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Research Article

Developing a Low-Cost Safety Improvement Program for Intersections in an Urban Roadway Network: A Case Study

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In the US, about 40% of all crashes involve intersections. As improving safety at intersections and nonintersections are significantly different, it is important to manage them separately within a limited budget. In this study, a safety improvement program was developed for intersections and implemented in the city of Fort Wayne, Indiana, as a case study. Intersections included in the safety improvement program were selected using the following criteria and constraints: averaging more than 3 crashes per year during the study period, crash rate, and fatal and injury crash rate, limited budget, and safety benefits. Selected intersections were analyzed to characterize their crashes by type and frequency. Countermeasures were proposed and analyzed to address those crash types identified in the crash characterization. Linear integer optimization technique was employed to identify the best set of countermeasures within a limited budget. A safety improvement program was proposed based on this analysis that would cost $81,232 and provide a 5-year crash reduction benefit of more than $15 million preventing approximately 164 total crashes and 61 fatal or injury crashes.

1. Introduction

In the US, there were a total of 6.3 million crashes occurred in 2015 [1]. The monetary loss associated with these crashes was estimated as $871 billion on US citizens [2]. It is therefore crucial to improve safety of a transportation network. Roadway networks consist of two key elements, roadway segments and the intersections that connect them. Of these, intersections are often the most hazardous portion of the roadway network. 40% of crashes occur approaching or within intersections according to the Federal Highway Administration [3]. Due to the percentage of crashes relative to such a small area within the roadway network largely driven, intersection safety is a top priority for improving the safety of the roadway network as a whole. This study developed a methodology to improve safety at intersections in an urban network.

In order to improve safety, budget plays a critical role. As the budget increases, more crashes can be avoided. In transportation safety projects, benefits are estimated by converting the reduced number of crashes into monetary value, and costs are associated with implementing safety countermeasures. As such, the developed methodology incorporated optimization techniques to optimize budget for improving safety of a roadway network. Optimization techniques are commonly used in operational research and pavement management systems, but not common in safety management [4–6]. The optimization approach used in pavement management system (PMS) is quite different than the one used in safety management system (SMS). In PMS, a list of projects can be identified using optimization technique considering certain constraints, whereas in safety management system, the safety countermeasure is identified using optimization technique at a specific location.

Safety improvements at a location may include from low-cost improvements to complete reconstruction. Low-cost improvements include signing, pavement marking, signal enhancement, increase in pavement friction, double centerline, and rumble strips. Previous studies suggest that low-cost safety improvements may have significant impact on improving safety in a roadway network. Le et al. studied safety effects of low-cost improvements at signalized and stop-controlled intersections [7]. This study investigated signing, pavement marking, and signal enhancement using empirical Bayes before-and-after analysis. Results shows crash modification factors are above 0.85. Molino et al. studied simulator evaluation of low-cost safety improvements on rural two-lane undivided roads [8]. This study found very positive results implementing low-cost solutions. Satterfield et al. studied low-cost treatments for horizontal curves [9].

All the state agencies currently have a safety management system (SMS). SMS primarily identifies best safety countermeasure at an intersection or a roadway segment within a limited budget. To the authors' knowledge, very few studies investigated optimization techniques in SMS. Saha and Ksaibati [10] developed an optimization model for improving highway safety. In this study, linear integer programming was used to identify the best safety countermeasure at a location. In previous studies, identification of best low-cost safety countermeasure using optimization techniques may be missing.

This study identified best low-cost safety countermeasures using linear integer optimization technique. The methodology was implemented on a roadway network of Fort Wayne, Indiana (population: 253,691 from 2010 census), as a case study to verify the applicability of the methodology. In Fort Wayne, 10,797 crashes were occurred in 2017. In this city, a total of 1,167 centerline miles of roadway are owned and maintained by the local government. The monetary loss associated with these crashes is approximately $10.1 billion.

