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## Original Research Paper

# An optimization model for improving highway safety



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### ABSTRACT

This paper developed a traffic safety management system (TSMS) for improving safety on county paved roads in Wyoming. TSMS is a strategic and systematic process to improve safety of roadway network. When funding is limited, it is important to identify the best combination of safety improvement projects to provide the most benefits to society in terms of crash reduction. The factors included in the proposed optimization model are annual safety budget, roadway inventory, roadway functional classification, historical crashes, safety improvement countermeasures, cost and crash reduction factors (CRFs) associated with safety improvement countermeasures, and average daily traffics (ADTs). This paper demonstrated how the proposed model can identify the best combination of safety improvement projects to maximize the safety benefits in terms of reducing overall crash frequency. Although the proposed methodology was implemented on the county paved road network of Wyoming, it could be easily modified for potential implementation on the Wyoming state highway system. Other states can also benefit by implementing a similar program within their jurisdictions.

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## 1. Introduction

In 2014, there were 14,699 total crashes in the state of Wyoming, including 131 fatal, 2818 injury, and 11,750 property damage only (PDO) crashes (WYDOT, 2015b). The monetary loss associated with these crashes is approximately \$550 million. In the state of Wyoming, there are a total of 27,831 miles of roadway owned and maintained by federal, state,

and local entities (WYDOT, 2008). Although most states have their own traffic safety management system (TSMS), Wyoming does not have TSMS yet (Mishra et al., 2015). This research study focuses on developing a TSMS for county paved roads.

In Wyoming, there are 2444 miles of county paved roads (approximately 8.8% of total) (WYDOT, 2015a). The Wyoming Technology Transfer Center (WYT<sup>2</sup>/LTAP) is in the process of developing a pavement management system (PMS) for these

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county roads. As part of that effort, a comprehensive data collection program was conducted by the WYT<sup>2</sup>/LTAP and WYDOT in the summer of 2014. That effort expanded to the safety area and included developing a TSMS since some of the data collected for PMS can be used for developing TSMS. The collected PMS data included road identification information, traffic data, roadway width, rut depths, international roughness index (IRI), pavement condition index (PCI), and pavement serviceability index (PSI) (WYDOT, 2015a). Some of this information was instrumental in developing the model for TSMS.

Many Wyoming county roads were built over 40 years ago and had inconsistent maintenance, resulting in overall poor road conditions (Saha and Ksaibati, 2015). Moreover, the growth of oil and gas industries has increased truck traffic on county roads. The increase in truck traffic resulted in significant economic loss due to crashes which necessitates the development of an innovative TSMS to utilize limited resources more efficiently.

The developed methodology will ensure that selected safety projects will minimize the number of crashes especially the fatal-and-injury crashes within preset budgets. In the proposed methodology, selecting safety improvements does not only depend on traffic volumes but also on the crash reduction factor (CRF) of the countermeasures. A CRF is a crash reduction percentage that might be expected after implementing a countermeasure at a specific hot spot. Safety improvements will be selected based on the highest level of crash number reduction. There are 917 county paved roads with total length of 2444 miles in Wyoming. This study utilized all these roads to demonstrate the implementation of the proposed optimization model.

## 2. Literature review

The literature review which summarizes recent research on TSMS can be divided into three sections which are safety performance function (SPF), crash hot spots, and optimization methodology for safety management system.

### 2.1. Safety performance function

In order to improve safety, it is important to understand why crashes occur. There is a significant number of researches modeled crash occurrence (Abdel-Aty and Radwan, 2000; Ahmed et al., 2011; Cafiso et al., 2010; Chin and Quddus, 2003; Jovanis and Chang, 1986; Miaou and Lord, 2012; Tegge et al., 2010). Abdel-Aty and Radwan (2000) studied the modeling of traffic accident occurrence and involvement. The results showed that annual average daily traffic (AADT), speed, lane width, number of lanes, land-use, shoulder width, and median width have statistically significant impact on crash occurrence. Tegge et al. (2010) studied SPFs in Illinois and found that AADT, access control, land-use, shoulder type, shoulder width, international roughness index, number of lanes, lane width, rut depth, median type, surface type, number of intersections have a significant impact on safety. Cafiso et al. (2010) developed comprehensive accident models for two-lane rural highways and found that section

length, traffic volume, driveway density, roadside hazard rating, curvature ratio, and number of speed differentials higher than 10 km/h increased crash occurrences significantly. Highway safety manual (HSM) provides the safety performance functions for the roadways divided into rural two-lane two-way roads, rural multilane highways, and urban and suburban arterials (AASHTO, 2010). The safety performance functions provide the predicted total crash frequency for roadway segment base conditions. More accurate predicted crash frequency can be measured considering the CRFs from the geometric design and traffic control features.

