Optimization based Prioritization Model for Highway Safety
Countermeasure Implementation Strategy

by

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ABSTRACT
Highway safety improvement countermeasures are evaluated to reduce occurrence of crashes and to enhance economic viability. The Highway Safety Manual 2010 suggests benefit-cost and cost effectiveness analysis methods to justify implementation of potential countermeasures. These methods are efficient for analyzing alternative countermeasures of a single location. Every fiscal year highway agencies are required to evaluate many safety improvement countermeasures for different locations and select candidate locations for possible funding. Often this process is mostly manual and does not guarantee optimum benefit. Moreover, it fails in estimating the future funding requirements. In this paper, an optimization model encompassing multiple time periods based on the benefit-cost and cost effectiveness analysis methods is developed to optimally allocate countermeasures to candidate location to maximize safety benefits subjected budget, and other policy constraints. The proposed model can suggest implementation plans of safety improvement countermeasures to be implemented at candidate locations in a multi-year analysis period. The paper also reviews the budget sensitivity analysis over a multi-year horizon to assess the optimum future funding needs. A real world case study is used to showcase applicability and efficiency of the proposed optimization model. The proposed optimization model extends the cost-benefit and cost effectiveness analysis methods are in line with the economic appraisal and project prioritization process suggested in the Highway Safety Manual 2010.
INTRODUCTION
The funding for Highway Safety Improvement Program (HSIP) recommends evaluating highway network to identify locations with high crash rate. All highway locations with high crash rates are reviewed for feasible countermeasure implementation plans to reduce the average crash frequency. These improvement plans are evaluated for safety benefits in terms of reduction in traffic crashes and crash cost savings. The Crash Modification Factors (CMFs) as suggested in Highway Safety Manual 2010 (HSM 2010) are generally used in quantifying the reduction in traffic related crashes. The annual fund allocation decision-making process is relatively simple when few location improvement projects compete for funding in a fiscal year. The location improvement projects that are not funded in a particular fiscal year due to budget constraints, again competes for funding along with other safety improvement projects in the following fiscal year. This process lacks the holistic approach where every possible location with all feasible alternative safety improvement plans is evaluated for a base analysis period with possible budget constraints. Moreover, the process fails to provide clear indication of future safety improvement fund requirements.

Such safety improvement can be described as a fund allocation and improvement scheduling problem. However, selection of highway safety improvement locations, estimating the improvement cost and assessing the benefit is different from the much-researched scheduling problems in operations research and other focus areas of engineering. Each highway location is different in terms of geometry, right-of-way, traffic operation etc. and hence, the effect of safety improvement countermeasure is not expected to be similar. Also, locations considered for safety improvement funding is high in number. This makes the prioritization model for highway safety countermeasure implementation strategy unique and complex. This paper proposes an optimization model based on benefit-cost and cost effectiveness analysis method that can yield countermeasure implementation schedule for a multi-year analysis period. A real world case study on 104 locations is conducted to showcase applicability and efficiency of the proposed optimization model. The case study considers eight possible alternative countermeasures for each location and is analyzed for a base period of five years.

LITERATURE REVIEW
The literature review is presented four sub-sections: (1) studies on resource allocation using steps mentioned in HSM, (2) optimization methods on highway safety resource allocation, (3) complexities in resource allocation and (4) challenges in data collection. Finally a summary of literature review is presented and focus of this paper is described.

Highway Safety Manual and Resource Allocation
HSM is a useful resource that provides step-by-step measures and guidelines to facilitate improved decision making based on safety performance at highway intersections and mid-blocks (1). HSM provides quantitative methods for potential reduction of crashes for various highway facility types for various urban geographies. One of the chapters in HSM is on effective resource allocation that discusses on use of possible optimization of cost estimation techniques to maximize the potential economic value of reduction of crashes. Resource allocation and prioritizing highway safety projects is identified as an important element in
transportation safety (2). Depending on the severity of crashes, investment in capital and operation and maintenance (O&M) cost may vary significantly causing adverse impact on the planning process to utilize scares budgets efficiently (3–6). The literature contains a number of studies devoted to identification of hazardous locations. However, only a fraction of locations initially identified as hazardous are actually selected for implementation of safety projects because of funding limitations. These are discussed extensively in the literature (7–12). The key question remains “with knowledge of pre-determined hazardous crash locations and available possible countermeasure to reduce crashes how to prioritize the fund allocation process considering varying real life constraints.” Literature appears to be limited that uses techniques provided in HSM and applied in real world case study to demonstrate the effectiveness of resource allocation in highway safety.

