APPENDIX **D**

SAFETY EFFECTS OF IMPROVING PAVEMENT SKID RESISTANCE

NOTE: The following is taken from a TRB paper that was presented at the 2007 Annual Meeting and has been accepted for publication in *Transportation Research Record*.

INTRODUCTION

The study examined the safety impacts of improving pavement skid resistance using data from New York State. The New York Department of Transportation (NYDOT) runs a skid accident reduction program (SKARP) (*1*) which identifies sections of pavement with a high proportion of wet-road accidents, friction-tests these locations, and treats those with both a high proportion of wet-road accidents and low friction numbers.

Criteria for identifying high wet road accident sites have evolved since the commencement of the program in 1995. For the first year, locations were identified at which 40% or more of total reported accidents were wet road crashes during the most recently available two year period. Rural sites were required to have at least six wet road crashes while urban sites were required to have at least ten wet road crashes during the same two year period. In succeeding program years, the minimum number of wet road crashes required to qualify remained the same, but the percentage threshold was reduced from 40 to 35.

All locations captured in the accident analysis screen were friction-tested with a skid trailer. Tests are taken at each tenth mile segment of the qualifying location in each direction.

Locations generating one or more friction numbers below 32 were then subjected to the remedial treatment. Treatment was sometimes extended to include adjoining stretches of pavement, especially where friction numbers were only marginally acceptable. The treatment generally involves a 1 ½" hot mix asphalt resurfacing or a ½" microsurfacing using non-carbonate aggregates, and costs an estimated $20,000 per lane mile.

The basic objective of the study on which this paper is based was to estimate the change in crashes at sites after treatment to improve skid resistance. Intersections and road segments were separately analyzed. Target crash types considered in the analysis were:

- Total
- Wet-road
- Rear-end
- Dry
- Rear-end wet-road
- Right-angle (for intersections)
- Right-angle wet-road (for intersections)
- Single vehicle (for segments)
- Single vehicle wet-road (for segments)

The rest of the paper summarizes the methodology, the data collected, some analytical details and the results, followed by a short wrap-up that places the results in the context of highway engineering practice.

METHODOLOGY

The empirical Bayes (EB) methodology used is different from those used in the past, benefiting from significant advances made in safety analysis for the conduct of observational before-after studies, which culminated in a landmark book by Hauer (*2*) and a recent paper that summarizes successful applications of this methodology in the past 20 years (*3*). Hauer's book also provides guidance on study design elements such as size and selection criteria for treatment and comparison groups and the pooling of data from diverse sources. All these are crucial elements in successfully conducting a study to obtain results that will have wide applicability. Specifically, the analysis:

- Properly accounts for regression-to-the-mean, which is clearly an issue in this study because high accident locations were selected for treatment and accident reductions would have been observed even if these sites were left untreated (*2*, *3*);
- Overcomes the difficulties of using crash rates in normalizing for volume differences between the before and after periods;
- Reduces the level of uncertainty in the estimates of safety effect.

In the EB approach, the change in safety for a given crash type at a site is given by:

$$\lambda - \pi \qquad \text{D1)}$$

where λ is the expected number of crashes that would have occurred in the after period without treatment and π is the number of reported crashes in the after period.

In estimating λ, the effects of regression to the mean and changes in traffic volume were explicitly accounted for using safety performance functions (SPFs) relating crashes of different types to traffic flow and other relevant factors for each jurisdiction *based on untreated reference sites*. Annual SPF multipliers were calibrated to account for the temporal effects on safety of variation in weather, demography, crash reporting and so on.

In the EB procedure, the SPF 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 the one being analyzed. The sum of these annual SPF estimates (P) is then combined with the count of crashes (x) in the before period at a treatment site to obtain an estimate of the expected number of crashes (m) before treatment. This estimate of m is:

$$m = w_1(x) + w_2(P), \qquad \text{D2)}$$

where the weights w_1 and w_2 are estimated from the mean and variance of the regression estimate as:

$$w_1 = P/(P + 1/k) \qquad \text{D3)}$$

$$w_2 = 1/k(P + 1/k), \quad \text{D4)}$$

where k is a constant for a given model and is estimated from the SPF calibration process with the use of a maximum likelihood procedure. (In that process, a negative binomial distributed error structure is assumed with k being the dispersion parameter of this distribution.)