Researchers have utilized different approaches to establish the relationship among crash occurrences, geometric characteristics, and traffic related explanatory variables using statistical models of multiple linear regression, Poisson regression, Zero-Inflated Poisson (ZIP) regression, Negative Binomial (NB) regression, and Zero-Inflated Negative Binomial (ZINB) regression. In 1986, Jovanis and Chang (1986) studied why multiple linear regression is not appropriate for modeling crash occurrence since accident frequency data did not fit well with the basic assumptions underlying the model. The major assumption with linear regression models is that the frequency distribution of observations must be normally distributed. Most crash frequency data violates this assumption. It was also observed that crash frequency data possesses special characteristics such as count data and overdispersion. In 1993, Miaou and Lord (2012) studied on the performance evaluation of Poisson and Negative Binomial regression models in modeling the relationship between truck accidents and geometric design of road sections. This research recommended that the Poisson regression or ZIP model could be the initial model for relationship establishing because of the crash frequencies. But in most crash data, the mean value of accident frequencies is lower than the variance, which is termed as overdispersion (Saha et al., 2015). If overdispersion is present in crash frequency data, NB or ZINB would be appropriate models since they account for overdispersion. In most accident data, crash frequencies show significant overdispersion and exhibit excess zeroes, in which the ZINB regression model appears to be the best model.

### 2.2. Crash hot spots

There are 12 crash hot spot analysis techniques discussed in HSM (AASHTO, 2010). These techniques basically rank the sites with potential safety issues. The criteria for ranking the sites are based on average crash frequency, crash rate, relative severity index, critical crash rate, level of service of safety, and predicted crash frequency. Some states have their own identification methods in addition to the 12 HSM crash hot spot analysis techniques. Moreover, a significant amount of researches have been performed to identify crash hot spots using different identification methodologies and screening methods such as sliding scale analysis, empirical Bayesian (EB) method, Kernel density estimation (KDE), Moran's I Index method and Getis-Ord  $G_i^*$  (Anderson, 2009; Cheng and Washington, 2008; Elvik, 2008; ESRI, 2010; Getis and Ord, 1992; Hauer et al., 2004; Montella, 2010; Persuad et al., 1999; Saha,

2014). The most accurate technique can be selected based on two considerations, which are accounting for regression-to-the-mean bias and estimating of a threshold level of crash frequency or crash severity (AASHTO, 2010). Among the available techniques, the EB method should be the standard approach in the identification of crash hot spots.

### 2.3. Optimization methodology for safety management system

Identification of safety projects within limited budget is an important element for transportation planning. Crash hot spots should be identified, because not all of these spots can be selected for implementing safety countermeasures due to fund limitations. In order to identify the best set of crash hot spots within budget, optimization techniques provides the best approach over project prioritization.

The TSMS is a multi-objective optimization problem for three reasons, first, engineers or decision makers want to minimize overall crash frequency within budget; second, fatal-and-injury crashes should be minimized; the third, high traffic volume roadways should have higher priority when selecting safety projects. The problem has been characterized as a multi-objective optimization in many researches (Mishra et al., 2015).

Optimization techniques are commonly used for resource allocation in operation research, transportation, management, finance and manufacturing. In transportation, optimization technique has been applied to PMS and they can also be implemented in TSMS (Saha and Ksaibati, 2015). In TSMS, optimization usually involves minimizing predicted crash frequency comprising a set of decision variables subject to various constraints such as budget and risk. There are different optimization techniques, linear, integer, nonlinear and dynamic programming (Mishra et al., 2015). Optimization techniques in TSMS include both linear and integer programming.

## 3. Modeling methodology

This section presents the formulation of TSMS model used in this research. The primary parameter of this model, crash hot spots identification, is discussed briefly. Identifying crash hot spots requires crash data analysis which is followed by field investigation to identify appropriate treatment types. The algorithm for identifying the best combination of safety projects is illustrated in Fig. 1. This process consists of two main steps which are identification of crash hot spots and potential countermeasures and allocation of funding. Each step is discussed in detail in the following subsections.