Methods for Highway Safety Resource Allocation
Optimization techniques have been extensively used to efficiently allocate resources in diverse areas such as operations research, manufacturing, management, finance, and transportation. Optimization usually involves the maximization or minimization of an objective function comprising a set of decision variables, subject to various constraints (13, 14). The constraints are designed to reflect limitations imposed by practical and/or policy considerations, expressed in the form of inequalities or equalities. Different optimization techniques such as linear programming, integer programming, nonlinear programming, and dynamic programming have been used to allocate resources on various engineering and management problems (15, 16). Resource allocation on highway safety improvements methods include application of mixed integer programming techniques, based on branch and bound algorithm for highway safety projects (17); linear programming techniques to maximize savings resulting from alcohol-crash reduction (18); linear programming to select safety and operational improvement on highway networks (19); integer programing for reduction in crashes (20); integer programming to minimize total number of crashes (21); linear programming for highway safety improvement alternatives ; and linear programming to incorporate uncertainty in safety resource allocation (22).

Complexities in Highway Safety Resource Allocation
Safety resource allocation falls in the general regime of discrete or integer programming approach. Integer programming needs to be coupled with crash prediction model to adequately address safety resource allocation. If decision variables are uni-modal in nature then finding optimality in integer problems is quite easier. However, often in reality the decision variables are not uni-modal which allows use of alternative optimization techniques of direct (branch and bound), and heuristic (hill climbing, simulated annealing etc.) methods. The literature review shows that within the general framework of optimization approach, researchers have used different model formulations and solution techniques to address their respective issue (17, 23). Objective functions include minimizing crashes and maximizing benefits measured in dollars. Most of the papers reviewed allocated resources for one year; only a limited few attempted multi-year allocation with a planning horizon in mind. Different researchers have treated constraints differently to reflect various policy and practical considerations. Resource allocation in highway safety research is limited because of
the need for integer programming to be combined with crash prediction model (17). Since optimally considering proposed alternatives is a discrete decision variable, literature recommends application of complex integer programming (15, 24, 25).

**Challenges in Data Collection**

Preparing a robust database for safety resource allocation requires (1) identifying hazardous locations by considering frequency and severity of crashes, (2) classifying various crash types, (3) associating highway geometry and traffic operation characteristics to individual crashes (4) drawing location specific collision diagrams to understand crash causalities, (5) assigning set of appropriate countermeasures to each location, (6) establishing costs of each countermeasure and its respective crash modification factor (CMF), and (7) estimating possible economic benefits of each countermeasure if they are selected for implementation. All these steps must be carried out in preparing a database before conducting a resource allocation planning. Some of the data is easy to collect where others are often difficult and requires much manual intensive work (20, 24, 25). For example, crash data usually is available for United States by cities, counties, and metropolitan planning organizations (MPOs) or state DOTs (26). However, finding exact crash locations and location specific highway geometry and traffic operations is not readily available. Often this task is done by sequentially by reading crash reports and recording location specific data from areal imageries. Designing countermeasures requires engineering screening and highway specific particulars. All these tasks require sufficient time and effort to prepare the highway safety resource allocation database.

In the summary, the literature is limited in showing resource allocation to prevent occurrence of highway crashes approaches specified in HSM. Specifically, HSM development took more than a decade with a combined effort from FHWA, AASHTO and special TRB taskforce development. In the field of highway safety resource allocation, this paper attempts to use the optimization techniques using crash reduction factors from HSM. In this paper, the authors present an approach to optimize the safety benefits in a given region by maximizing economic value (in benefit-cost and cost effectiveness) of the crashes saved at intersections each year over a multi-year planning horizon using HSM procedure in the optimization model.

**METHODOLOGY**

Funding for highway safety improvement projects are decided based on effectiveness of the considered countermeasures. Every countermeasure is associated with implementation cost and impact of the implemented countermeasure is estimated by quantifying the reduction in crash cost or crash frequency over its service life. A highway agency selects the most effective countermeasure for implementation. The economic evaluation of the alternatives ensures selection of the best alternative for a location. However, when many safety improvement countermeasures of different locations compete for funding in a particular fiscal year and prioritization is often warranted. The HSM 2010 presents three prioritization methods: ranking by economic effectiveness measures, incremental benefit-cost analysis ranking and optimization. As summarized in the HSM 2010, the ranking by safety-related measures and the incremental benefit-cost analysis methods does not ensure that the ranked
projects are optimized for a given budget \((I)\). Hence, only the optimization method can provide a true optimal selection of projects for a given budget when analyzed for many project alternatives or projects across many locations in a region. The optimization method also has the potential to develop a project implementation plan in a planning horizon. To develop the overall optimization model, a comprehensive understanding of the crash cost estimation model, countermeasure implementation cost model and economic evaluation of countermeasures models is required. Details of these models are described next.

