Optimal Investment Decision-Making Strategies for Safety Improvements on Urban Intersections

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ABSTRACT

Urban intersections crashes cause significant economic loss among all roadways. The safety management process undertaken by most states in the United States is referred as hazard elimination program, and consists of three standardized steps i.e. (i) identification of critical crash locations, (ii) development of countermeasures and (iii) resource allocation among identified crash locations. Often these three steps are undertaken independently with limited detail of each step at the state planning agencies. Literature review underlines the importance of third step and lack of sophisticated tools available to state planning agencies for leveraging information obtained from first two steps. Further, non-strategic approaches and unavailability of methods for evaluating policies lead to sub-optimal fund allocation. This paper overcomes these limitations and proposes multiple optimal resource allocation strategies for improvements at urban intersections that maximize safety benefits, under budget and policy constraints. Policy measures based on benefits maximization (economic competitiveness), priority to locations with higher severity of crashes (relative urgency), equitable allocation (equity), and pure dominance (multiple alternatives at one location) produces significantly different alternative and fund allocation. The model is applied to selected intersections in four counties of southeast Michigan. Results from model application reinforce pragmatic consideration of developed strategies/policies and tools for resource/fund allocation of highway safety projects on critical urban intersections.

INTRODUCTION

Moving Ahead for Progress in the 21st Century (MAP-21) is a milestone that envisions research and application focus areas for surface transportation in the United States (US) *(1)*. MAP-21 sanctioned continuation of legacy Highway Safety Improvement Program (HSIP) as a core Federal-aid program. HSIP envisions significantly reducing traffic fatalities and serious injuries on the highway system. Under HSIP, state Departments of Transportation (DOT's), along with the US Department of Transportation (USDOT) spend billions of dollars annually for safety improvement programs at urban intersections.

The safety management process undertaken by most states is often referred to as the hazard elimination program, which consists of three steps: (1) selection of candidate locations where safety improvements are warranted; (2) development of countermeasures for potential crash reduction; and (3) allocation of resources among candidate locations in conformance with budgetary and other constraints. State planning agencies often consider these three steps as independent and sequential. Literature suggests that resource allocation (third step) is the most critical phase and suffers from sub-optimal fund allocation with low safety benefits and long-term capital loss due to lack of sophisticated analysis tools.

Two critical components of safety improvement program are crash prediction and fund allocation for preventative measures. Each of these components should be strategically analysed. The crash prediction component needs to consider random nature of crashes, and require appropriate methods that can provide robust results in a long-term planning. Most of the previous literature ignores randomness by assuming deterministic growth that can lead to inappropriate allocation of highway safety improvements. Moreover, current fund allocation (second component) approach of state planning agencies needs to go beyond short-term planning and strategize allocation based on some concrete policies. State planning agencies should consider optimization-based resource allocation tools and policies that maximise long-term safety benefits by implementing the proposed alternatives under budget and other constraints.

In addition, both of these critical components need to be integrated for simultaneous crash prediction and resource allocation to hazardous locations. Hence, four key research questions addressed in this paper are:

(i) *"How to allocate funds considering random nature of crashes at pre-determined crash locations to implement preventative alternatives?*

(ii) *"What methods should be employed to maximize safety benefits from implementation of alternatives within budget, planning period and policy/strategic constraints?"*

(iii) *"Which state and federal level strategies/policies should form basis for investment and fund allocation?"*

(iv) *"What will be the most optimal policy for resource allocation in safety improvements on urban intersections?"*

The remainder of the paper is organized as follows: Next section presents the literature review specific to resource allocation models followed by the methodology and model formulation. The data set used for demonstration and model application is discussed next. Finally, the research is summarized and recommendations for future research are outlined.

LITERATURE REVIEW

The literature review is organized into three sections (1) highway safety resource allocation, (2) crash occurrence and it's impact on allocation, and (3) methods of highway safety resource allocation. The review presented is by no means a comprehensive one; rather it is designed to capture a representative cross-section of studies conducted on this subject in past two decades.

