects responded to roughness but not to the skid measure.

Janoff cited a study of the relation between roughness and wet pavement accident experience on a section where the surface was grooved, which increased its PSI from 2.1 to 3.6 *(49)*. The wet pavement accident rate decreased 15 percent whereas it increased from 35 to 82 percent on untreated control sections.

INTERACTIONS

There are so many driver-vehicle-road elements interacting in such complex and poorly understood ways that unclear and conflicting results are likely. However, the experience on previous RRR projects involving other improvements should be of value. It would be expected that resurfacing would be less effective alone than in combination with other changes. Larsen found accident decreases *(14)* in a study of 79 extensive RRR projects in New York. All accidents decreased 21 percent, property damage accidents decreased 40 percent, and injuries decreased 9 percent (a 10 percent severity increase) following the improvement. Both wet and dry pavement accidents decreased significantly—33 and 17 percent, respectively.

Sanford recently described Illinois studies involving 44 rural, two-lane, major-route RRR projects with a total length of 284 mi *(50)*. Each section was more than 2 mi long, the improvements were made between 1978 and 1981, and accidents were analyzed for 2 years before and after the improvements. There were no control sections, and two-thirds of the projects involved widening and resurfacing and one-third resurfacing with some roadside improvements plus treatment at high-accident locations. No information on site selection techniques was given. The total AR decreased 25 percent, from 2.32 to 1.73, and the fatal-personal injury rate decreased 18 percent, from 0.89 to 0.73, another 10 percent increase in severity per accident.

The magnitude of potential accident payoff at locations with wet weather accident problems where multiple improvements are made is shown in the French study summarized by Schultze *(35, 42)*. At 51 locations with high wet pavement accident experience, there was an average of 64 wet pavement accidents out of a total of 85 in 1969—a ratio of 75 percent. Following treatment, which included traffic controls and widening as well as surfacing and antiskid treatments, wet pavement accidents averaged 6.6, and the total was down to 35. The overall reduction was 59 percent (90 percent for wet pavement accidents); no significant effect on dry pavement accident experience was recorded. This study probably suffers from regression-to-the mean effects, however.

Sensitivity to Roadside Conditions

Of particular importance are interactions involving roadside hazards and road geometry—two improvement types expected to be important alternatives to or supplements in RRR projects involving resurfacing.

Two fundamental physical factors are at work when considering the interaction of roadside improvements and resurfacing: the increased energy that must be dissipated because of higher speeds, and the greater ability of a road with a higher SN to dissipate this energy. With an increase in speed, the errant vehicle is more likely to reach a roadside hazard. For the small increases in speed that have been described in this review and typical improvements in friction, calculations show that fewer accidents involving braking might be expected because the increased friction, if needed, can quickly dissipate the energy that is created by the higher speed. Also, the driver may be expected to maintain greater control after the pavement is resurfaced.

Only one study relating resurfacing and roadside hazards was found *(13)*. In New York two types of improvements were made involving 81 resurfacing projects in 1981–1982 with almost 6 years of before-after accident data available. Thirty-four of the projects involved both resurfacing and extensive roadside safety work. For these projects, all accidents were reduced by a significant 6 percent, fatal and injury accidents were reduced by a significant 10 percent, and severity was reduced by 5 percent. Wet pavement accidents were reduced by 17 percent and dry pavement accidents were reduced by 7 percent—both significant values. Snow- and ice-related accidents increased by a nonsignificant 12 percent. Considering the type of accidents, head-on collisions were reduced by a significant 63 percent, and fixed-object accidents decreased by a significant 20 percent. Left-turn collisions increased by a significant 75 percent.

The remaining 47 projects were resurfaced without roadside improvements. All accidents were up a significant 6 percent, and severity increased slightly as fatal and injury accidents increased 9 percent. Both wet and dry pavement accidents decreased a nonsignificant 4 and 2 percent, respectively. There was an 84 percent improvement in head-on collisions counteracted by increases of 22 percent in fixed-object accidents and 103 percent in left-turn collisions.

A comparison of the fixed-object accidents on these two types of sites is of particular interest because of the different treatment of these hazards. The 22 percent increase where the roadside was not improved was 90 percent of the increase at these sites. At the 34 sites where the roadside was improved, fixed-object accidents decreased 20 percent, 63 percent of the safety improvement. These reductions were concentrated among accidents involving utility poles and trees. One-third of the fixed-object accidents at the nonimproved roadside locations involved trees and utility poles.

Sensitivity to Geometric Design

Recent quantitative data on the safety effects of resurfacing as related to geometric design is almost completely lacking. In 1966 Jorgensen concluded that resurfacing roads with poor geometrics would lead to higher speeds and an increase in accident experience *(15)*. The data supporting this conclusion were not shown although the conclusions are consistent with other findings reported in this paper. Early German studies of wet weather accidents revealed the surprising importance of geometric design *(51)*. MRI could identify no relation between wet weather accident rate and geometry *(5)*. Cleveland's analysis of part of the MRI data set indicated a strong effect of intersection density and horizontal curvature on accident frequency but no effect involving resurfacing itself *(9)*.

Zegeer found a high correlation between roughness and the percent of accidents on curves with this percent increasing on the rougher roads *(45)*, but found no identifiable correlation between skid resistance and the fraction of accidents on curves.

The data sets analyzed as a part of this synthesis undoubtedly have confounding geometric effects. For example, in the analysis of the MRI rural data set, there was an indication that lane width differences among the 54 sites might be important although the results were far from statistically significant.

ANALYSIS PROBLEMS

Many problems exist in accident analysis methodologies and all of the studies reviewed have some defects. The problem is exacerbated by the complexity of the causal element interactions, the wide variability in results, and the small effects that have been found. These effects are usually far less than the uncertainty in the results. For example, the MRI data for accident rate changes at individual sites range from an improvement of 50 percent to a worsening of 400 percent, averaging the 2 percent change as described previously *(6)*.

Reference has been made to the regression-to-the-mean effect throughout this paper. Another problem is accident rate measures. An analysis of the MRI data revealed that the effects of section length and ADT could not be accounted for by the linear relation needed to use accident rate and accident frequency (accident per mile per year) rates across the range in length and traffic flow desired *(9)*. In the model, the accident rate was found to be directly proportional to ADT and varied as the square root of section length. Because the sections in the MRI study varied in length from 0.6 to 18.4 mi, the effect is substantial, and accident rate values on longer sections of this data set cannot be compared with confidence with those on shorter lengths.

Changes over time may also be important. For example, the problems of lighter automobiles are accentuated where the pavement is rough and the friction is low *(1)*. The expected continuing increase in the numbers of these vehicles argues in favor of resurfacing.

The overall effects of resurfacing may be summed up as follows by type of project. For projects selected because of structural quality or poor riding condition, all accidents increase immediately an average of 2 percent. Typically, this will be made up of a 10 percent increase in dry pavement accidents offset by a similar decrease in wet pavement accidents. For projects selected because of high wet pavement accident experience, total accident experience will drop as much as 5 percent. In the first year, dry pavement accidents will increase (up to 15 percent) but wet pavement accidents will decrease from 15 to 70 percent. Over the life of the project, wet pavement accidents probably average a 20 percent reduction.

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