**Crash Cost Estimation Model**

Implementation of safety improvement countermeasures may change the average crash frequency of a highway location. The change can be estimated by multiplying the existing average crash frequency with suitable countermeasure specific CMF. Typically, CMFs for different crash categories such as all severity crashes, injury crashes, property damage only crashes, rear end crashes, angled crashes etc. are available in HSM 2010. The service life of a countermeasure may vary from location to location depending various site-specific geometric and traffic parameters. Safety improvement countermeasure induced changes in average crash frequency are applicable for the entire service life. Hence, total changes in average crash frequency of \(i^{th}\) type of crash for \(j^{th}\) type of countermeasure with total service life of \(Y_j^n\) at \(n^{th}\) location is mathematically represented as follows:

\[
TACF_{i,j}^{n,Y_j^n} = \sum_{y=1}^{Y_j^n} \{1 - CMF_{i,j}\} ACF_{i,y}^{n,y}
\]  \(\text{(1)}\)

where,

- \(TACF_{i,j}^{n,Y_j^n}\) = Total change in average crash frequency of \(i^{th}\) type of crash at \(n^{th}\) location for \(j^{th}\) type of countermeasure at the end of service life, \(Y_j^n\)
- \(CMF_{i,j}\) = Crash modification factor of \(i^{th}\) type of crash for \(j^{th}\) type of countermeasure
- \(ACF_{i,y}^{n,y}\) = Average crash frequency of \(i^{th}\) type of crash at \(n^{th}\) location on \(y^{th}\) year of countermeasure’s service life

If present value of societal crash cost for each crash type is known, the total savings in crash cost at the end of service life for the \(j^{th}\) type of countermeasure at \(n^{th}\) location can be estimated from the above equation as follows:

\[
TCCS_j^n = \sum_{i=1}^{I} TACF_{i,j}^{n,Y_j^n} \times SCC_i^n
\]  \(\text{(2)}\)

where,

- \(TCCS_j^n\) = Total crash cost savings for \(j^{th}\) type of countermeasure at \(n^{th}\) location
- \(SCC_i^n\) = Societal crash cost of \(i^{th}\) type of crash at \(n^{th}\) location
- \(I\) = Total type of crashes such as fatal, injury, property damage only etc.

A highway agency selects countermeasure that yields maximum benefit, i.e. high total crash cost savings with low implementation or construction, and maintenance cost. In other words the difference between the total crash cost savings over the service life of the countermeasure and the implementation cost should be maximum to ensure economic viability.
Countermeasure Implementation Cost Estimation Model

Implementation of safety improvement countermeasure incurs cost. Average implementation cost for specific countermeasure can be estimated from historic project cost data or by conducting location specific preliminary engineering study. A highway agency might have feasible alternative countermeasures with varying implementation cost for a highway location. However, as discussed in the previous section, a highway agency selects a countermeasure that yields maximum benefit. The HSM 2010 (I) proposes benefit-cost analysis and cost-effectiveness analysis for economic evaluation of alternative safety improvement countermeasures at an individual location. If the average implementation cost of \( j^{th} \) type of countermeasure for \( n^{th} \) location (\( AIC^n \)) is in present value, irrespective of implementation year the countermeasure implementation cost will remain at the same present value cost. However, it can be argued that future implementation cost should be estimated based on inflation rate (\( IR \)) and then converted back to present value by applying discount rate (\( DR \)). In this process the final implementation cost will be different only if inflation rate and discount rate are different. The final implementation cost (\( FIC^n \)) of \( j^{th} \) type of countermeasure for \( n^{th} \) location implemented on \( k^{th} \) year can be estimated as follows:

\[
FIC^n = AIC^n \frac{(1+IR)^k}{(1+DR)^k} \tag{3}
\]

Economic Evaluation of Countermeasures

The HSM 2010 (I) recommends evaluating safety improvement countermeasures for economic justification and selecting the most cost effective alternative. As mentioned in the previous section, benefit-cost analysis and cost-effectiveness analysis are the two common analysis methods used for the evaluation. The net present value (NPV) or benefit-cost ratio (BCR) methods are used for benefit-cost analysis, whereas the cost-effectiveness index method is used for cost effectiveness analysis. These methods are effective in evaluating and identifying the best countermeasure for an individual highway location. The primary target is to select an alternative countermeasure that maximizes the benefit. After obtaining the final implementation cost and total crash cost savings of an alternative countermeasure, the economic evaluation index can be represented as follows:

a) Benefit-cost analysis:

i. Net present value

\[
EEI_{NPV} = TCCS^n_j - FIC^n \tag{4b}
\]

ii. Benefit-cost ratio

\[
EEI_{BCR} = \frac{TCCS^n_j}{FIC^n} \tag{4b}
\]

b) Cost effectiveness analysis:

i. Cost effectiveness index

\[
EEI_{CEI} = \frac{FIC^n}{TACF'^n_j} \tag{5}
\]