2. Methodology

This section presents the methodology developed in this study to improve intersection safety in an urban area. The methodology consisted of four primary components: identification of hazardous intersections, countermeasure evaluation, countermeasure selection, and selection of hazardous intersections for safety improvements within budget using linear integer optimization technique. The data analysis was performed using the data set provided by the Northeastern Indiana Regional Coordinating Council (NIRCC) and was mostly used to determine the intersections where the highest concentrations of crashes occurred. The countermeasure evaluation was conducted through the use of literature review, by which different methods were proposed and evaluated based on design criteria. The countermeasure selection consisted primarily of implementation of the selected safety countermeasures at specific design locations and detailed cost estimations. The methodology is summarized in Figure 1. In the following sections, the four primary components are discussed.

2.1. Identification of Hazardous Intersections. The data used to determine the top most hazardous intersections in the city of Fort Wayne were provided by the NIRCC. The data consisted of five years (2013–2017) of raw crash data, compiled from crash reports filled out by law enforcement. The data in all five years of the study period were combined to create a single pool of crashes. This pool was then analyzed to organize the crashes by their corresponding geocodes, which tracked to their intersections. To estimate the crash rate, average Annual Daily Traffic (AADT) was provided using the Traffic Count Database System (TCDS) and AADT map from 2018. The AADT map of Fort Wayne based off of 2018 traffic data was used primarily for finding the AADT for each intersection, except in the case where a road did not show up on the AADT map, where the Indiana Department of Transportation (INDOT) TCDS map was used as a backup.

2.2. Countermeasure Evaluation. Due to significant intersection-related crashes, many different remediation methods have been proposed and implemented. In Table 1, the CMF and cost of 15 countermeasures obtained from the CMF Clearing House and Highway Safety Manual can be seen.

2.3. Countermeasure Selection. A preliminary design was created by evaluating the abovementioned countermeasures that could resolve the main causes of crashes at each of the intersections which were selected according to engineering judgement based on literature review and consultations with the City of Fort Wayne. The most feasible ones were then selected based on a feasibility matrix, and the effectiveness of these countermeasures was quantified using their respective CMFs. A feasibility matrix was created for each intersection to determine the feasibility of each of the solutions based on constructability, social impact, environmental impact, political impact, and amount of data required to analyze the solution. The weighted feasibility matrix is based off of a 10-point scale (1–10), 10 being the best solution.

2.4. Optimization. In the optimization model, an optimization model was developed to identify the best mix of safety countermeasures. As the crash benefits increase, the possibility of selecting the countermeasures increase making sure that total costs is within a limited budget. The only constraint of the model is the budget. The CMF and the costs to implement the countermeasures played the most critical role while selecting intersections for safety improvements. This is a combinatorial optimization problem where one selects a collection of countermeasures of maximum value while satisfying some weight constraint.

3. Data Analysis

The developed methodology (see Figure 1) was employed on a roadway network of Fort Wayne to verify the applicability of the methodology. This section provides the data analysis summarized into four subsections: identification of intersections, characterization of intersections, selection of alternatives, and optimization.