Highway Safety Resource Allocation

Resource allocation and prioritizing highway safety projects is identified as an important element in transportation planning *(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. 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 *(3–8)*. 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.

Analytical Approaches for Highway Safety Resource Allocation

The topic of resource allocation (using optimization techniques) spans 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 *(9, 10)*. 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 *(11, 12)*. Resource allocation on highway safety improvements methods include application of mixed integer programming techniques, based on branch and bound algorithm for highway safety projects *(13)*; linear programming techniques to maximize savings resulting from alcohol-crash reduction *(14)*; linear programming to select safety and operational improvement on highway networks *(15)*; integer programing for reduction in crashes *(16)*; integer programming to minimize total number of crashes *(17)*; linear programming for highway safety improvement alternatives *(18)*; and linear programming to incorporate uncertainty in safety resource allocation *(19)*. 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. 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 *(13)*. Since optimally considering proposed alternatives is a discrete decision variable, literature recommends application of complex integer programming *(11)*. In this paper, the authors present an approach to optimize the safety benefits in a given region by maximizing the dollar value of the crashes saved at intersections each year over a multi-year planning horizon while predicting crashes simultaneously during the optimization procedure.

Equity in Transportation Planning

Further, there is a limited literature that incorporates equity in highway safety resource allocation problem. Equity in transportation has typically been considered under the umbrella of environmental justice in terms of distributing benefits and impacts among privileged and underprivileged populations (see, for instance, *(20, 21)*). However, the concept can more generally reflect the distribution of impacts by geographic region as well. Quantitative methods used to measure equity vary, and include least-squares *(22)*, ratio-based *(23)*, or accessibility measures *(24)*. This literature makes a sharp distinction between "equality of outputs" and "equality of outcomes" *(24)*. "Equality of outputs" refers to an equal allocation of resources, such as funding, while "equality of outcomes" refers to an equal allocation of benefits.

In the context of this literature, the paper has following contributions:

- *integrate crash prediction and resource allocation*

  The proposed model formulates two-step approach: In the first step, a crash prediction model forecasts the number of crashes at individual intersections. In the second step, a resource allocation model assigns proposed alternatives to locations based on the crash types so that overall benefit in terms of reduction of crashes are maximized subject to budget and policy constraints.

- *proposes four realistic policy options based on federal and state planning agencies vision*

  Four policy options are proposed and solved (in the results section) to represent realistic issues encountered in the planning agencies during fund allocation:
  - The first policy is based on economic competiveness to maximize total economic and safety benefits.
  - The second policy option deals with relative urgency of locations warranting improvements because of crash severity.
  - The third policy measure is equity consideration in the benefits and allocation of safety measures among counties.
  - Fourth policy is pure dominance that relaxes mutually exclusiveness nature of improvements and allows locations to receive more than one improvement at a given year such that benefit is maximized while satisfying specified constraints.

ECONOMIC COMPETITIVENESS-RESOURCE ALLOCATION MODEL (EC-RAM)

Economic competitiveness and safety are two of the five major goals of US DOT's Strategic Plan. National Safety Council (NSC) estimates the average costs of fatal and nonfatal unintentional injuries to illustrate their impact on the nation's economy. According to NSC, the costs are a measure of the dollars spent and income not received due to accidents, injuries, and fatalities that is another way to measure the importance of prevention work. In the proposed Economic Competitiveness-Resource Allocation Model (EC-RAM), the objective is to maximize total economic benefits (*Z*) derived from prevented crashes at set of locations upon implementation of alternatives for the proposed planning period of *N* years.

