

# **HIGHWAY SAFETY MANUAL METHODOLOGIES AND BENEFIT-COST ANALYSIS IN PROGRAM-LEVEL SEGMENT SELECTION AND PRIORITIZATION**

**FINAL REPORT**



**SOUTHEASTERN TRANSPORTATION CENTER**

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## EXECUTIVE SUMMARY

The Highway Safety Manual (HSM) provides highway agencies with recommended processes and guidelines for decision-making based on safety performance. Safety Performance Functions (SPFs) are negative binomial models used to estimate the predicted number of crashes for a site or road segment and are developed from data for a number of similar sites. The SPFs can be used to develop rank orders of roadway segments to determine the potential for crash reduction (PCR) and can be used to select appropriate countermeasures, allow for comparing safety consequences among various alternatives, and permit identification of cost-effective strategies. This study, using state-specific SPFs for rural interstates and rural 2-lane roads, identified the 20 segments of each type with the highest PCR values. Appropriate existing crash modification factors (CMFs) for the types of crashes occurring on these roadways were then selected and used as inputs for a benefit-cost analysis (BCA) in an effort to create an index that normalizes the safety benefit of all roadway classes based on the cost of implementation. The analysis showed that once road segments with the highest PCR values have been identified, benefit-cost analysis can play a valuable role in identifying which sites will provide a return on investment and in ranking the segments deserving treatment.

## DESCRIPTION OF PROBLEM

The first edition of the *Highway Safety Manual* (HSM) was published in 2010. The purpose of the HSM is to establish reliable quantitative methods that transportation agencies and other stakeholders can use to estimate safety improvements for U.S. highways. When it was introduced, the American Association of State Highway and Transportation Officials (AASHTO) expected that highway agencies would take advantage of the HSM's statistical methods and modeling techniques to determine the sites with the greatest safety issues, what factors influence crash rates, and the potential benefits of introducing new countermeasures to bolster road safety. Thus, its recommended safety-performance based processes and guidelines are intended to sharpen the ability of transportation officials to decide about the relative utility of various planning, design, maintenance, and operational procedures to enhance the safety of roads (AASHTO, 2010). Included in the HSM are regression models that are used to predict average crash frequency for a site based on data from a number of similar sites. These predictive models, which are identified as safety performance functions (SPFs) in the HSM, have been developed for specific site types and baseline conditions. To properly apply the HSM procedures, existed SPFs can be either calibrated or developed based on state-specific crash data.

This paper discusses the use of Kentucky-specific SPFs to identify rural two-lane and rural interstate segments on which the introduction of new safety countermeasures are warranted due to their high potential for crash reduction (PCR). After pinpointing the top 20 segments for each road type, a benefit-cost analysis (BCA) was conducted to determine where the use of safety countermeasures would provide the highest return on investment. Appropriate crash modification factors (CMFs), which are multiplicative factors used to compute the expected number of crashes at a site after implementing a specified countermeasure, were critical to quantify the anticipated benefits of adopting safety improvements. Incorporating BCA allows site selection to be based not merely on the PCR, but also on the net return in dollars spent. This more balanced approach offers hope of ameliorating the problems that arise when state transportation agencies make their decisions about implementing safety countermeasures based on PCR values alone. When only PCR values are used, there is a tendency for the highest class of roadways to monopolize site selection rankings due to a typically larger number of crashes and volumes. Combining BCA with analysis of potential crash reductions may improve the decision making process on questions related to road safety and therefore seems to hold the promise of establishing a better approach to the selection and prioritization of road segments for the introduction of new safety countermeasures.

## APPROACH AND METHODOLOGY

Before statistical modeling began, Kentucky's roadway network was divided into homogenous segments, as SPFs cannot be generated without this preliminary analysis. The roads were segmented using Highway Performance Monitoring System (HPMS) data, which allowed the compilation of a list of homogeneous road segments across the state, but only for those routes with an AADT value. AADT values were obtained from the Kentucky Transportation Cabinet (KYTC) for each segment based on the 2012 HPMS extract. Once the segments were identified and spatially corrected using ArcGIS, crash data for a 5-year period were collected and plotted on the state linear system using route and mile-point information and identifying all crashes (KABCO) and fatal/severe injury crashes (KAB). Crash data were gathered from Kentucky State Police records (CRASH database) for each roadway type. The records encompassed a 5-year period, 2009–2013. For each segment the total number of crashes and the total number of fatal/severe injury crashes were identified. As this research is focused on improving the site selection process for rural 2-lane roads and rural interstates, the top 20 PCR values for each of these two types of roads were calculated using statistical modeling (see below).

The HSM generally prescribes using historical data for specific sites to develop SPFs. The initial SPFs are then adjusted using the Empirical Bayes approach to improve the accuracy of estimates and address regression to the mean (AASHTO, 2010). HSM-recommended procedures were reviewed to identify the methods that would enable customized analyses of Kentucky crash data and the development of SPFs.