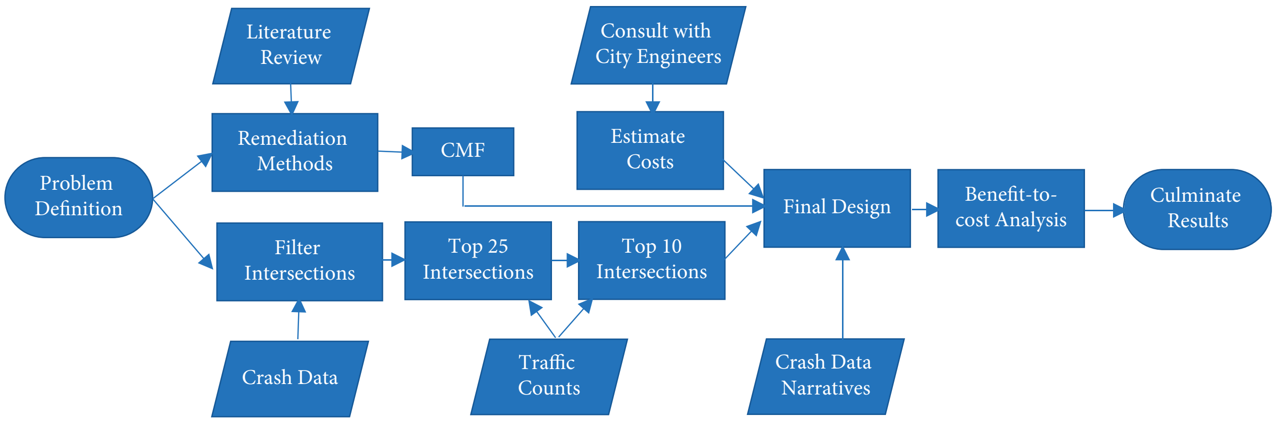

Figure 1: Research methodology for improving intersection safety.

Table 1: CMF and cost of 15 safety countermeasures.

No.	Safety countermeasures	CMF	Cost
1	Flashing red stop signs	0.90 (total), 0.87 (target)	$1,700/sign
2	Flashing signal	0.90 (total) 0.87 (target)	$15, 000/sign
3	Transverse rumble strips	0.72 (total)	$690
4	Roundabout	0.65 (total)	$1,500,000
5	Double centerline and stop bars	0.6 (total)	$1,250
6	Warning signs	0.85 (total) stop ahead 0.87 (total) curve ahead	$100/sign
7	Lane diet	0.91 (total)	$11.48/ft, (varies)
8	Guard rail	0.96 (total)	$8, 000
9	Median (concrete/delineator)	0.14 (target)	$28,800 (concrete) $5,250 (delineator)
10	Centerline rumble strips	0.86 (total) 0.79 (target)	$1,200
11	Increase pavement friction	0.76 (total) curve 0.8 (total), 0.58 (target): Braking	$16.50/square yard
12	Signal phasing	0.01 (target): protected left turn 0.92 (total), delayed red signal 0.93 (total), protected permissive left turn with flashing yellow arrow	$3,000
13	Dedicated left turn lanes	0.73 (total)	$10,332
14	Positive left turn offsets	0.62 (target)	$100,000
15	No turn on red signs	0.9375 (target)	$1,400

3.1. Identification of Intersections. Selection of the ten most hazardous intersections in the city of Fort Wayne was based upon three primary criteria mentioned above. First, each intersection for consideration had to have an average annual total number of crashes of 3 or more. Next, the intersections were then ranked by their total crash rate based upon the number of crashes within the study period and the entering vehicle AADT. The results of the top 10 most hazardous intersections ranked by their fatality and injury crash rate are shown in Table 2.

3.2. Characterization of Intersections. The police report narratives for each crash that occurred during the 2013–2017 study year period were provided by INDOT. The narratives for the top 10 most hazardous intersection were characterized to find common causes of crashes at each location. Characterizing the narratives involved reading each narrative and deciding what the cause of the crash was. An example of a narrative provided for the intersection of SR 1 and N. Clinton St. is shown below.

"***VEHICLE 1 WAS WESTBOUND*** ON STATE ROAD 1 WHEN IT ***FAILED TO YIELD ATTEMPTING*** TO MAKE ***A LEFT TURN*** IN THE INTERSECTION OF TONKEL AND STATE ROAD 1 COLLIDING WITH EASTBOUND VEHICLE 2 WHEN IT ENTERED THE INTERSECTION. BOTH VEHICLES HAD A GREEN

Table 2: Total and F/I crash rate for the top ten intersections.