A factor is then applied to m to account for the length of the after period and differences in traffic volumes between the before and after periods. 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 λ. The procedure also produces an estimate of the variance of λ , the expected number of crashes that would have occurred in the after period without treatment.

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

The Index of Effectiveness (θ) is estimated as:

$$\theta = (\pi_{sum}/\lambda_{sum}) \;/\; \{1 + [Var(\lambda_{sum})/\lambda_{sum}^2]\}. \quad \text{D5)}$$

The standard deviation of θ is given by:

$$Stddev(\theta) = [\theta^2\{[1/\pi_{sum}] + [Var(\lambda_{sum})/\lambda_{sum}^2]\} \;/\; [1 + Var(\lambda_{sum})/\lambda_{sum}^2]^2]^{0.5} \quad \text{D6)}$$

The percent change in crashes is in fact $100(1-\theta)$; thus a value of $\theta = 0.7$ with a standard deviation of 0.12 indicates a 30 percent reduction in crashes with a standard deviation of 12%.

DATA COLLECTION

All data were acquired from the NYDOT in electronic databases. These include data for intersections and segments both treated and untreated for the years 1994 to 2003. Tables D-1 and D-2 provide summary statistics of the treatment site data for intersections and road segments, respectively. Equivalent data were also assembled for untreated reference sites used to develop the safety performance functions used in the empirical Bayes methodology. There were 3393 intersection reference sites and 2108 reference segments (1242.4 miles).

Table D-1. Summary statistics for 256 treated intersection sites.

Variable	Mean	Minimum	Maximum
Years before	4.77	1.00	8.00
Years after	4.23	1.00	8.00
Crashes/site-year before	2.34	0.00	17.75
Crashes/site-year after	1.46	0.00	9.67
Wet-road crashes/site-year before	1.00	0.00	8.50
Wet-road crashes/site-year after	0.23	0.00	3.17
Dry-road crashes/site-year before	1.21	0.00	10.86
Dry-road crashes/site-year after	1.09	0.00	7.17
Rear-end crashes/site-year before	0.40	0.00	6.60
Rear-end crashes/site-year after	0.19	0.00	3.10
Rear-end wet-road crashes/site-year before	0.46	0.00	5.00
Rear-end wet-road crashes/site-year after	0.06	0.00	1.00
Right-angle crashes/site-year before	0.41	0.00	3.38
Right-angle crashes/site-year after	0.31	0.00	3.40
Right-angle wet-road crashes/site-year before	0.12	0.00	1.50
Right-angle wet-road crashes/site-year after	0.04	0.00	0.83
Major road AADT	24,893	3,475	65,850
Minor road AADT	2,974	174	10,055
Number of legs	3 legged – 199; 4 legged – 57		
Traffic control	Signalized – 73; Stop-controlled – 176 Yield-controlled – 7		
Area type	Rural – 30; Unincorporated community – 34 Village < 5,000 population – 13 Suburban – 54; City – 1 Village > 5,000 community – 124		

Table D-2. Summary statistics for 118 treated segments (36.3 miles).

Variable	Mean	Minimum	Maximum
Years before	5.01	1.00	8.00
Years after	3.99	1.00	8.00
Crashes/mile-year before	20.04	0.83	102.50
Crashes/mile-year after	18.92	0.00	80.63
Wet-road crashes/mile-year before	7.91	0.00	53.14
Wet-road crashes/mile-year after	3.13	0.00	16.67
Dry-road crashes/mile-year before	9.75	0.00	47.00
Dry-road crashes/mile-year after	13.40	0.00	62.50
Rear-end crashes/site-year before	6.41	0.00	34.00
Rear-end crashes/site-year after	6.21	0.00	37.50
Rear-end Wet-road crashes/site-year before	2.23	0.00	11.67
Rear-end Wet-road crashes/site-year after	1.05	0.00	7.50
Rear-end Dry-road crashes/site-year before	3.45	0.00	20.00
Rear-end Dry road crashes/site-year after	4.59	0.00	31.25
Single Vehicle crashes/mile-year before	4.88	0.00	50.00
Single Vehicle crashes/mile-year after	4.27	0.00	30.00
Single Vehicle Wet-road crashes/mile-year before	2.28	0.00	33.71
Single Vehicle Wet-road crashes/mile-year after	0.93	0.00	10.00
Major road AADT	38,297	1,814	185,570
Number of lanes	2 – 14.5 mi.; >2 – 21.8 mi.		
Area type	Rural – 8.7 mi. Unincorporated community – 9.4 mi. Village < 5,000 population – 2.1 mi. Suburban – 6.9 mi.; City – 2.2 mi. Village > 5,000 community – 7.0 mi.		