### 3.1. Identification of crash hot spots

Traffic crashes are rare and random events having a tendency to cluster together at certain locations. The straightforward process of plotting crash map reveals clustering characteristics of crash occurrence. Road conditions, weather condition, horizontal alignment of roadway, grade and lighting conditions are the most contributing factors of crashes. In this

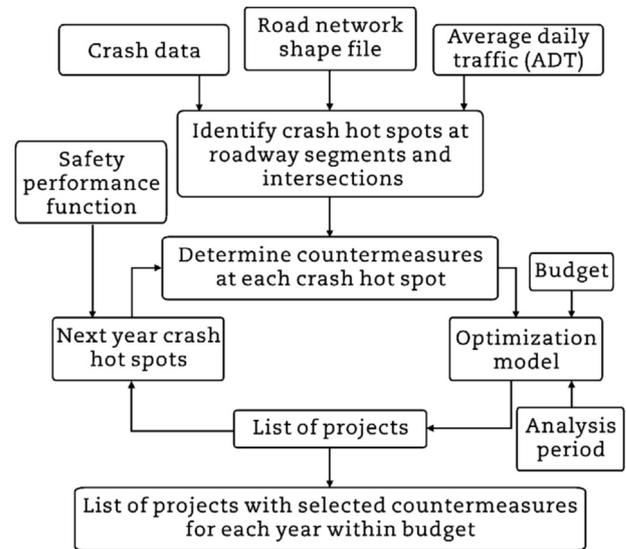


Fig. 1 – Research methodology for TSMS.

research, crash frequency was calculated for each segment using five years of crash data (2010–2014). As the length of each segment is different, the crash frequency was normalized by one mile, so that the segments can be compared. In order to identify crash hot spots, the EB method has been implemented. In this method, the expected crashes were calculated using the SPF of two-lane two-way roadways from HSM.

Sometimes, decision makers or engineers might have different objectives to improve the safety of the network, such as reducing overall crash frequency and reducing severe crashes. This research considered both of the objectives to identify the best combination of safety improvement projects. In the process of identifying the projects, priority was given to the hot spots that were involved with fatal-and-injury crashes.

### 3.2. Funding allocation strategy

After identifying crash hot spots, the next step is to conduct field evaluation to identify safety countermeasures. A list of the possible low-cost safety countermeasures associated with unit cost for county paved roads are summarized in Table 1. The WYT<sup>2</sup>/LTAP uses these low-cost safety countermeasures to enhance the safety of county paved roads. When a major safety improvement is needed, it is normally combined with other major pavement rehabilitation projects. At each location, the best countermeasure is chosen based on CRF and cost with consideration of the overall safety budget. It's an optimization method where the objective function is to minimize the predicted crash frequency within budget by selecting the best combination of safety improvement projects on roadways with higher ADT.

### 3.3. The optimization model

The proposed TSMS for county paved roads considers CRF as well as local conditions of crash frequency and ADT. The

**Table 1 – CRFs and costs of safety countermeasures for paved county roads.**

Countermeasures	Unit cost (\$)	CRF (%)
Install guide signs (general)	400	15
Install advance warning signs (positive guidance)	400	40
Install chevron signs on horizontal curves	400	35
Install curve advance warning signs	400	30
Install delineators (general)	500	11
Install delineators (on bridges)	300	40
Install centerline markings	0.2 per LF	33
Improve sight distance to intersection	1.5 per LF	56
Install guardrail (at bridge)	60 per LF	22
Install guardrail (outside curves)	30 per LF	63
Install transverse rumble strips on approaches	500	35
Lengthen culvert	150 per LF	40

Note: LF is linear feet.

objective of the developed model is to minimize the overall predicted crashes on the segments with high traffic volume giving the priority to the segments experiencing fatal-and-injury crashes. The model is described as Eq. (1).