Researchers have used negative binomial models to predict crashes because these models assume that unobserved crash variation across roadway segments follows a gamma distribution. Conversely, within-site crash variation follows a Poisson distribution (Washington, 2005). The Poisson, Poisson-Gamma (negative binomial), and other related models are collectively called generalized linear models (GLM). These models have the general form:

$$E[N] = L e^{b_0 + b_1 X_1 + b_2 X_2 + \dots + b_n X_n} \quad (1)$$

where  $E[N]$  = predicted number of crashes per year for a roadway segment,  $L$  = length of roadway segment,  $b_0, \dots, b_n$  = regression coefficients, and  $X_1, \dots, X_n$  = predictor variables (e.g. Average Annual Daily Traffic (AADT) and shoulder/median widths). The unit of analysis is a roadway segment with its associated crash history. Models developed similar to the generalized form described above identify the relationship between the number of crashes at a site and the various elements under consideration. Two SPFs were developed using Equation 1, both predicting the number of crashes at a site as a function of traffic conditions and the values of geometric elements. One of these models predicts the total number of crashes. The second model predicts fatal and severe injury crashes. For this analysis, the second model included incapacitating injury and non-incapacitating injuries.

Like many other states, Kentucky's state and local police classify the severity of vehicle crashes using the KABCO scale. This scale assigns a crash to preset categories, with K, A, and B representing fatal, incapacitating injury, and non-incapacitating injury, respectively. C is used to designate crashes in which there was a possible injury, and O encompasses incidents that only resulted in property damage. Building from Equation 1, the models that were developed took on the following general form:

$$E[N] = L e^a AADT^b \quad (2)$$

where  $a$  and  $b$  are coefficients that describe the behavior between AADT and the predicted number of crashes. These models were developed using the statistical software program R (R Foundation, 2013). The resulting model predicts crashes over a five-year period. It should be noted that the SPF model parameters are reflective of this, yielding an SPF that is five times the scale of a typical SPF (e.g. as it would be from the HSM).

Once the predicted number of crashes per roadway segment was calculated, the Empirical Bayes (EB) estimate for each segment was derived. This estimate established the required correction that was needed to account for small sample size, model reliability, temporal issues, and natural fluctuation of crashes over time. It uses the over-dispersion parameter of the prediction model for each site. The overdispersion parameter indicates the distribution of crash counts around the estimated mean. Models with a high overdispersion parameter assign more weight to the model and less weight to the actual data to account for data variability. The EB estimate is calculated as:

$$EB[N] = w E[N] + (1 - w) N \quad (3)$$

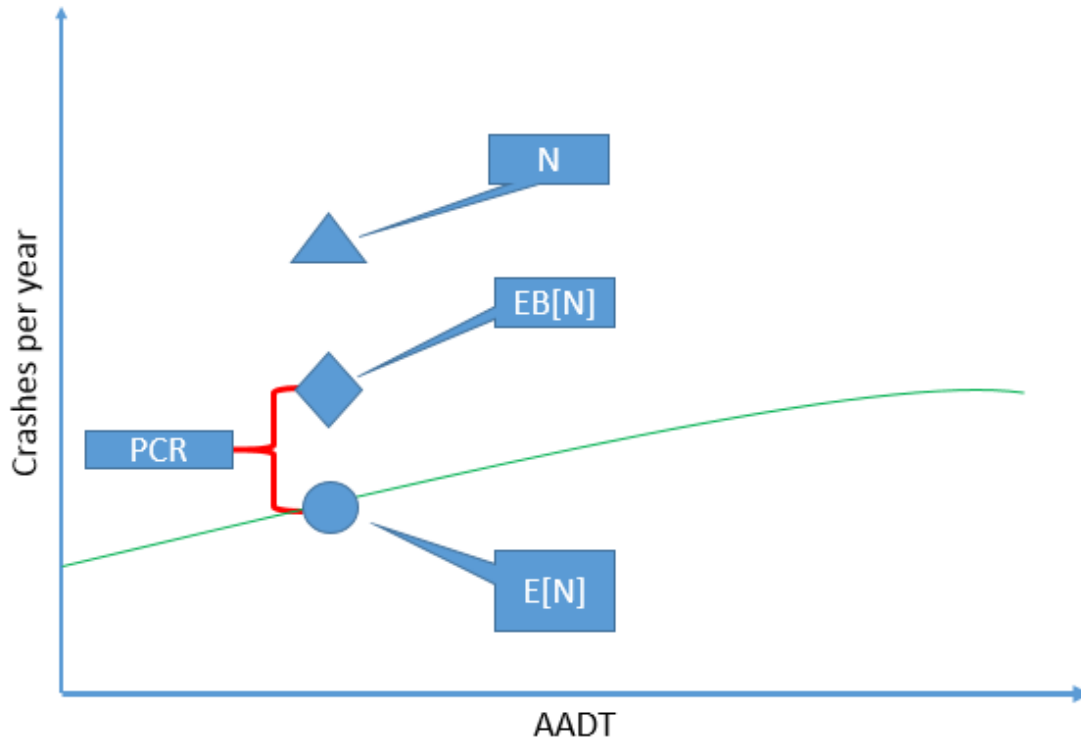
where  $EB[N]$  = EB estimate,  $E[N]$  = predicted number of crashes,  $N$  = number of observed crashes,  $w$  = weight where  $w = 1 / [1 + (E[N]/\theta)]$ , and  $\theta$  = overdispersion parameter.

The estimated difference between the predicted crashes and EB corrected crash estimate was then used to evaluate the potential for crash reduction (PCR) at a specific site. PCR is calculated with the following equation:

$$PCR = EB[N] - E[N] \quad (4)$$

Figure 1 demonstrates this concept.