The following are a number of points regarding the data used and, correspondingly, the applicability of the results.

a. Only reportable accidents are considered.
b. Intersection accidents are assigned to a specific intersection within the data supplied by NYDOT and those accidents occurring within 33 feet of an intersection on the major or minor road are included.
c. The entire year during construction is removed from analysis.
d. For this study, rural environment has been defined as rural and unincorporated community, while urban has been defined as a village with population less than 5000 population; suburban is defined as city or village with a population of more than 5000.

DEVELOPMENT OF SAFETY PERFORMANCE FUNCTIONS

Generalized linear modeling was used to estimate safety performance functions (SPFs) using the untreated reference group data and the software package SAS, and assuming a negative binomial error distribution, all consistent with the state of research in developing these models. In specifying a negative binomial error structure, the “dispersion” parameter, *k*, which relates the mean and variance of the SPF estimate, is iteratively estimated from the model and the data. The value of *k* is such that the smaller its value the better a model is for a given set of data.

Separate SPFs were successfully calibrated for the following crash types:

- Total
- Wet-road
- Rear-end
- Dry
- Rear-end wet
- Right-angle (for intersections)
- Right-angle wet-road (for intersections)
- Single vehicle (for segments)
- Single vehicle wet-road (for segments)

SPFs for Intersections

Two model forms were used for the intersection SPFs:

$$\text{accidents/year} = \exp(\text{intercept})(\text{AADTmajor}+\text{AADTminor})^{b1} \qquad \text{D7)}$$

or

$$\text{accidents/year} = \exp(\text{intercept})(\text{AADTmajor})^{b1}(\text{AADTminor})^{b2} \qquad \text{D8)}$$

SPFs were calibrated for intersection groups categorized by number of legs, environment (urban or rural) and control type. Due to space limitations, only the SPFs for total and wet road accidents are reported in this paper. Tables D-3 and D-4 present these SPFs for the various intersection groups, based on the model forms in Equations D7 or D8, as applicable.

Table D-3. SPF parameter estimates for total accidents at stop-controlled and signalized intersections (based on equations D7 or D8).

Parameter	Estimate and standard error for signalized intersections				Estimate and standard error for stop-controlled intersections			
	3-legged		4-legged		3-legged		4-legged	
	Urban	Rural	Urban	Rural	Urban	Rural	Urban	Rural
Intercept	-16.3676 (1.5134)	-7.9616 (1.8240)	-13.4198 (1.1039)	-8.4784 (1.4067)	-7.6175 (0.6291)	-7.0266 (0.9001)	-7.4102 (1.0459)	-3.6512 (1.5747)
Exponent of AADT		0.8817 (0.1840)	1.4247 (0.1085)	0.9806 (0.1395)	n/a	n/a	0.7598 (0.1050)	0.3954 (0.1629)
Exponent of major AADT	1.2769 (0.2860)	n/a	n/a	n/a	0.2901 (0.1508)	0.5030 (0.1792)	n/a	n/a
Exponent of minor AADT	0.5270 (0.2395)	n/a	n/a	n/a	0.5933 (0.1355)	0.2698 (0.1338)	n/a	n/a
Dispersion parameter (k)	1.3760 (0.1053)	0.8892 (0.1389)	1.3557 (0.1042)	0.4919 (0.0840)	1.2268 (0.0505)	0.9396 (0.0583)	1.0741 (0.0944)	1.0674 (0.1457)

Table D-4 SPF parameter estimates for wet road accidents at stop and signal controlled intersections (based on equations D7 or D8).