$$\begin{cases} \text{Minimize } \sum_{i=1}^n N_i \\ \text{Minimize } \sum_{i=1}^n N_{f\&i} \end{cases} \quad (1)$$

where  $N_i$  and  $N_{f\&i}$  represent the predicted crashes and fatal-and-injury crashes on road  $i$ , respectively. This is a combinatorial optimization problem where one must select a collection of projects of minimum value while satisfying some constraint. The predicted crashes  $N_i$  is the crashes of the segment multiplied by the CRF if the segment is selected for improvements. This model is a multi-level optimization where two objective functions were considered as shown in Eq. (2). More formally, the problem can be written as

$$\begin{cases} \text{Minimize } \sum_{i=1}^n N_i \\ \text{Minimize } \sum_{i=1}^n N_{f\&i} \\ \text{Subject to } \left( \sum_{i=1}^n \text{safety improvement cost}_i * x_i \right) \leq \text{Budget} \\ x_i \in \{0, 1\} \end{cases} \quad (2)$$

where  $x_i$  is an integer equal to 1 if the project is selected and 0 if it is not selected. The best combination of safety improvement projects are selected using linear programming methods.

#### 4. Case study for data collection (county paved roads in Wyoming)

Table 2 summarizes data sources with the type and number of collected data units for the case study. Fig. 2 shows the study area representing the county paved roads totaling 2444 miles divided into 917 routes. The datasets obtained from WYDOT and WYT<sup>2</sup>/LTAP are described briefly in the following subsections.

##### 4.1. County paved roads

The road inventory of county paved roads used in this research were obtained from WYDOT containing information on road identification number (RIN), primary name of the road, beginning and ending milepost. There are 917 county paved roads in Wyoming with 2444 miles.

##### 4.2. Crash data

The crash data for the study area was obtained from WYDOT and the base bulk data was used for this research. The base bulk dataset contains information on accident time, location, accident type, impact type, severity level, reported weather conditions, lighting condition, road condition, and roadway geometry for each accident. For this study, crash severity, accident route, location, relation to intersection, and crash date are needed. Crash data from January 2010 to December 2014 were used to ensure there were no major changes of roadway geometrics in the study area.

##### 4.3. Functional classification

Functional classification of county paved roads was also obtained from WYDOT. All roads were divided into rural and urban land-use. In each land-use, the roads are classified into arterial, collector and locals. Some arterial and collectors are subdivided into major and minor.

##### 4.4. Traffic counts

A total of 144 traffic counts were conducted to prioritize the functional classification of roadways used in the optimization model.

##### 4.5. Data base for TSMS

All variables used in this study were collected from different sources for each roadway segment and then combined in a comprehensive data base for the optimization model. The

**Table 2 – Features and data collected for county roads.**

Feature	Data source	Quantity	Units	Data types
County paved roads	WYDOT	917	Roads	GIS layer of county paved roads
Crash data	WYDOT	5 years	Events	Crash locations
Functional classification	WYT <sup>2</sup> /LTAP	2250	Segments	Arterial, collector and rural
Traffic counts	Field	144	Counts	ADT