Overall Optimization Model
The economic evaluation of countermeasure helps in obtaining the best alternative for an individual highway location. Many such locations with selected set of location specific alternative countermeasures are analyzed before being considered for funding in a particular fiscal year. A highway agency selects locations for funding in such a way that the total safety improvement countermeasure implementation cost does not exceed the fiscal budget. The highway locations that cannot be funded in a particular financial year are reconsidered in the selection process for the following fiscal year. However, the locations that are funded in the previous years are also considered in the following fiscal year for supplementary countermeasures (if there is potential for further reduction in crash occurrence). The supplementary countermeasures enhance safety without reducing service life of the countermeasures implemented in the previous fiscal years. Hence, combining all the objectives a mathematical optimization model can be represented as follows:

a) Benefit-cost analysis:

i. Net present value

\[
\text{Max} \sum_{i=1}^{N} \sum_{k=1}^{K} \frac{TCCS_{i}^{n,k}}{FIC_{j}^{n,k}} \times BDV_{j}^{n,k} \\
\]

\[
= \text{Max} \sum_{i=1}^{N} \sum_{k=1}^{K} \sum_{j=1}^{J_{n}} \left( 1 + \frac{CMF_{i,j}^{n}}{ACF_{i}^{n,y}} \right) ACF_{i}^{n,y} \times BDV_{j}^{n,k} \\
\]

ii. Benefit-cost ratio

\[
\text{Max} \sum_{i=1}^{N} \sum_{k=1}^{K} \sum_{j=1}^{J_{n}} \left( TCCS_{j}^{n,k} \right) FIC_{j}^{n,k} \times BDV_{j}^{n,k} \\
\]

\[
= \text{Max} \sum_{i=1}^{N} \sum_{k=1}^{K} \sum_{j=1}^{J_{n}} \left( 1 + \frac{CMF_{i,j}^{n}}{ACF_{i}^{n,y}} \right) ACF_{i}^{n,y} \times BDV_{j}^{n,k} \\
\]

b) Cost effectiveness analysis:

i. Cost effectiveness index

\[
\text{Max} \sum_{i=1}^{N} \sum_{k=1}^{K} \sum_{j=1}^{J_{n}} \sum_{l=1}^{L_{i,j}} \frac{FIC_{j}^{n,k}}{TACF_{i,j}^{n,y}} \times BDV_{j}^{n,k} \\
\]

\[
= \text{Max} \sum_{i=1}^{N} \sum_{k=1}^{K} \sum_{j=1}^{J_{n}} \sum_{l=1}^{L_{i,j}} \left( 1 + \frac{CMF_{i,j}^{n}}{ACF_{i}^{n,y}} \right) ACF_{i}^{n,y} \times BDV_{j}^{n,k} \\
\]

Subject to:

\[
FIC_{j}^{n,k} \times BDV_{j}^{n,k} \times FB^{k} \times k = 1 \text{ to } K \\
\]

\[
BDV_{j}^{n,k} \times 1 \text{ if the } j^{th} \text{ alternative is chosen for } n^{th} \text{ location at } k^{th} \text{ year} \\
0 \text{ otherwise} \\
\]
where,

\[
BDV_{j}^{n,k} = \text{Binary decision variable for } j^{th} \text{ alternative of } n^{th} \text{ location at } k^{th} \text{ year}
\]

\[
FB^{k} = \text{Fiscal budget of } k^{th} \text{ year}
\]

\[
J^{n} = \text{Total type of alternatives for } n^{th} \text{ location}
\]

\[
K = \text{Years in analysis period}
\]

In the above formulation the equation (6) and (7) respectively represents the summation of benefit-cost ratio and cost effective index for all locations over the analysis period. Maximizing these factors eventually ensures optimized selection of projects for funding in the fiscal years of the analysis period. The constraints presented in equation 8 and 9 ensure maintaining implementation cost within the budget limit and selecting a countermeasure once for a particular location. On the other hand, equation (10) represents the binary decision variable, which ensures selection of one safety improvement countermeasure for a location once in the analysis period. Similar constraints can be added to incorporate location specific dependency among the countermeasures (i.e. some countermeasures may be considered only after implementing some specific countermeasures in the previous fiscal year), maintaining time gap between successive implementation of countermeasures at one location etc.