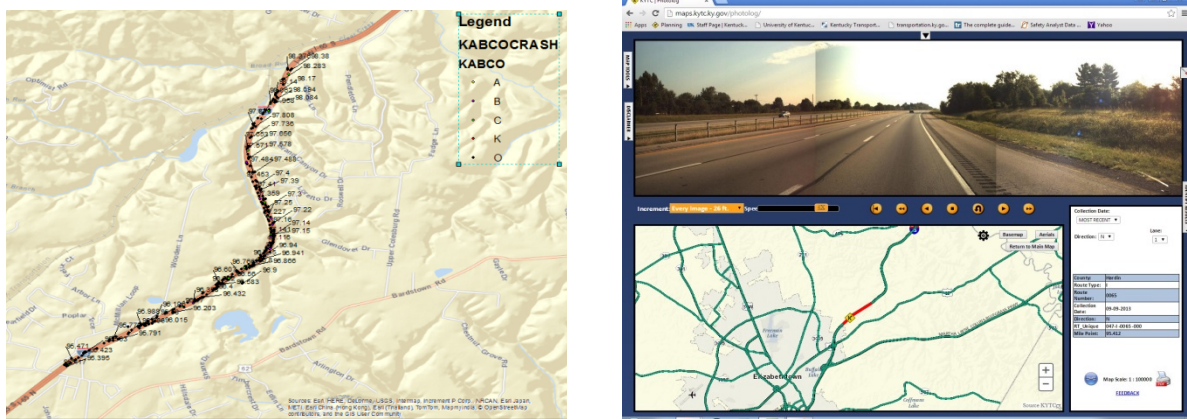


**FIGURE 1: Estimation of Potential Crash Reduction for a Site**

After identifying the 40 road segments with the highest PCR values, detailed data on the types of crashes that occurred during the study period was acquired using the Kentucky Justice and Public Safety Cabinet’s Kentucky Open Portal Solution (KyOPS) software. This yielded rich information concerning variables related to the crashes, including time, weather, road conditions, light conditions, number killed and the manner of collision. At this point, the total number of crashes documented in KyOPS was checked against the number used to obtain the PCRs. In three cases the data did not match. After investigating these mismatches, it was determined that some crashes were not assigned to the correct segment. Crashes for these cases occurred on ramps located along different road segments. Once these crashes were appropriately classified, three segments that previously had the highest PCR rankings fell out of the top twenty lists. Accordingly, rankings were adjusted and a new list was formulated.

Once the rankings were finalized, road segments were analyzed using KYTC’s Photolog. Photolog is a database maintained by KYTC that contains maps and photographs of roads located throughout the state of Kentucky. Images from Photolog were placed alongside maps generated in ArcGIS of each road segment identified as being high risk. Summary statistics were also developed to describe the type and nature of the recorded crashes. At this point, an expert panel that consisted of traffic safety engineers and highway designers from the team of Highway Safety Manual Methodologies and Benefit-Cost Analysis in Program-Level Segment Selection and Prioritization

authors was convened to identify and assess the safety hazards that were inherent to each route. The panel conducted a road safety audit using photos of the roadway and Excel pivot tables that summarized the time of day, weather, and nature of the crashes. Figure 2, which illustrates a three-mile segment of I-65 in Hardin County, depicts the information the expert panel had access to on Photolog. The panel drew on all this information to identify what safety countermeasures would be most appropriate to lessen probability of these crash types occurring on the selected road segments.



**FIGURE 2: CMF-Selection Tools (ArcGIS maps & KYTC's Photolog)**

Once the expert panel selected safety countermeasures for each site, the Federal Highway Administration's Crash Modification Factor (CMF) Clearinghouse was searched to identify CMFs that would be applicable in evaluating the effect of safety countermeasures on the safety of rural two-lane and interstate segments. The CMF Clearinghouse is a centralized website that stores and provides access to CMFs developed as part of previous research (FHWA, 2010). For each safety countermeasure, multiple CMFs and their associated CRF (Crash Reduction Factor) are available. For the purposes of determining the number of crashes reduced, CRFs were used. During the search of the Clearinghouse, priority was given to CRFs that were included in the HSM, to those having higher star ratings, and to those that matched the segment features (e.g. geometry, AADT). When available, CRFs that were equipped to handle the full range of crash severities were chosen. Table 1a lists the CRFs that were selected for rural 2-lane segments. Table 1b lists the CRFs chosen for rural interstates.

Safety Countermeasure	CRF	Crash Type	Crash Severity
Add Shoulder Rumble Strips	0.16	Run off Road	All
Widen Shoulder	0.71	Run off Road	Fatal/Serious/Minor Injury
Add Guardrails	0.47	Run off Road	Serious/Minor Injury
Add Pavement Markings	0.37	All	Fatal/Serious/Minor Injury
Add Advanced Curve Warning Signs	0.30	Run off Road	All
Add Shoulder	0.19	All	All
Access Management (limit entry and exit points)	0.11	Cross Median	All
Add Turning Lane	0.47	Rear End	All
Add Curb and Gutter	0.11	All	All
Apply High Friction Surface Treatment	0.54	Wet Road	All
Add Edge Treatment	0.06	Run off Road	All

**TABLE 1a: CRFs for Rural 2-Lane Segments**

*Note 1:* The CRFs both for Adding and Widening the Shoulder are for a width  $\leq 1$  meter.