An integer programing model is proposed based on three binary variables, indexed by the intersection *i*, safety improvement choice *j*, and year of implementation *n*. Each improvement *j* has an effective duration of l_j years. The binary variable $x_{i,j}^{n} = 1$ if alternative *j* is implemented at location *i* during year *n*, is equal to zero otherwise and $y_{i,j}^{n,n'} = 1$ if alternative *j* is implemented at location *i* during year *n*, and is still active during year *n'* else zero. (i.e. $y_{i,j}^{n,n'} = 1$ if $x_{i,j}^{n} = 1$ and $0 \le n' - n \le l_j$). Here, *x* indicates the year of construction, while *y* indicates the years of effectiveness. The objective function is based on maximization of benefits, with three type of constraints: a budget constraint, constraints based on the feasible alternatives for each intersection, and definitional constraints relating *x* and *y*.

Objective Function

Let f_i^n, m_i^n, and p_i^n denote the expected number of fatal crashes, injury or non-fatal crashes, and property damage only (PDO) collisions at location *i* during year *n*. Similarly, let $r_{i,j}^{f}$, $r_{i,j}^{f}$, and $r_{i,j}^{f}$ denote the crash reduction factors for these three types of crashes if treatment *j* is applied at intersection *i*, and let c^f, c^m, and c^p denote the economic costs of each type of crash obtained from National Safety Council (NSC, 2013). Hence, the objective function can then be written as:

Maximize

$$Z = \sum_{n=1}^{N} \sum_{j=1}^{J} \sum_{i=1}^{I} \sum_{n'=1}^{N} \left[f_i^n r_{i,j}^{f} c^f + m_i^n r_{i,j}^{m} c^m + p_i^n r_{i,j}^{p} c^p \right] y_{i,j}^{n,n'} \tag{1}$$

Constraints

Equation (2) is a budget constraint, that ensures the sum total of capital investment and operation and maintenance (O&M) costs does not exceed the total budget of the planning period. However, there is a flexibility of expenditure between the years in the planning period. Such flexibility in expenditure between years within a planning period can be incorporated into the procedure through a planning based budget model applied in transit resource allocation (Mishra et al. 2013). In these models a planning period budget is based on the assumption that the agency has the flexibility of borrowing monies from subsequent years' allocation or past year surplus. Let $\pi_{i,j}^{n}$ represent the capital cost of constructing improvement *j* at intersection *i* in year *n*, and $o_{i,j}^{n,n'}$ the operating costs in year *n'*. Also, let b_n be the available budget available for year *n*. Then budget constraints are as follows:

$$\sum_{n=1}^{N}\sum_{j=1}^{J}\sum_{i=1}^{I}\left[\pi_{i,j}^{n}x_{i,j}^{n}+\sum_{n'=1}^{N}o_{i,j}^{n,n'}\ y_{i,j}^{n,n'}\right]\leq\sum_{n=1}^{N}b_{n} \tag{2}$$

For a variety of reasons, not all alternatives can be implemented at all locations. Accordingly, constraint (3) ensures that the alternatives implemented at a location, using pre-specified alternative parameters $\hat{x}_{i,j}^{n}$. Based on engineering design, the suggested alternatives tend to be location- specific :

$$x_{i,j}^{n}\leq\hat{x}_{i,j}^{n}\ \forall\ i,j,n \tag{3}$$

Expression (4) denotes that each location *i* can have a limited number of active alternatives (γ_{i}^{n}) during the analysis year *n*, pre-specified by the planning agency.

$$\sum_{j=1}^{J}\sum_{n=1}^{N}y_{i,j}^{n,n'}\ \leq\gamma_{i}^{n}\ \ ,\forall\, i,n' \tag{4}$$

When the alternatives are mutually exclusive, as in the economic competitiveness case, γ_{i}^{n} is equal to one. This provides the following features:

- *Feature 1*: A location can receive only one alternative in a given year.
- *Feature 2:* A location, that has the carry-over effect from an alternative implemented in previous years, may not receive any funds during the service life of the alternative. (Note: This constraint can be modified as desired).