CASE STUDY

A set of 104 intersections from Livingstone (30 intersections), Macomb (35 intersections) and Monroe (39 intersections) County, in southwest Michigan, U.S. is selected for the case study. Southeast Michigan Council of Governments (SEMCOG) has classified these counties as urban county. Hence, the CMFs for urban setup as provided in HSM 2010 (1) and CMF Clearinghouse (27) are explored and considered here for estimating the change in average crash frequency. The last ten-year crash data is collected to estimate the average crash frequency. Since detail improvement plans for these locations are not available to the authors, it is assumed that no significant improvement, influencing the number of crashes at the location had occurred in the past. Therefore, the average crash frequency for different type of crashes is obtained by estimating the average from ten-year crash data. Table 1 lists the computed average crash frequency of few representative locations from Livingstone, Macomb and Monroe County. Intersection traffic control strategy, intersection lighting, presence of red light camera etc. information are obtained by reviewing each locations in Google Earth. Also, possible countermeasures are identified for each location by analyzing existing condition.
TABLE 1 Computed average crash frequency of sample locations

<table>
<thead>
<tr>
<th>County</th>
<th>Location ID</th>
<th>Fatal</th>
<th>PDO</th>
<th>Injury A</th>
<th>Injury B</th>
<th>Injury C</th>
<th>Angle</th>
<th>Rear End</th>
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<td>41.9</td>
<td>0.5</td>
<td>0.9</td>
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<tr>
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<td>1</td>
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<tr>
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<td>0.1</td>
<td>2</td>
<td>1.9</td>
<td>7.2</td>
<td></td>
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<tr>
<td><strong>Macomb</strong></td>
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</tbody>
</table>

A total of eight countermeasures are considered for three counties in SEMCOG region. The CMF values of the countermeasure considered, average expected cost of implementing each countermeasure and expected service life is listed in Table 2. While compiling the available CMFs of various countermeasures in urban setup, it is observed that in almost all cases the CMFs for property damage only (PDO) and fatal crashes are not available. For some countermeasures, CMFs for all severity crashes and injury crashes are available. Whereas, for others, either all severity or injury crash CMFs are readily available. Since fatal crashes are random and often difficult to predict, in this study it is assumed that the average fatal crash frequency will remain unchanged over time. Also, average crash frequency for fatal crashes for the 10-year study period are very low (see Table 1) and CMFs are not available, hence this assumption is made. If only all severity crash CMF is available, the injury and PDO crash CMFs are calculated based on their average crash frequency proportion as given in equation (11) and (12). Similarly, if all severity and injury crash CMFs are available, the CMF of PDO crashes is estimated as per equation 13. Some countermeasures don’t have CMFs specifically for urban setup. One such countermeasure considered in this study is converting all way stop control intersection to roundabout. In this
particular case, the CMF available for all settings is used for the case study. However, highway agencies are encouraged to develop their own CMFs for these situations.

\[ CMF_{PDO} = \frac{ACF^n_{PDO}}{ACF^n_{PDO} + ACF^n_{Injury}} \]  

(11)

\[ CMF_{Injury} = \frac{ACF^n_{Injury}}{ACF^n_{PDO} + ACF^n_{Injury}} \]  

(12)

\[ CMF_{PDO} = \left( \frac{ACF^n_{All\crash} \cdot CMF^n_{All\ severity} \cdot ACF^n_{Injury} \cdot CMF^n_{Injury}}{ACF^n_{PDO}} \right) \]  

(13)