Safety Countermeasure	CR F	Crash Type	Crash Severity
Apply High Friction Surface Treatment	0.46	Wet Road	All
Add Lighting	0.20	All	Serious/Minor Injury
Add Reflectors	0.45	All	Serious/Minor Injury
Add Cable Barrier	0.91	Cross median/Frontal & opposing direction sideswipe/Head on	All
Improve Pavement	0.53	Rear end/Wet road	All

**TABLE 1b: CRFs for Rural Interstate Segments**

Using the data from tables 1a and 1b, the number of crashes reduced per segment was then calculated for each countermeasure. To find the crashes reduced per segment, the reduction factor was multiplied by the number of crashes fitting the specifications for the CRF. For example, for adding guardrails on rural 2-lane roads, the CRF of 0.47 was applied to run off

road crash types and serious/minor crash severities. For each of the top 20, 0.47 was multiplied by the number of run off road crashes that included serious and/or minor injuries.

After completing CRF adjustments, the cost of implementing different safety countermeasures on a per mile basis was determined by working with KYTC representatives and through the United States Road Assessment Program (usRAP). Estimates were based on the upfront cost to implement each countermeasure as well as their life expectancy. Calculations were performed to determine the total cost to maintain the safety improvement for one generation (20 years). Some countermeasures had lifespans greater than 20 years. For all such cases, the costs were nevertheless apportioned across a 20-year span and benefits beyond that span were not given weight. Rural 2-Lane segments' countermeasures data are presented in Table 2a, while Table 2b summarizes results for rural interstates.

Safety Countermeasure	Cost/mile	Treatments[1]	Total Cost[2]	Cost/year
Shoulder Rumble Strips	\$4,224	2	\$8,448	\$422
Widening Shoulder (Unpaved)[3]	\$36,432	1	\$36,432	\$1,822
Guardrails	\$168,960	1	\$168,960	\$8,448
Pavement Markings (Two Stripes)	\$845	8	\$6,760	\$338
Curve Signage[4]	\$4,800	2	\$9,600	\$480
Add Shoulder (Unpaved)[3]	\$36,432	1	\$36,432	\$1,822
Access Management[5]	\$31,382	1	\$31,382	\$1,569
Turning Lane[6]	\$150,000	1	\$150,000	\$7,500
Curb and Gutter	\$158,400	1	\$158,400	\$7,920
High Friction Surface Treatment[7]	\$62,230	3	\$186,690	\$9,335
Edge Treatment	\$3,000	2	\$6,000	\$300

**TABLE 2a: CRF Costs for Rural 2-Lane Segments, 20-year lifespan**

*Note 1:* "Treatments" denotes the number of times CRFs would have to be applied to create a 20-year continuous effect.

*Note 2:* "Total Cost" is the price required to generate a 20-year implementation period.

*Note 3:* Both widening and adding a shoulder are based on an increase in width of 3 feet, which is just under the maximum value of 1 meter called out in the CRF.

*Note 4:* The "Curve Signage" price is not calculated on a per mile but rather based on the number of significant curves in each segment.

*Note 5:* "Access Management" CRF is for adding a 10' traversable median

*Note 6:* "Turning Lane" price is not calculated on a per mile but rather a per intersection basis.

*Note 7:* The "HFST" price is calculated based on an 800ft x 20ft section that is applied once on segments  $\leq 1$  mile, 2 times on segments  $>1$  mile but  $\leq 2$  miles, and so on.

Safety Countermeasure	Cost/mile	Treatments	Total Cost	Cost/year
High Friction Surface Treatment[1]	\$280,000	3	\$840,000	\$42,000
Lighting [2]	\$400,000	1	\$400,000	\$20,000
Reflectors	\$2,956	2	\$5,912	\$296
Cable Barrier	\$150,000	1	\$150,000	\$7,500
Improve Pavement[3]	\$331,000	2	\$662,000	\$33,100

**TABLE 2b: CRF Costs for Rural Interstate Segments , 20-year lifespan**

*Note 1:* The “HFST” price is calculated based on a 1,500ft x 24ft section that is applied (in both directions) once on segments ≤1 mile, 2 times on segments >1 mile but ≤2 miles and so on.

*Note 2:* The “Lighting” price is not calculated on a per mile but rather a per intersection basis.

*Note 3:* “Improve Pavement” CRF is for improving pavement friction (increasing skid resistance)

Once the annual costs were estimated for each countermeasure, the required cost to apply them to each of the targeted road segments was calculated. On most segments, this entailed multiplying the cost of the countermeasure by the length of the respective segment. The process to calculate expenses for Lighting, Turning Lane, and Curve Signage countermeasures, however, was slightly more complex. Photolog was used to scan the entire length of each segment. The number of interchanges, intersections, and significant curves on each segment was recorded. This number was used as a multiplicative factor to arrive at a final cost estimate. For the High Friction Surface Treatment countermeasure, it was applied once for all lengths up to and including one mile. For values above that and up to two miles, the cost for two treatments was used, and for values above two miles, calculations similarly used one-mile increments.

With these costs in hand, estimating the cost per crash reduced for each countermeasure was the next step. For this, KyOPS data were examined to assess the influence of each countermeasure on the number of crashes. Then, as described earlier, the appropriate crash reduction factor was used to estimate how many crashes would be prevented by each safety countermeasure. Annual costs were then divided by this number to derive the yearly cost per crash reduction for each countermeasure. These data, for each road segment, were averaged to evaluate the mean cost per crash reduced for every countermeasure. Table 3 summarizes these results.