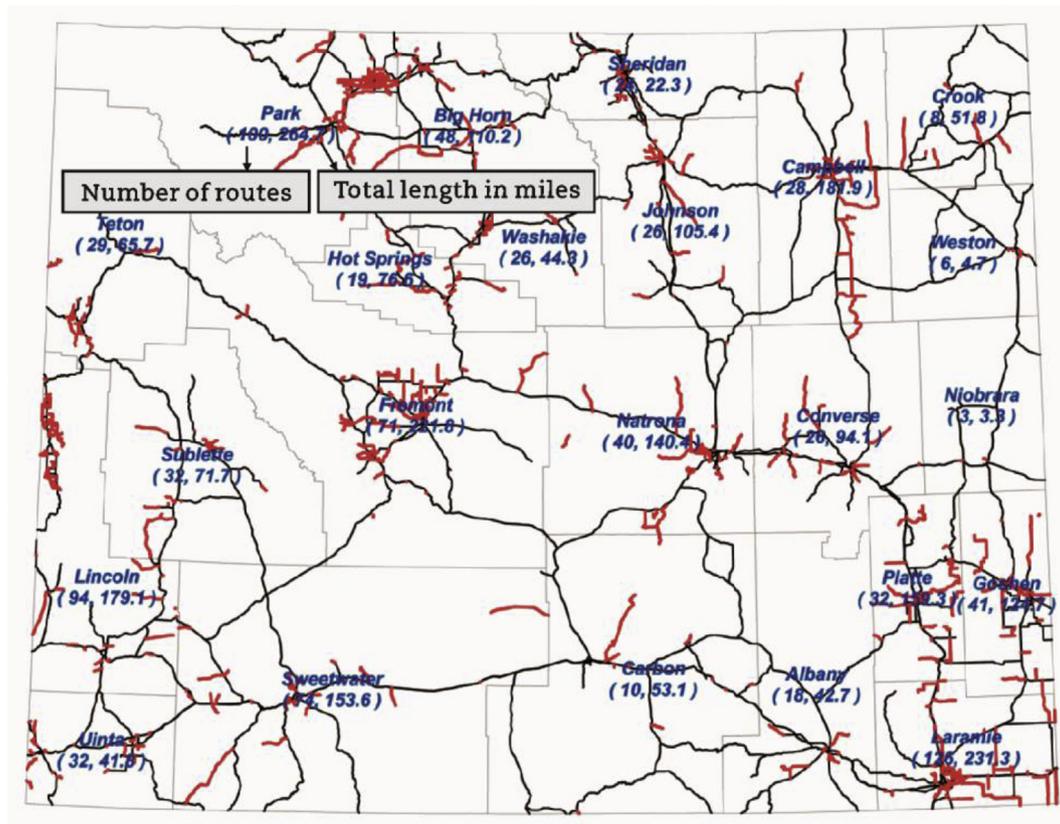


Fig. 2 – Locations of county paved roads.

Table 3 – Combined dataset for implementing TSMS model.

Route	Beg. milepost	End milepost	Crash freq.	Crash freq. per mile	Functional class	Countermeasure	CRF	Cost (\$)
ML5349B	7.740	7.870	5	38	16	3	0.35	55,200
ML8448B	0.000	0.080	3	38	16	5	0.11	11,200
ML7650B	1.960	2.464	6	12	16	2	0.40	25,600
ML5349B	2.860	3.640	9	12	16	4	0.30	9600
ML7650B	3.464	3.920	3	7	16	6	0.40	4800
ML5338B	4.175	4.790	4	7	16	1	0.15	9600
ML5716B	7.514	8.514	6	6	16	6	0.40	4800

Table 4 – Crashes on county roads from 2010 to 2014.

Crash type	Not-intersection-related		Intersection-related		Total
	Frequency	Percentage (%)	Frequency	Percentage (%)	
Fatal crashes	11	34.8	3	15.1	14
Injury crashes	285		67		352
Property damage only	506	59.5	382	82.5	888
Unknown	49	5.8	11	2.4	60
Total crashes	851		463		1314

combined dataset contained beginning and ending mileposts, crash frequency, functional class, selected countermeasure with associated CRF, and cost for each roadway segment. Functional classification of roadways was incorporated to give a higher priority to the segments with higher traffic volumes. A sample dataset for the model is shown in Table 3.

## 5. Preliminary analysis

A preliminary analysis was conducted on the crash data to examine crash severity in the network. It is important to mention that not only intersection-related crashes were considered. In Table 4 the intersection-related and not-

intersection-related crashes are divided into three crash severity, fatal, injury, and property damage only. It can be seen that 34.8% of not-intersection-related crashes were fatal and injury.

In order to identify the best combination of safety improvement projects, it is important to determine the traffic

counts for each segment. There is a total of 917 county roads in Wyoming. Traffic counts are not available for all roads but the functional classes of these roadways are available. A sample data collection was conducted to determine average traffic counts of each functional class. A total of 144 traffic counts were conducted in the summer of 2014. [Table 5](#)

**Table 5 – ADT & average daily truck traffic (ADTT) by functional classification on selected segments.**

Functional classification of roadways	Selected number of segments	ADT			ADTT		
		Maximum	Minimum	Average	Maximum	Minimum	Average
Rural major collector	7	871	124	379	40	14	24
Rural minor collector	36	2784	29	400	170	2	32
Rural local	79	1841	4	307	249	0	24
Urban minor arterial	2	1146	192	669	195	24	110
Urban collector	10	1313	36	651	196	6	59
Urban local	10	1980	118	635	311	0	75