**TABLE 2 Countermeasures considered and corresponding CMFs**

<table>
<thead>
<tr>
<th>Countermeasure</th>
<th>All settings</th>
<th>Urban</th>
<th>Implementation Cost ($)</th>
<th>Service Life (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All way stop Control to roundabout</td>
<td>1.03 0.544</td>
<td>1 Lane: 464,137&lt;sup&gt;2&lt;/sup&gt; 2 Lane: 1977270&lt;sup&gt;2&lt;/sup&gt; 3 Lane: 1957854&lt;sup&gt;2&lt;/sup&gt;</td>
<td>25&lt;sup&gt;3&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Minor way stop Control to roundabout</td>
<td>0.56 0.18 0.61&lt;sup&gt;3&lt;/sup&gt; 0.88&lt;sup&gt;4&lt;/sup&gt; 0.78&lt;sup&gt;5&lt;/sup&gt; 0.22&lt;sup&gt;6&lt;/sup&gt; 0.19&lt;sup&gt;7&lt;/sup&gt;</td>
<td>1 Lane: 464,137&lt;sup&gt;2&lt;/sup&gt; 2 Lane: 1977270&lt;sup&gt;2&lt;/sup&gt; 3 Lane: 1957854&lt;sup&gt;2&lt;/sup&gt;</td>
<td>25&lt;sup&gt;3&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Signal control to roundabout</td>
<td>0.52 0.22 0.99 0.40</td>
<td>1 Lane: 464,137&lt;sup&gt;2&lt;/sup&gt; 2 Lane: 1977270&lt;sup&gt;2&lt;/sup&gt; 3 Lane: 1957854&lt;sup&gt;2&lt;/sup&gt;</td>
<td>25&lt;sup&gt;3&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Minor road stop control to all way stop control</td>
<td>0.319&lt;sup&gt;1&lt;/sup&gt; 0.23&lt;sup&gt;1&lt;/sup&gt; 0.30</td>
<td>5000&lt;sup&gt;4&lt;/sup&gt;</td>
<td>Pavement Marking: 2 Stop signs: 6&lt;sup&gt;7&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Minor road stop control to signalised</td>
<td>0.95</td>
<td>From 50,000 - 200,000&lt;sup&gt;6&lt;/sup&gt;</td>
<td>10&lt;sup&gt;7&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Providing intersection lightning</td>
<td>0.881&lt;sup&gt;1&lt;/sup&gt; 0.62 0.91&lt;sup&gt;1&lt;/sup&gt;</td>
<td>Bulb: 1500-3000 Pole: 3000-12000&lt;sup&gt;7&lt;/sup&gt;</td>
<td>15&lt;sup&gt;7&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Installing flashing beacons</td>
<td>0.95 0.90 1.12&lt;sup&gt;1&lt;/sup&gt;</td>
<td>Average: 9000 High: 27500&lt;sup&gt;3&lt;/sup&gt;</td>
<td>Atleast 10&lt;sup&gt;5&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Installing red light camera</td>
<td>0.74 (angle) 1.18 (rear-end)&lt;sup&gt;1&lt;/sup&gt;</td>
<td>Camera: 50,000 Installation: 5000&lt;sup&gt;9&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>1</sup>Cross!!!!!!!!!!!!!!

<sup>2</sup>Evaluating the Performance and Safety Effectiveness of Roundabouts (28)

<sup>3</sup>FHWA (29)

<sup>4</sup>Evaluation of the conversion from two-way stop sign control to all-way stop sign control at 53 Locations in North Carolina (30)

<sup>5</sup>Safety Evaluation of Flashing Beacons at Stop-Controlled Intersections (31)

<sup>6</sup>Intersection Safety Issue Briefs (32)

<sup>7</sup>Texas DOT (33)

<sup>8</sup>Reducing Late-Night/Early Morning Intersection Crashes By Providing Lighting (34)

<sup>9</sup>Red light cameras (35)

<sup>10</sup>One Lane

<sup>11</sup>Two Lane

<sup>12</sup>Both one and two lane
Though red-light camera improves overall safety of an intersection, CMFs related to injury, PDO or all severity is not available in HSM 2010 (1). As a red-light camera reduces angle crashes but increases rear-end crashes, CMFs for angled and rear-end crashes are available in CMF Clearinghouse (27). Installing red-light camera is relatively a new application and may be for this reason the service life or effectiveness period is not documented in literature. Since, red-light camera operates in conjunction with traffic signal, the service life or effectiveness period of red-light camera is considered as 10 years for this study. The comprehensive crash cost as obtained from HSM 2010 and FHWA’s Executive

Summary on “Safety Evaluation of Red-light Cameras” (36) is used in this study to estimate the profit for benefit cost ratio, and NPV in the optimization model. The crash cost information is listed in table 3.

### TABLE 3 Crash cost

<table>
<thead>
<tr>
<th>Crash Severity and Type</th>
<th>Comprehensive Crash Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatality (K)</td>
<td>$40,08,900(^3)</td>
</tr>
<tr>
<td>Disabling Injury (A)</td>
<td>$2,16,000(^6)</td>
</tr>
<tr>
<td>Evident Injury (B)</td>
<td>$79,000(^6)</td>
</tr>
<tr>
<td>Possible Injury (C)</td>
<td>$44,900(^6)</td>
</tr>
<tr>
<td>PDO (O)</td>
<td>$7,400(^3)</td>
</tr>
<tr>
<td>Angled</td>
<td>$64,468(^{88})</td>
</tr>
<tr>
<td>Rear-end</td>
<td>$53,659(^{88})</td>
</tr>
</tbody>
</table>

\(^3\) HSM 2010 (1)  
\(^{88}\) Report no. FHWA HRT-05-049 (36)