Rural 2-Lane Segments		Rural Interstate Segments	
Safety Countermeasure	AVG Cost	Safety Countermeasure	AVG Cost
Guardrail	\$13,676	HFST	\$12,388
Add Turn Lane	\$10,416	Cable Barrier	\$8,677
HFST	\$5,285	Lighting	\$6,839
Access Management	\$4,449	Improve Pavement	\$3,192
Widen Shoulder	\$1,940	Reflectors	\$83
Curb & Gutter	\$1,126		
Curve Signage	\$419		
Edge Treatment	\$375		

*Note:* AVG Cost =  $\Sigma$   
(CRF yearly unit cost \* )

<b>Shoulder Rumble Strips</b>	\$208	required units/segment) ÷ Σ (# of crashes prevented across the 20 segments)
<b>Add Shoulder</b>	\$150	
<b>Pavement Markings</b>	\$103	

**TABLE 3: Average Cost per Crash Reduction**

Safety countermeasure rankings were then generated for each road segment to determine which would produce the largest reduction in crashes for the smallest financial investment. Lastly, actuarial/cost tables supplied by the National Safety Council were used to establish whether the benefits of particular countermeasures outweighed the costs and whether it was possible to identify and recommend candidate projects to improve highway safety. The data used for these calculations are presented in Table 4.

<b>Crash Severity</b>	<b>Economic Cost</b>	<b>Comprehensive Cost</b>
K	\$1,410,000	\$4,538,000
A	\$72,200	\$230,000
B	\$23,400	\$58,700
C	\$13,200	\$28,000
O	\$2,500	\$2,500

**TABLE 4: Crash Severity and Costs**

*Note 1:* National Safety Council data (2012)

*Note 2:* Economic Costs are calculable costs of motor vehicle collisions (e.g. wage loss, medical expense, administration costs, property damage, and employer costs).

*Note 3:* Comprehensive Costs include not only the economic cost components but also a measure of the value of lost quality of life associated with deaths and injuries.

## FINDINGS; CONCLUSIONS; RECOMMENDATIONS

### Cost Calculations

This analysis brought several interesting findings to light about the use of safety countermeasures on rural two-lane road segments. For example, adding guardrails was consistently a low-ranked countermeasure (in the bottom two) for 15 out of 20 segments and high friction surface treatment was in the bottom two for 12 out of 20 segments. Conversely, there were two safety countermeasures that never ranked outside the top four of the 11 that were considered: adding shoulder rumble strips and pavement markings. The only other countermeasure that ranked among the top four for a majority of the segments was adding a shoulder. These data are presented in Table 5.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
AS	AS	PM	S	SRS	PM	PM	PM	SRS	AS	AS	PM	SRS	PM	SRS	PM	SRS	S	AS	PM
PM	SRS	AS	SRS	WS	AS	S	AS	WS	PM	SRS	AS	WS	SRS	PM	AS	WS	SRS	SRS	AS
CG	PM	SRS	PM	G	CG	AS	S	G	SRS	PM	S	G	S	S	SRS	G	ET	PM	SRS
SRS	S	ET	ET	PM	SRS	SRS	SRS	PM	ET	ET	SRS	PM	ET	ET	ET	PM	PM	ET	ET

**TABLE 5: Rankings of Least Cost CRFs per Crash Reduction (Rural 2-Lane Segments)**

*Note:*

PM = Adding Pavement Markings      ET = Adding Edge Treatments      S = Adding Curve Signage  
 SRS = Adding Shoulder Rumble Strips      CG = Adding Curb and Gutter      AS = Adding Shoulder  
 WS = Widening Shoulder      G = Adding Guardrail

For rural interstates, on all 20 segments, installing reflectors was rated as the most cost-effective strategy to reduce crashes, and for 15 of the segments, improving the pavement ranked as the second best choice. The least economical choice was applying a high friction surface treatment (last on 14 of 20 segments). These results are summarized in Table 6.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
L	P	P	P	P	P	P	L	P	P	P	L	P	P	P	L	P	P	CB	P
P	CB	CB	HFS	L	HFS	CB	CB	L	CB	HFS	CB	HFS	HFS	L	CB	CB	CB	P	L
CB	L	HFS	CB	CB	CB	HFS	P	CB	HFS	L	P	CB	CB	HFS	P	L	L	HFS	CB

**TABLE 6: Rankings of Least Cost CRFs per Crash Reduction (Rural Interstate Segments)**

*Note 1:*

R = Adding Reflectors      CB = Installing Cable Barriers      L = Adding Lighting  
 P = Improving Pavement      HFS = Applying High Friction Surface Treatment

*Note 2:*

For Segments 3, 6, 7, 10, 11 & 13, only four of five CRFs were applicable.



### Benefit-Cost Calculations

After obtaining cost estimates, the net benefits of applying safety countermeasures to each segment were assessed. Estimates of crash severity and costs (Table 4) were used as a starting point to calculate the benefits of preventing crashes. Economic benefits were defined as the gain from not having to pay medical expenses, administration and employer costs, and property damage. Comprehensive benefits included economic benefits plus the benefits individuals would accrue by not having a reduced quality of life due to injuries suffered in an accident. This study focused primarily on comprehensive benefits, as they capture the full range of economic consequences implicated in safety-related decision-making. Economic benefit calculations were used as a supplemental analysis to provide an alternative method of quantifying the magnitude of benefits or losses stemming from these decisions. To determine net benefits, the annual cost of implementing each countermeasure on each segment was subtracted from the annual comprehensive benefit.