Parameter	Estimate and standard error for signalized intersections				Estimate and standard error for stop-controlled intersections			
	3-legged		4-legged		3-legged		4-legged	
	Urban	Rural	Urban	Rural	Urban	Rural	Urban	Rural
Intercept	-15.8694 (1.5659)	-9.0669 (2.1054)	-13.3028 (1.1148)	-9.3464 (1.6905)	-10.4433 (0.6639)	-8.9727 (0.9230)	-7.3217 (1.3006)	-5.2118 (n/a)
Exponent of AADT		0.8279 (0.2116)	1.2623 (0.1091)	0.9222 (0.1670)	0.8658 (0.0669)	0.7492 (0.0972)	0.5958 (0.1302)	0.5958 (0.1302)
Exponent of major AADT	1.0202 (0.2934)	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Exponent of minor AADT	0.5888 (0.2467)	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Dispersion parameter (k)	1.1727 (0.1207)	1.0697 (0.2174)	1.1792 (0.1143)	0.5556 (0.1157)	1.4465 (0.0894)	1.3247 (0.1194)	1.3214 (0.1551)	1.3214 (0.1551)

SPFs for segments

Two model forms were used for the segment SPFs:

$$\text{accidents/year} = (\text{length})\exp(\text{intercept})(\text{AADT})^{b1} \qquad \text{D9)}$$

or

$$\text{accidents/year} = (\text{length})\exp(\text{intercept})(\text{AADT})^{b1}\exp^{(b2*\text{NUM\_OF\_ROADWAYS})} \qquad \text{D10)}$$

where: NUM_OF_ROADWAYS = 1 if undivided, 0 if divided

SPFs were calibrated for segment groups categorized by number of lanes (two-lane or multilane), and environment (urban or rural). Due to space limitations, only the SPFs for total and wet road accidents are reported in this paper. Tables D-5 and D-6 present these SPFs for the various segment groups, based on the model forms in Equations D9 or D10, as applicable.

Table D-5. SPF parameter estimates for total accidents on segments (based on equations D9 or D10).

Parameter	Estimate and standard error for two-lane segments		Estimate and standard error for multilane-lane segments	
	Urban	Rural	Urban	Rural
Intercept	-8.8153 (0.8983)	-7.4554 (0.4158)	-8.8878 (0.7457)	-6.2030 (0.5468)
Exponent of AADT	1.1241 (0.0962)	0.9950 (0.0457)	1.1088 (0.0716)	0.8406 (0.0523)
Coefficient for NUM_OF_ROADWAYS	n/a	n/a	0.3501 (0.0886)	0.3998 (0.1037)
Dispersion parameter (k)	1.1042 (0.0796)	0.3277 (0.0236)	0.8506 (0.0474)	0.5914 (0.0430)

Table D-6. SPF parameter estimates for wet road accidents on segments (based on equations D9 or D10).

Parameter	Estimate and standard error for two-lane segments		Estimate and standard error for multilane-lane segments	
	Urban	Rural	Urban	Rural
Intercept	-11.8198 (1.0902)	-9.1464 (0.5850)	-10.3669 (0.8343)	-6.9352 (0.6469)
Exponent of AADT	1.2694 (0.1160)	1.0066 (0.0639)	1.0930 (0.0797)	0.7519 (0.0615)
Coefficient for NUM_OF_ROADWAYS	n/a	n/a	0.3959 (0.0979)	0.3056 (0.1220)
Dispersion parameter (k)	0.8847 (0.0898)	0.4447 (0.0412)	0.8755 (0.0576)	0.6217 (0.0552)

RESULTS

Results are presented separately for intersections and segments.

Results for Intersections

Estimates of the index of effectiveness,θ, for the crash frequency analysis are given in Table D-7. Results emphasized in boldface indicate statistically significant reductions (i.e., $\theta < 1$) at the 5% level in total, wet-road, rear-end, and rear-end wet-road crashes for most intersection categories. Effects tend to be less positive for right-angle accidents; in fact the only statistically significant increase was in this crash type for 4-legged stop controlled intersections.

Table D-7. Index of Safety Effect (θ) for Intersections.
Note: % reduction in crashes is 100(1-θ)