In this study the inflation rate and discount rate is considered equal. Hence, the final implementation cost is considered as equal to the average implementation cost (equation 3). Also, the growth pattern of average crash frequency is unknown at this stage. Therefore, the average crash frequency is assumed to remain constant over the service life of the countermeasure. The countermeasures considered for the case study are assumed to be mutually exclusive and considered one implementation for one location. Hence, a location may not receive funding for countermeasure implementation and if it receives funding, it will receive once for one countermeasure implementation during the analysis period. These assumptions are made due to unavailability of realistic data on inflation rate, discount rate and growth rate of average crash frequency. Based on these assumptions, equations (6a), (6b) and (7) are appropriately modified and solved for the optimum benefit-cost ratio, NPV and cost effectiveness index. Overall goal of the optimization process is to obtain the optimum countermeasure implementation schedule that meets the budget requirements over the analysis period. An efficient schedule would utilize all available budget and pace out the improvements in such a way that benefit over the analysis period is maximized. In this study, the analysis period is considered as five years and a fixed budget of $6 million is imposed for each year analyzed. The annual budget is assumed to be the same for all years in the planning horizon. A linear programming optimization based solver is used to solve the problem.
RESULTS AND ANALYSIS

The countermeasure implementation schedule of sample locations is given in Table 4. These countermeasures are chosen from the pre-identified list developed by reviewing each location. It is observed that the countermeasure implementation schedule is different for the three methods considered. The total number of locations scheduled for improvement in benefit-cost ratio method in 97, whereas for NPV and cost effectiveness index this number is 78 and 46 respectively. However, all the three methods utilized the annual budget reasonably well (see Figure 1 for details).

<table>
<thead>
<tr>
<th>Location ID</th>
<th>Improvement schedule (Countermeasure, Implementation year)</th>
<th>Benefit-cost ratio</th>
<th>Net present value</th>
<th>Cost effectiveness index</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>Roundabout, 5</td>
<td>No improvement</td>
<td>No improvement</td>
<td></td>
</tr>
<tr>
<td>L2</td>
<td>Intersection lighting, 5</td>
<td>Intersection lighting, 1</td>
<td>No improvement</td>
<td></td>
</tr>
<tr>
<td>L3</td>
<td>Intersection lighting, 5</td>
<td>Intersection lighting, 2</td>
<td>No improvement</td>
<td></td>
</tr>
<tr>
<td>L4</td>
<td>Intersection lighting, 5</td>
<td>Intersection lighting, 2</td>
<td>No improvement</td>
<td></td>
</tr>
<tr>
<td>L6</td>
<td>Intersection lighting, 5</td>
<td>Roundabout, 2</td>
<td>Red-light camera, 1</td>
<td></td>
</tr>
<tr>
<td>L7</td>
<td>Roundabout, 3</td>
<td>No improvement</td>
<td>No improvement</td>
<td></td>
</tr>
<tr>
<td>L17</td>
<td>Flashing beacon, 2</td>
<td>Flashing beacon, 3</td>
<td>Flashing beacon, 5</td>
<td></td>
</tr>
<tr>
<td>L31</td>
<td>All-way Stop, 1</td>
<td>Flashing beacon, 3</td>
<td>All-way Stop, 1</td>
<td></td>
</tr>
<tr>
<td>MC1</td>
<td>Red-light camera, 5</td>
<td>Roundabout, 3</td>
<td>No improvement</td>
<td></td>
</tr>
<tr>
<td>MC2</td>
<td>Red-light camera, 5</td>
<td>Roundabout, 4</td>
<td>No improvement</td>
<td></td>
</tr>
<tr>
<td>MC4</td>
<td>Intersection lighting, 2</td>
<td>Roundabout, 1</td>
<td>No improvement</td>
<td></td>
</tr>
<tr>
<td>MC5</td>
<td>Intersection lighting, 5</td>
<td>Intersection lighting, 5</td>
<td>No improvement</td>
<td></td>
</tr>
<tr>
<td>MC6</td>
<td>Intersection lighting, 5</td>
<td>Roundabout, 1</td>
<td>No improvement</td>
<td></td>
</tr>
<tr>
<td>MC8</td>
<td>Intersection lighting, 5</td>
<td>Intersection lighting, 2</td>
<td>No improvement</td>
<td></td>
</tr>
<tr>
<td>MC9</td>
<td>Red-light camera, 1</td>
<td>Roundabout, 2</td>
<td>Red-light camera, 4</td>
<td></td>
</tr>
<tr>
<td>MC10</td>
<td>Red-light camera, 5</td>
<td>Roundabout, 4</td>
<td>Red-light camera, 5</td>
<td></td>
</tr>
<tr>
<td>M1</td>
<td>Intersection lighting, 5</td>
<td>Intersection lighting, 5</td>
<td>No improvement</td>
<td></td>
</tr>
<tr>
<td>M2</td>
<td>Red-light camera, 2</td>
<td>No improvement</td>
<td>Red-light camera, 4</td>
<td></td>
</tr>
<tr>
<td>M3</td>
<td>Roundabout, 3</td>
<td>No improvement</td>
<td>No improvement</td>
<td></td>
</tr>
<tr>
<td>M6</td>
<td>Intersection lighting, 5</td>
<td>Intersection lighting, 2</td>
<td>No improvement</td>
<td></td>
</tr>
<tr>
<td>M20</td>
<td>All-way Stop, 2</td>
<td>Flashing beacon, 3</td>
<td>All-way Stop, 1</td>
<td></td>
</tr>
<tr>
<td>M26</td>
<td>Roundabout, 2</td>
<td>Roundabout, 4</td>
<td>Roundabout, 4</td>
<td></td>
</tr>
<tr>
<td>M34</td>
<td>All-way Stop, 1</td>
<td>Roundabout, 2</td>
<td>Intersection lighting, 4</td>
<td></td>
</tr>
<tr>
<td>M42</td>
<td>All-way Stop, 5</td>
<td>Flashing beacon, 3</td>
<td>All-way Stop, 2</td>
<td></td>
</tr>
</tbody>
</table>