**Table 6 – Selected crash hot spots using EB method.**

Route	Beg. milepost	End milepost	Crash freq.	Fatal and injury	ADT	Expected crashes ( $\pi$ )	Index of effectiveness ( $\theta$ )
ML5314B	1.000	2.000	4	0	307	1.05	3.05
ML8658B	6.190	7.190	4	0	307	1.27	2.61
ML5849B	0.940	0.980	4	0	307	1.38	2.45
ML7860B	0.000	1.000	4	0	307	0.99	2.31
ML5349B	0.000	1.000	4	0	669	1.49	2.29
ML5836B	1.790	2.790	4	3	379	1.49	2.29
ML7852B	14.950	15.950	4	0	400	1.49	2.29
ML8325B	0.090	0.180	3	1	400	1.12	2.18
ML7650B	0.960	1.960	5	0	669	2.04	2.12
ML7452B	1.000	1.520	3	1	400	1.23	2.01
ML7453B	0.000	1.000	3	1	307	1.23	2.01
ML7454B	1.000	2.000	3	2	307	1.23	2.01
ML7676B	0.000	1.000	3	0	400	1.23	2.01
ML5531B	2.073	3.073	3	0	651	1.24	2.01
ML5349B	5.842	6.842	4	0	669	1.73	1.96
ML6257B	2.150	3.150	3	0	400	1.22	1.95
ML7461B	3.610	4.360	4	0	307	1.80	1.89
ML7673B	3.660	4.660	4	0	400	1.80	1.89
ML5584B	4.112	5.112	6	1	651	2.88	1.82
ML5349B	5.095	5.842	9	0	669	4.15	1.75
ML5789B	2.490	3.500	3	0	307	1.42	1.75
ML8647B	3.000	4.000	3	0	400	1.43	1.73
ML7852B	13.950	14.950	6	0	400	3.15	1.68
ML8035B	2.300	3.270	3	0	379	1.49	1.67
ML5547B	2.790	3.790	3	0	400	1.49	1.67
ML5828B	5.000	5.714	3	0	307	1.49	1.67
ML7653B	0.000	1.000	3	1	307	1.49	1.67
ML7674B	8.070	9.070	3	0	400	1.49	1.67
ML8448B	3.376	4.376	3	0	669	1.49	1.67
ML5339B	2.881	3.684	6	0	651	3.30	1.61
ML5338B	4.175	4.790	4	2	669	2.08	1.59
ML8450B	1.003	1.500	6	0	635	3.35	1.59
ML7650B	3.464	3.920	4	0	669	2.20	1.52
ML5716B	9.514	10.514	6	0	669	2.92	1.49
ML5349B	4.390	5.095	3	0	669	1.72	1.40
ML7963B	5.510	6.020	4	1	651	2.49	1.37
ML8030B	1.010	1.530	4	1	307	2.49	1.37
ML5322B	3.000	4.000	3	0	379	1.82	1.34
ML5339B	7.880	8.600	3	0	651	1.83	1.32
ML5365B	24.030	25.030	3	1	379	2.03	1.22
ML7704B	0.067	1.067	3	0	307	2.03	1.22

summarizes the average traffic counts for the six different functional classes of roadways. It can be seen that there is a significant difference of average ADTs between urban and rural classes.

## 6. Data analysis

The data analysis section summarizes the analysis in three sections, crash hot spots, optimization process, and sensitivity analysis. The crash hot spots section identifies the locations where increasing number of crashes occurred compared to the expected crashes using the appropriate SPF from HSM. Then, the optimization process identifies the projects among the selected crash hot spots within the approximate budget currently allocated to improve safety on county paved roads. Finally, a sensitivity analysis was conducted to identify the critical budget that gives the most benefit to society.

### 6.1. Crash hot spots

The EB method has been implemented to identify the crash hot spots. Table 6 shows the list of the crash hot spots where the most of the crashes occur. The expected crashes of this table were calculated using the SPF of two-lane two-way roadways obtained from HSM. In this table, the last column is the index of effectiveness, which represents the increase of actual crashes compared to the expected crashes, if its value is greater than 1. There are a total of 41 crash hot spots identified from all 3762 segments, because of their higher values for one mile in length.