Grouping	**Total (standard error)**	**Wet-road (standard error)**	**Rear-end (standard error)**	**Rear-end Wet (standard error)**	**Right-angle (standard error)**	**Right-angle Wet (standard error)**
All	**0.799 (0.028)**	**0.426 (0.030)**	**0.582 (0.034)**	**0.322 (0.041)**	1.045 (0.078)	0.799 (0.123)
3 leg signalized	**0.667 (0.050)**	**0.372 (0.053)**	**0.554 (0.065)**	**0.261 (0.066)**	0.787 (0.125)	**0.470 (0.161)**
3 leg stop-controlled	**0.819 (0.048)**	**0.355 (0.046)**	**0.586 (0.057)**	**0.335 (0.075)**	0.828 (0.218)	0.828 (0.218)
3 leg yield-controlled	**0.590 (0.114)**	**0.217 (0.103)**	**0.304 (0.086)**	**0.221 (0.161)**	n/a	n/a
4 leg signalized	**0.797 (0.052)**	**0.546 (0.070)**	**0.585 (0.068)**	**0.361 (0.084)**	0.898 (0.117)	1.105 (0.294)
4 leg stop-controlled	1.271 (0.143)	**0.597 (0.137)**	0.943 (0.188)	**0.482 (0.215)**	**1.687 (0.323)**	0.829 (0.351)
4 leg yield-controlled	0.589 (0.216)	0.361 (0.371)	**0.504 (0.248)**	n/a	n/a	n/a

To see if the principal benefits of improved skid resistance, i.e., reduction in wet-road accidents, declined over time, the effect on wet-road accidents was analyzed by year after treatment. As shown in Table D-8, there is no discernable trend over the six years of after period data.

Table D-8. Wet-road safety effectiveness by year following treatment.

Year After Treatment	**Index of effectiveness (standard error)**
First	0.508 (0.057)
Second	0.359 (0.051)
Third	0.429 (0.061)
Fourth	0.427 (0.070)
Fifth	0.352 (0.082)
Sixth	0.405 (0.107)
All Years	0.426 (0.030)

Results for Segments

Estimates of the index of effectiveness, θ, for the crash frequency analysis for segments are given in Table D-9. Results emphasized in boldface indicate statistically significant reductions (i.e., $\theta < 1$) at the 5% level in total, wet-road, rear-end, rear-end wet-road, single vehicle and single vehicle wet-road crashes for most roadway categories. For dry road crashes, statistically significant reductions were found for rural roads with more than two lanes but statistically significant increases were found for urban roads with more than two lanes.

Table D-9. Index of Safety Effect (θ) for segments.
Note: % reduction in crashes is $100(1-\theta)$

Grouping	Total (standard error)	Wet-road (standard error)	Rear-end (standard error)	Dry (standard error)	Rear-end Wet-road (standard error)	Rear-end Dry-road (standard error)	Single-vehicle (standard error)	Single-vehicle Wet-road (standard error)
All	**0.764 (0.023)**	**0.434 (0.024)**	**0.828 (0.043)**	1.003 (0.043)	**0.575 (0.055)**	0.977 (0.068))	**0.698 (0.040)**	**0.399 (0.039)**
Rural 2 lanes	0.964 (0.073)	0.852 (0.126)	1.047 (0.149)	1.167 (0.114)	0.971 (0.256)	1.235 (0.219)	1.078 (0.141)	1.125 (0.287)
Rural >2 lanes	**0.684 (0.032)**	**0.346 (0.028)**	**0.776 (0.068)**	**0.875 (0.061)**	**0.474 (0.079)**	0.838 (0.098)	**0.588 (0.046)**	**0.292 (0.038)**
Urban 2 lanes	**0.599 (0.082)**	**0.260 (0.066)**	**0.612 (0.142)**	0.992 (0.195)	**0.344 (0.145)**	0.695 (0.216)	0.921 (0.232)	0.523 (0.247)
Urban > 2 lanes	**0.862 (0.038)**	**0.538 (0.045)**	**0.866 (0.059)**	**1.132 (0.065)**	**0.640 (0.084)**	1.120 (0.099)	**0.800 (0.083)**	**0.615 (0.115)**

CONCLUSIONS

The results show that skid resistance improvement projects can yield substantial safety benefits for both road segments and intersections. The key to achieving these benefits is that the projects must be targeted at locations that have low skid resistance and a correspondingly high frequency of wet weather accidents. This proviso is especially important in the light of research reviewed and conducted by Hauer et al. (4) that showed that there can be minimal benefits or even a degradation in safety following pavement resurfacing, due to an increase in speeds that may be unsafe for the project environment. Given the relatively low cost of this treatment in comparison to the safety benefits, it is recommended that skid resistance improvements be considered at sites that warrant such treatment for safety considerations. To this end, warrants such as those employed by New York State DOT will need to be developed and deployed for use in highway engineering practice.

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