5 Signalized intersection
10 5 All-way stop control intersection
12 5 Two-way stop control intersection

The area coverage of benefit-cost ratio method in terms of number of locations scheduled for countermeasure implementation is better than the other two methods. The total number of countermeasure implementations scheduled in each year varies widely for all the three methods. However, the benefit cost ratio and NPV method yielded highest number of improvements on the last year of the analysis period. These numbers are more than 50% of
the total number of scheduled improvements in the analysis period. The cost-effectiveness index method did not show such trend. A highway agency should be careful with the total number of improvements been scheduled every year as any limitation in available resources may impact implement. Among the eight countermeasures considered, intersection lighting is the highest chosen countermeasure by benefit to cost ratio and NPV methods. Similarly, converting the signalized intersection to roundabout is the highly preferred countermeasure in cost effectiveness index method. This explains the difference in total number of locations scheduled for countermeasure implementation by the three methods.

Comparing the three methods, cost effectiveness index method utilized the budget most efficiently. In the five-year analysis period with total amount of unutilized fund is minimum for the cost effectiveness index method and maximum for benefit-cost ratio method. The year wise unutilized fund is almost uniform for cost effectiveness index method and is less than 0.2% of the annual budget. On the other hand, the year wise unutilized fund for benefit-cost ratio varies significantly with the highest being more than 7% of the annual budget and the lowest being less than 0.3%. So, overall cost effectiveness index is better than the benefit-cost ratio and NPV methods in terms of fund utilization during multi-year analysis.

![Figure 1 Budget Utilization](image)

The Figure 2 shows NPV with budget sensitivity. The total budget for the planning period is varied from $5 million to $50 million. The corresponding NPV obtained is 133.83 million and 278.95 million respectively. The budget and NPV does not show a linear relationship because of the binary nature of the decision variables. The NPV increases sharply with increase in budget from $5 million to $25 million. However, beyond $25 million of budget, the rate of increase is relatively small. The smaller increment of NPV beyond budget of $30 million can be explained by the law of diminishing return. The budget sensitivity demonstrates the flexibility of the mode structure presented in the paper to run
sensitivities much faster. Such sensitivity analysis will help the planning agencies to assess
the effect of various budgets on NPV (or B/C ratio or cost effectiveness).

\[ \text{FIGURE 2 Budget sensitivity analysis} \]

**CONCLUSIONS AND DISCUSSIONS**

The proposed optimization models are efficient in prioritizing highway countermeasure
implementation plans over a multi-year planning horizon. Results obtained for number of
locations in three counties in Michigan, U.S. and suggested improvement alternatives appear
reasonable. The proposed can be easily extended for application in more number of locations
with additional improvement options over a longer analysis period. Though case study
locations selected are all intersections, the formulation provided is generic and is applicable
for other location types such as highway sections, interchanges etc. Also, various other
alternative countermeasure can be considered provided CMFs, crash frequency, improvement
cost etc. are available. A field visit, crash report review and traffic analysis are certainly
recommended before selecting the potential countermeasure alternatives. It is suggested to
consider developing location specific CMF, countermeasure implementation cost to improve
accuracy.

Highway agencies following the ranking method as suggested in HSM 2010 (1) may
find the proposed optimization based prioritization method not complementing their practice.
However, using the ranking method for initial screening followed by the proposed
optimization method would help in better management of HSIP funds. With minor
modifications this method can also be used to estimate future funding requirement.
Particularly, carrying out budget sensitivity analysis as shown in figure 2 would provide a
clear idea of the future funding requirement to obtain maximum benefit.
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REFERENCES