### 6.2. Optimization

The limited funding is not adequate to fund all these crash hot spots identified in the previous sections. An optimization model was implemented to identify the best combination of safety improvement projects within the limited budget. The

**Table 7 – Low-cost safety countermeasures.**

Countermeasure ID	Countermeasures	Crash reduction factors (%)	Cost (\$)
1	Install guide signs (general)	15	9600
2	Install advance warning signs (positive guidance)	40	25,600
3	Install chevron signs on horizontal curves	35	55,200
4	Install curve advance warning signs	30	9600
5	Install delineators (general)	11	11,200
6	Install delineators (on bridges)	40	4800

**Table 8 – Selected safety improvement projects for \$250,000 spending.**

Route	Beg. milepost	End milepost	Crash freq.	Fatal and injury	ADT	Countermeasure	CRF	Cost (\$)
ML8658B	6.190	7.190	4	0	307	5	0.11	11,200
ML7860B	0.000	1.000	4	0	307	4	0.30	9600
ML5349B	0.000	1.000	4	0	669	6	0.40	4800
ML5836B	1.790	2.790	4	3	379	1	0.15	9600
ML7852B	14.950	15.950	4	0	400	6	0.40	4800
ML8325B	0.090	0.180	3	1	400	5	0.11	11,200
ML7650B	0.960	1.960	5	0	669	6	0.40	4800
ML7452B	1.000	1.520	3	1	400	5	0.11	11,200
ML7453B	0.000	1.000	3	1	307	1	0.15	9600
ML7454B	1.000	2.000	3	2	307	5	0.11	11,200
ML5349B	5.842	6.842	4	0	669	5	0.11	11,200
ML7461B	3.610	4.360	4	0	307	5	0.11	11,200
ML5584B	4.112	5.112	6	1	651	2	0.40	25,600
ML5349B	5.095	5.842	9	0	669	4	0.30	9600
ML7852B	13.95	14.950	6	0	400	4	0.30	9600
ML7653B	0.000	1.000	3	1	307	4	0.30	9600
ML8448B	3.376	4.376	3	0	669	6	0.40	4800
ML5338B	4.175	4.790	4	2	669	6	0.40	4800
ML8450B	1.003	1.500	6	0	635	5	0.11	11,200
ML5716B	9.514	10.514	6	0	669	5	0.11	11,200
ML5349B	4.390	5.095	3	0	669	6	0.40	4800
ML7963B	5.510	6.020	4	1	651	6	0.40	4800
ML8030B	1.010	1.530	4	1	307	5	0.11	11,200
ML5322B	3.000	4.000	3	0	379	1	0.15	9600
ML5339B	7.880	8.600	3	0	651	5	0.11	11,200
ML5365B	24.030	25.030	3	1	379	1	0.15	9600
<b>Total</b>			<b>108</b>	<b>15</b>				<b>248,000</b>

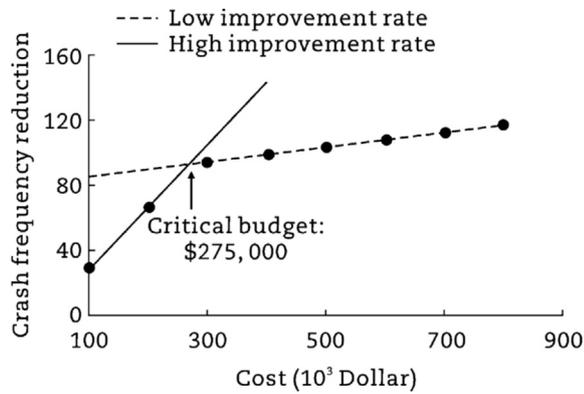


Fig. 3 – TSMS performances for different budgets.

optimization model developed in this research was based on the following principles.

- Countermeasures with higher CRF and lower cost are the most cost effective.
- Roadways with high traffic volume should have higher priority when selecting safety projects.

Table 7 shows the list of the low-cost safety countermeasures considered for county paved roads. In order to demonstrate the characteristics of the proposed TSMS, general safety countermeasures were selected. Future

implementation of the proposed TSMS would require conducting field visitation to each hot spot to identify potential safety improvements.

The optimization model proposed in this research was used to select the best combination of safety improvement projects. For each crash hot spot, expected crashes were determined by multiplying CRF and crashes occurred. The objective was to minimize the overall expected number of crashes by selecting the projects involved with fatal and injury after implementing the safety countermeasures within budget.

WYDOT currently allocates around \$500,000 annually to improve the safety of all county roads in the state. Assuming that half of the funding will be spent on paved roads, the annual budget is set at \$250,000. Running the optimization model resulted in the list of projects shown in Table 8. The implementation of the selected countermeasures is expected to reduce crashes by 82 (from 160 to 78).