When comparing the costs of safety countermeasures to their comprehensive benefits for rural 2-lane segments, only three yielded positive returns in every case: 1) adding a shoulder, 2) adding a curb and gutter, and 3) adding pavement markings. Adding a shoulder returned the most significant benefit on eight of the segments and never dropped out of the top four. High friction surface treatment was the top choice for another eight segments and adding turning lane was the top choice for four. Adding curve signage and curbs and gutters consistently ranked near the top, and fell outside of the top four for only seven segments. Regarding less beneficial countermeasures, adding guardrails provided a negative return on a majority of the segments (11 of 20). Access management did not reach the break-even point on half of the segments, and high friction surface treatment was negative for 40%. Overall, eight countermeasures provided a negative return on at least one segment. Table 7 summarizes these results.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1st	AS	TL	AS	HFS	HFS	AS	TL	AS	HFS	AS	AS	TL	HFS	HFS	HFS	TL	HFS	HFS	AS	AS
2nd	TL	AS	CG	S	S	TL	AS	TL	S	TL	TL	AS	S	AS	AS	AS	S	S	CG	TL
3rd	CG	CG	TL	AS	AS	CG	CG	CG	AS	CG	CG	CG	AS	S	S	CG	WS	AS	TL	CG
4th	PM	S	PM	R	R	PM	S	PM	R	S	S	PM	R	WS	CG	PM	AS	R	S	PM

**TABLE 7: Rural 2-Lane CRFs with Largest Net Positive Benefits (Comprehensive Valuation)**

*Note:*

PM = Adding Pavement Markings      ET = Adding Edge Treatments      S = Adding Curve Signage  
 SRS = Adding Shoulder Rumble Strips      CG = Adding a Curb and Gutter      TL = Adding Turning Lane  
 HFS = High Friction Surface Treatment      AS = Adding Shoulder      G = Adding a Guardrail

To better understand the magnitude of the economic effect of implementing these countermeasures, the gain or loss was calculated for each segment and then these amounts were aggregated to assess the total gain or loss that would be realized if the countermeasure

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were applied to each segment. From this, the average per segment economic impact was also determined. Table 8 lists this information for rural two-lane segments.

	<b>Total Gain or Loss</b>	<b>AVG Gain/Loss</b>
<b>Add Shoulder</b>	\$4,047,645	\$202,382
<b>HFST</b>	\$3,245,738	\$162,287
<b>Curve Signage</b>	\$2,857,641	\$142,882
<b>Curb &amp; Gutter</b>	\$2,322,592	\$116,130
<b>Turning lane</b>	\$2,207,945	\$110,397
<b>Widen Shoulder</b>	\$1,541,252	\$77,063
<b>Shoulder Rumble Strips</b>	\$1,524,382	\$76,219
<b>Pavement Markings</b>	\$1,493,967	\$74,698
<b>Guardrail</b>	\$659,394	\$32,970
<b>Edge treatment</b>	\$595,802	\$29,790
<b>Access Management</b>	\$73,737	\$3,687

**TABLE 8: Net Benefits (Comprehensive Valuation) from 20 Segment (Rural 2-Lane) CRF Application**

To determine the overall return on investment for each countermeasure on rural two-lane segments, economic benefits were used. The general formula for these calculations was:

$$ROI = (AEB - AEC) / AEC * 100 \quad (5)$$

where ROI = Return on Investment, AEB = the Annual Economic Benefit from the reduction in crashes from some CRF, and AEC = the Annual Economic Cost to Apply a CRF.

Countermeasures such as adding a shoulder, pavement markings and a curb and gutter yielded a positive return on investment for all segments, and adding curve signage, edge treatments, and shoulder rumble strips provided positive returns for 19 of the 20 segments. Conversely, access management provided a positive return on just three segments, guardrails on nine, and widening the shoulder on just twelve. Table 9 highlights these findings.

	1	2	3	4	5	6	7	8	9	10
<b>Shoulder Rumble Strips</b>	663	46,781	2,321	79,066	77,657	-77	15,731	911	24,396	1,569
<b>Widen Shoulder</b>	-92	180	25	10,333	8,922	-98	2,560	-12	2,318	-52
<b>Guardrail</b>	-99	-80	-88	886	702	-100	141	-92	129	-95
<b>Pavement Markings</b>	8,287	27,693	27,894	25,494	22,247	43,521	55,439	20,038	6,537	4,727
<b>Signage</b>	440	57,915	920	258,902	134,759	-84	59,064	1,947	31,403	1,553
<b>Add Shoulder Access</b>	194,030	1,065,833	124,208	44,457	44,090	136,104	75,744	52,922	15,323	38,564
<b>Management</b>	-21	-47	N/A	318	511	-97	-76	-78	-36	-99
<b>Turn Lane</b>	20,501	309,018	436	-98	-33	3,265	13,359	2,028	-98	607
<b>Curb &amp; Gutter</b>	14,869	82,092	9,485	3,336	3,307	10,402	5,748	3,988	1,089	2,881
<b>HFST</b>	-68	4,552	-88	17,156	21,777	N/A	1,750	-91	4,661	-4
<b>Edge Treatment</b>	67	10,183	431	17,264	16,955	-95	3,372	122	5,273	266

	11	12	13	14	15	16	17	18	19	20
<b>Shoulder Rumble Strips</b>	1,684	778	26,303	285,694	16,568	984	42,780	21,773	4,323	1,426
<b>Widen Shoulder</b>	-92	-55	5,435	121,020	2,415	-3	24,548	1,844	-12	45
<b>Guardrail</b>	-99	-96	423	7,607	138	-91	2,229	84	-92	-86
<b>Pavement Markings</b>	1,322	6,949	16,161	476,832	11,394	6,952	55,373	4,419	1,985	27,481
<b>Signage</b>	914	1,993	20,182	326,308	21,344	674	37,742	56,563	2,671	1,286
<b>Add Shoulder Access</b>	76,368	31,200	17,697	258,087	17,373	18,037	22,041	11,565	23,933	66,532
<b>Management</b>	-72	-91	-20	397	-59	-48	-84	-21	-59	-78
<b>Turn Lane</b>	3,317	12,719	-16	2,352	120	898	317	-91	569	1,944
<b>Curb &amp; Gutter</b>	5,796	2,314	1,272	19,808	1,247	1,298	1,607	799	1,753	5,038