No.	Intersection	Crash rate	F/I crash rate
1	Oxford St. and Smith St.	2.740	1.369
2	Clay S. and E. Lewis St.	2.975	1.095
3	S. Coliseum Blvd. and E. Pontiac St.	2.752	1.017
4	N. Clinton St. and SR 1	2.129	0.858
5	S. Anthony Blvd. and Chartwell Dr.	4.489	0.841
6	E. California Rd. and Parnell Ave.	2.244	0.626
7	Fairfield Ave. and W. Rudisill Blvd.	3.154	0.495
8	St. Joe Center Rd. and St. Joe Rd.	2.912	0.459
9	Maplecrest Rd. and Stellhorn Rd.	2.047	0.409
10	Maplecrest Rd. and St. Joe Center Rd.	2.062	0.356

Table 3: Applied CMF analysis at an intersection.

Applied crash countermeasure	Total crashes	FI crashes	Total crash reduction	FI crash reduction	Total cost ($)	Total benefit ($)	BCR
Rumble strips	13.68	5.04	5.32	1.96	690	519,631	709.93
Roundabout (total)	12.35	4.55	6.65	2.45	1.5 million	649.5 k	0.40
Stop sign ahead	16.15	5.95	2.85	1.05	350	278.3 k	749.77
Flashing red stop signs (target)	16.53	6.09	2.47	0.91	6,800	241.2 k	33.44
Flashing overhead signal (target)	16.53	6.09	2.47	0.91	15,000	241.2 k	15.16
Double ctr. line and stop bars (cons.)	11.4	4.2	7.6	2.8	1,250	742.3 k	559.83
Double ctr. line and stop bars (avg.)	8.99	3.31	10.01	3.68	1,250	978 k	737.57

Table 4: Proposed safety improvement program.

Intersection	Proposed solutions	Crashes prevented total (F/I)	Total cost	Total 5 year benefit	Total BCR
Oxford St. and Smith St.	Flashing red stop signs	2.4 (1.2)	$1,700	$234,420	130
Clay St. and E. Lewis St.	Double centerline and stop bars	7.6 (2.8)	$1,250	$278,374	737
S. Coliseum Blvd. and E. Pontiac St.	Median (delineators)	18.9 (14.6)	$5,350	$2,191,866	331
SR 1 and N. Clinton St.	Protected left + all clear phasing	27.7 (18.4)	$3,000	$2,708,528	851
S. Anthony Blvd. and Chartwell Dr.	Dedicated left turn lanes	4.3 (0.8)	$10,332	$421,956	38
Parnell Ave. and E. California Rd.	Install left turn lanes	11.4 (4.2)	$36,000	$1,113,495	29
W. Rudisill Blvd and Fairfield Ave.	PPLT/FYA + all clear phasing	7.8 (1.3)	$6,600	$757,958	108
St. Joe Rd. and St. Joe Ctr. Road	All clear phasing	10 (1.5)	$3,000	$984,564	309
Maplecrest Rd. and Stellhorn Rd.	PPLT/FYA + all clear	20.9 (4.2)	$6,000	$2,045,119	321
Maplecrest Rd. and St. Joe Ctr. Road	Protected left only + all clear phasing	40.3 (10.9)	$3,000	$3,932,943	1235
Total		153.8 (60.8)	$81,232	$15,025,013	174

> LIGHT ACCORDING TO BOTH DRIVERS. DRIVER 2 WAS TREATED AT THE SCENE FOR KNEE AND SIDE PAIN."

The main cause of the crash was then labeled as "failing to yield right of way on a left turn," based on the information highlighted in bold. Each of the top ten most hazardous intersections and their crash characterizations were investigated.

3.3. Selection of Alternatives. The selection of alternatives involved finding the crash reduction due to each countermeasure at the intersections and quantifying the effect that each crash reduction has in terms of a monetary benefit. The monetary benefit, which is the benefit to cost ratio, was then implemented into the final safety program. The countermeasures for each intersection were analyzed to find the total number of crashes after the applied CMF (see Table 3).