### 6.3. Sensitivity analysis

Decision makers need to allocate appropriate funding to provide the maximum benefit to society. In this study, the appropriate budget was determined based on the expected crash reduction. The optimization model was performed at different budgets levels between \$100,000 and \$800,000. Fig. 3 shows the trend in expected crashes reduction as budget increases. It can be seen that the slope of the estimated crash reduction is higher when budget is between \$100,000 and \$275,000 than the one with budget between \$275,000

Table 9 – Selected safety improvement projects for \$275,000 spending.

Route	Beg. milepost	End milepost	Crash freq.	Fatal and injury	ADT	Countermeasure	CRF	Cost (\$)
ML8658B	6.190	7.190	4	0	307	2	0.11	11,200
ML7860B	0.000	1.000	4	0	307	4	0.30	9600
ML5349B	0.000	1.000	4	0	669	6	0.40	4800
ML5836B	1.790	2.790	4	3	379	1	0.15	9600
ML7852B	14.950	15.950	4	0	400	6	0.40	4800
ML8325B	0.090	0.180	3	1	400	5	0.11	11,200
ML7650B	0.960	1.960	5	0	669	6	0.40	4800
ML7452B	1.000	1.520	3	1	400	5	0.11	11,200
ML7453B	0.000	1.000	3	1	307	1	0.15	9600
ML7454B	1.000	2.000	3	2	307	5	0.11	11,200
ML5349B	5.842	6.842	4	0	669	5	0.11	11,200
ML7461B	3.610	4.360	4	0	307	4	0.11	11,200
ML5584B	4.112	5.112	6	1	651	4	0.40	25,600
ML5349B	5.095	5.842	9	0	669	4	0.30	9600
ML7852B	13.950	14.950	6	0	400	4	0.30	9600
ML8035B	2.300	3.270	3	0	379	4	0.30	9600
ML5547B	2.790	3.790	3	0	400	4	0.30	9600
ML7653B	0.000	1.000	3	1	307	1	0.30	9600
ML7674B	8.070	9.070	3	0	400	6	0.15	9600
ML5338B	4.175	4.790	4	2	669	6	0.40	4800
ML8450B	1.003	1.500	6	0	635	5	0.11	11,200
ML5716B	9.514	10.514	6	0	669	5	0.11	11,200
ML5349B	4.390	5.095	3	0	669	6	0.40	4800
ML7963B	5.510	6.020	4	1	651	6	0.40	4800
ML8030B	1.010	1.530	4	1	307	5	0.11	11,200
ML5322B	3.000	4.000	3	0	379	1	0.15	9600
ML5339B	7.880	8.600	3	0	651	1	0.11	11,200
ML5365B	24.030	25.030	3	1	379	4	0.15	9600
<b>Total</b>			<b>114</b>	<b>15</b>				<b>272,000</b>

and \$800,000. Therefore, \$275,000 is the appropriate budget level based on the assumptions of the optimization model. The selected safety improvement projects based on \$275,000 funding level can be seen in Table 9.

## 7. Conclusions

The state of Wyoming does not currently have a traffic safety management system (TSMS) to optimize the use of safety funds. In this study, an optimization methodology was developed to identify the best combination of safety improvement projects that utilizes limited available resources. The developed methodology was implemented on the county paved road network consisting of 917 roads with 2444 miles. This methodology minimized the overall expected crashes by selecting the best combination of safety improvement projects. A sensitivity analysis was also conducted to identify the most appropriate budget to provide maximum benefit to society.

The developed methodology can be highlighted as follows

- It is tailored specifically to county paved roads.
- It considers countermeasures CRF, countermeasures cost, functional classification of roadways, and annual safety budget.
- It provides a higher priority to projects on roadways with higher ADTs and functional classification.
- It identifies the best set of safety improvement projects to minimize the overall expected crashes based on a specific budget level.
- It requires field evaluation and crash analysis to identify crash hot spots and appropriate safety countermeasures.
- It identifies the minimum budget needed to achieve the maximum benefits to society in terms of crashes reduction.

This proposed methodology can be implemented on the Wyoming state highway system with minor modifications. Other states can follow the same process described in this paper to develop their own TSMS. When public agencies have limited budgets, it becomes more important to allocate resources in a cost effective manner. This study demonstrated how optimization techniques can be utilized to justify budget setting for safety improvements and then allocate the funding to achieve the maximum reduction in crashes.

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