				47,61			8,52	3,63		
	-89	-83	5,101	4	3,407	-79	4	6	66	-77
<b>HFST Edge Treatment</b>	291	93	5,691	62,58	3,556	138	9,30	4,69	870	235
				5			5	8		

**TABLE 9: Percentage Return on Investment in CRFs for Rural 2-Lane Segments (Economic Valuation)**

These data indicate that not all countermeasures will provide commensurate returns. Countermeasures can be partitioned into two groups based on their returns on investment. The first group encompasses countermeasures that offer high-magnitude, positive returns and includes adding a shoulder, curve signage, turn lanes, pavement markings, and shoulder rumble strips. A second group produces moderately positive returns, and includes widening shoulders, adding curbs and gutters, incorporating edge treatments, and high friction surface treatments. Access management, because of its small average return, falls outside the previous categories. The average returns on investment for each countermeasure are summarized in Table 10.

	<b>AVG</b>
<b>Add Shoulder</b>	116,705%
<b>Signage</b>	50,825%
<b>Pavement Markings</b>	42,537%
<b>Shoulder Rumble Strips</b>	32,567%
<b>Turn Lane</b>	18,556%
<b>Widen Shoulder</b>	8,961%
<b>Curb &amp; Gutter</b>	8,907%
<b>Edge treatment</b>	7,065%
<b>HFST</b>	6,193%
<b>Guardrail</b>	566%
<b>Access Management</b>	13%

**TABLE 10: Rural-2-Lane-Segment CRF's Average Return on Investment (Economic Valuation)**

For rural interstates, comprehensive benefits were used to initially assess the value of each countermeasure. Improving pavement was the clear favorite, ranking first on all of the segments. Applying a high friction surface treatment (ranked second best thirteen times and

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third best five times) and adding reflectors (ranked second best seven times and third best eleven times) were countermeasures that also showed very positive economic returns. The countermeasure with the least value was cable barriers. It ranked last for 13 segments and second-to-last for three others. For six segments, cable barrier installation produced negative returns. As a point of reference, there were only 10 incidences where implementing countermeasures yielded negative results for rural interstates. This is summarized in Table 11.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1 <sup>st</sup>	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
2 <sup>nd</sup>	HFS	HFS	HFS	HFS	R	HFS	HFS	R	R	R	HFS	HFS	HFS	HFS	HFS	R	HFS	R	HFS	R
3 <sup>rd</sup>	R	R	R	R	L	R	R	HFS	HFS	HFS	R	CB	R	R	R	HFS	R	CB	CB	HFS
4 <sup>th</sup>	L	L	CB	CB	HFS	CB	CB	CB	L	CB	L	R	CB	CB	L	L	CB	L	R	L

**TABLE 11: Rural Interstate CRFs with Largest Net Positive Benefits (Comprehensive Valuation)**

*Note:* R = Adding Reflectors      CB = Installing Cable Barriers      L = Adding Lighting  
P = Improving Pavement      HFS = Applying High Friction Surface Treatment

As with rural two-lane roads, the economic outcomes of applying these countermeasures to rural interstates across all twenty segments was calculated. This was used to derive the average per segment economic impact. Table 12 catalogues these results.

	Total Gain/ Loss	AVG Gain/Loss
Improve Pavement	\$10,131,453	\$506,573
High Friction Surface Treatment	\$4,573,652	\$228,683
Reflectors	\$3,765,446	\$188,272
Lighting	\$1,368,411	\$97,744
Cable Barriers	\$1,029,431	\$54,181

**TABLE 12: Net Benefits (Comprehensive Valuation) from 20 Segment (Rural Interstate) CRF Application**

*Note 1:* For six segments, Lighting was not a possible CRF. Therefore, its average is divided by the fourteen segments where its use was possible.

*Note 2:* For one segment, a Cable Barrier was not a possible CRF. Therefore, n = 19.

Looking at economic benefits solely through the prism of economic benefits, the addition of reflectors and enhancing pavement quality had positive returns for every segment. Reflectors, moreover, had the most significant positive return by far. Conversely, installing cable barriers often showed a negative return (for nine out of 20 segments). These data are presented in Table 13.

	1	2	3	4	5	6	7	8	9	10
<b>HFST</b>	1,586 %	4,260 %	595%	3,217 %	76%	1,640 %	82%	33%	139%	356%
<b>Lighting</b>	2,794 %	1,257 %	N/A	N/A	884%	N/A	N/A	489%	770%	N/A
<b>Reflectors</b>	244,58 2%	211,9 96%	16,05 7%	56,26 3%	128,8 13%	46,48 1%	25,03 2%	55,68 0%	95,93 9%	154,7 49%
<b>Cable Barrier</b>	588%	1,268 %	342%	-70%	23%	-91%	-72%	390%	243%	-27%
<b>Improve Pavement</b>	10,320 %	25,11 1%	2,608 %	7,289 %	9,904 %	4,226 %	3,140 %	1,691 %	5,691 %	4,385 %