For the selection of the best options, each of the ten intersections were analyzed on an individual basis and a countermeasure was selected for recommendation by considering both the best benefit to cost ratio and the countermeasure that would be expected to produce the best total reduction of crashes. The recommendations for each of the ten intersections were made based on both the value of the results and engineering judgement. To obtain the benefit to cost ratio, an average benefit, which was defined to be the average cost of one crash or the average amount of money

Table 5: Alternate safety countermeasures at a location.

Intersection	Countermeasure option 1	Countermeasure option 2	Countermeasure option 3
Oxford St. and Smith St.	Flashing red stop signs	Flashing signal	Roundabout
Clay St. and E. Lewis St.	Double centerline and stop bars	Transverse rumble strips	Roundabout
S. Coliseum Blvd. and E. Pontiac St.	Median (delineators)	Median (delineator) + warning signage	Centerline rumble strips
SR 1 and N. Clinton St.	Protected left + all clear phasing	Delayed red signal	Increase pavement friction
S. Anthony Blvd. and Chartwell Dr.	Dedicated left turn lanes	Dedicated left turn lane 0.94 s w/No lane Diet	Dedicated left turn lanes (1 approach)
Parnell Ave. and E. California Rd.	Install left turn lanes	Close the median	
W. Rudisill Blvd and Fairfield Ave.	PPLT/FYA + all clear phasing	Increase pavement friction + PPLT/FYA + delayed red signal	
St. Joe Rd. and St. Joe Ctr. Road	All clear phasing	Delayed red signal + increase pavement friction	Increase pavement friction
Maplecrest Rd. and Stellhorn Rd.	PPLT/FYA + all clear	Opposing left turns	Increase surface friction
Maplecrest Rd. and St. Joe Ctr. Road	Protected left only + all clear phasing	Protected left only (PLO)	

that would be saved for every crash reduced, was calculated by summing the total cost of each of the crash types within the Allen county (1 crash costs on average $97,675).

3.4. Optimization. For this program, $100,000 was advised by the city as the maximum budget for a safety improvement program. At this time, the city of Ft. Wayne does not have a set safety budget, and therefore, this value may increase or decrease if implemented by the city. To select the most effective program, all intersections' countermeasures and their combinations were arrayed in an excel spreadsheet and Excel's solver addon was utilized to determine the countermeasures for each intersection that maximized the fatal and injury crash reduction while constraining the costs to stay under $100,000. Only one countermeasure or combination of countermeasures could be selected for each intersection. Once the solver found a maximally effective solution, the program developed was as follows in Table 4.

In this study, the best countermeasure was identified based on the benefit-to-cost ratio of the safety countermeasure. The benefits come from crash reduction and the cost is estimated from installing the countermeasure. For higher budget levels, more effective safety countermeasures can be selected for safety improvement. In the Table below, multiple safety countermeasures are proposed for each location. For example, in Table 5, countermeasure option 2 (third column) costs higher than option 1; similarly, option 3 is higher than option 2. In this study, countermeasure option 1 was considered within the $100,000 budget level. If budget level increases, engineers may choose option 2 or 3.

4. Conclusions and Recommendations

The main research objective of this study was to develop a methodology for improving intersection safety in an urban area. In order to verify the applicability, the methodology was implemented on the roadway network of Fort Wayne, Indiana, as a case study. In the city of Fort Wayne, there are a total of 922 intersections with at least one crash. After screening all 922 locations, top 10 intersections were identified to be used for detail analysis. A detail characterization of intersections, crash narratives, and analysis of 15 potential safety countermeasures were evaluated to identify the best safety countermeasure at each intersection within budget. Despite the limited budget, the $100,000 was not fully utilized by the proposed program. This results from the fact that many of the proposed countermeasures for a single intersection cost more than the entire proposed budget. The developed methodology has the potential to be implemented for a roadway network. Overall, it is expected that the model would benefit the nation by utilizing the budget efficiently.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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