	11	12	13	14	15	16	17	18	19	20
<b>HFST</b>	2,379 %	370 %	2,78 8%	486 %	402 %	889%	410 %	-93%	328 %	139 %
<b>Lighting</b>	342%	314 %	N/A	-78%	93%	5,969 %	81%	-70%	-66%	64%
<b>Reflectors</b>	103,7 73%	18,5 32%	45,7 81%	11,4 39%	37,4 40%	566,0 02%	26,5 47%	14,9 92%	14,2 82%	37,5 90%
<b>Cable Barrier</b>	N/A	981 %	-49%	-77%	-76%	1,698 %	377 %	-76%	1,01 1%	-64%
<b>Improve Pavement</b>	7,475 %	1,19 3%	6,74 1%	1,56 6%	1,96 9%	7,556 %	4,88 9%	2,56 0%	1,48 0%	989 %

**TABLE 13: Percentage Return on Investment in CRFs for Rural Interstate Segments (Economic Valuation)**

In general, the return on investment for safety countermeasures on rural interstates was quite good. When the countermeasures were averaged across all 20 segments, they all demonstrated moderate to high positive returns on investment, to which the data in Table 14 attest.

	<b>AVG</b>
<b>Reflectors</b>	95,598%
<b>Improve Pavement</b>	5,539%
<b>HFST</b>	1,004%
<b>Lighting</b>	917%
<b>Cable Barrier</b>	333%

**TABLE 14: Rural-Interstate-Segment CRF's Average Return on Investment (Economic Valuation)**

The final set of calculations attempted to identify the segments traffic safety engineers would select if they ranked segments based on the net benefit attained by applying the most cost-effective countermeasure for each segment. Rural two-lane and interstate segments were ranked in a single group. Seven of the top ten were rural interstate segments. Of the rural interstate segments, five were in the top ten as originally ranked by PCR values. Of the three top ten rural two-lane segments, two were originally in the top ten PCR rankings. The results are summarized in Table 15.

BCA Rank	PCR Rank	CR F	Net Benefits
1	I-2	P	\$2,588,625
2	I-5	P	\$1,560,198
3	2L-14	HF S	\$1,510,339
4	I-16	P	\$884,998
5	2L-2	TL	\$846,554
6	I-1	P	\$784,194
7	I-9	P	\$601,699
8	I-13	P	\$559,047
9	2L-5	HF S	\$501,565
10	I-4	P	\$472,401

BCA Rank	PCR Rank	CR F	Net Benefits
11	I-11	P	\$468,344
12	I-17	P	\$455,174
13	2L-7	TL	\$445,110
14	I-12	P	\$369,439
15	2L-4	HF S	\$332,602
16	I-8	P	\$224,259
17	2L-17	HF S	\$217,023
18	I-6	P	\$211,931
19	I-3	P	\$211,790
20	I-15	P	\$185,467

BCA Rank	PCR Rank	CR F	Net Benefits
21	2L-12	TL	\$149,725
22	2L-9	HF S	\$146,622
23	I-10	P	\$146,332
24	I-20	P	\$144,518
25	2L-18	HF S	\$128,478
26	2L-15	HF S	\$126,749
27	2L-1	AS	\$114,064

BCA Rank	PCR Rank	CR F	Net Benefits
31	2L-8	AS	\$93,592
32	2L-20	AS	\$80,045
33	I-18	P	\$68,169
34	2L-3	AS	\$62,482
35	2L-16	TL	\$59,667
36	2L-11	AS	\$57,767
37	2L-19	AS	\$52,699

28	2L-13	HF S	\$108,338	38	I-7	P	\$49,685
29	2L-6	AS	\$105,175	39	I-14	P	\$47,198
30	I-19	P	\$97,984	40	2L-10	AS	\$46,691

**TABLE 15: Top-CRF-Based Segment Prioritization (Comprehensive Valuation)**

Note: P = Improving Pavement      HFS = Applying High Friction Surface Treatment  
CG = Adding a Curb and Gutter      TL = Adding a Turning Lane

The PCR is a commonly used metric that aids state agencies in their effort to allocate increasingly scarce safety improvement funds. This research examined the usefulness of BCA as a secondary tool to refine the ranking and selection of road segments for the implementation of countermeasures. From the data, it seems evident that BCA can play a valuable role in guiding the decision-making processes by indicating what safety countermeasures will provide the greatest return on investment over the short- and medium-term. Engineers must carefully study the full range of implications related to countermeasures under consideration. In some cases, the cost of particular countermeasures will be so cost prohibitive that, as a rule of thumb, they should be rarely used, and only after the state transportation agencies can articulate why such an expensive countermeasure is required.

This research used state-specific SPFs to identify road segments with the highest PCR values. Using Kentucky-specific SPFs, this research also identified 20 road segments with the highest PCR values on rural interstates and two-lane roads, respectively. Appropriate crash modification factors (CRFs) for the type of accidents occurring on these roadways were then selected and used as inputs for a benefit-cost analysis in an effort to create an index that normalized the safety benefit of all roadway classes based on the cost of implementation. The analysis showed that using the PCR values was a valuable first-level assessment tool to identify road segments with the highest potential for crash reduction. In addition, benefit-cost analysis can play a valuable role, as it can help transportation officials determine which countermeasures were economically viable as well as those to avoid investing in because they will not provide a significant return on investment. Moving forward, this type of analysis can help to solve the problem of higher class roadways consistently rising to the top of rankings simply due to their higher AADT.

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## APPENDIX

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