Furthermore, the definitions of *x* and *y* require:

$$y_{i,j}^{n,n'}\ \leq\begin{cases} x_{i,j}^{n}\,, & 0\leq n'-n\leq l_{j} \\ 0, & \text{otherwise}\end{cases},\ \forall\, i,j,n,n' \tag{5}$$

$$x_{i,j}^{n}\ \leq y_{i,j}^{n,n'}\,,\ \forall\, i,j,n,n' \tag{6}$$

$$x_{i,j}^{n},y_{i,j}^{n,n'}\ \in\{0,1\},\forall\ i,\ j,\ k_{j} \tag{7}$$

Equation (5) requires that the *y* values are consistent with the *x* values such that an improvement cannot be active at a given year unless it was implemented in a year within its duration of effectiveness. Equation (6) prohibits an already-active improvement from being selected again during its duration of effectiveness. Finally, Equation (7) reflects the binary nature of the decision variables. It must be noted that details of the integration of crash prediction model are not presented in this paper for brevity and length limitations but can be found on the web[1].

MODEL APPLICATION

Study Area

The state of Michigan is used as the study area in this paper. The resource allocation model for highway safety improvements is applied to a set intersections in the Southeast Michigan region comprising of four counties (Wayne:County-1, Washtenaw:County-2, St. Clair: County-3, and Oakland: County-4). The 20 highest crash frequency locations from each of the four counties were selected (a total of 80 intersections) representing a sub-set of 25,000 intersections in the region. A practical application of the model would consider a larger subset of intersections, but a smaller subset is used in this paper demonstrations purpose.

An implied assumption in limiting the study to intersections is that there is a targeted budget for the treatment of these types of locations. Annualized crash data (over a 10-year period) compiled from the website of the Southeast Michigan Council of Governments (SEMCOG) is presented in Figure 1 (SEMCOG 2008) for each intersection, listed in decreasing order of total crashes for each county. Figure 1 show that locations in County-4 has the highest whereas County-3 has the least number of crashes. Detailed input data for all locations is shown in Table 1. In addition to total crashes, type of crash data is also shown for each location.

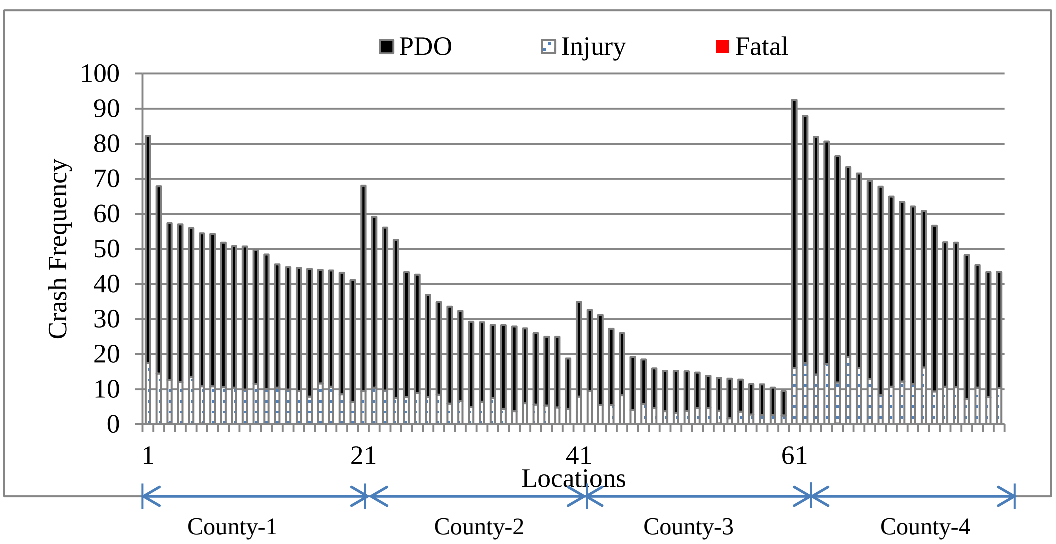

FIGURE 1 Crashes by Severity for all locations

[1] Mishra, S., Sharma, S., Golias, M, Boyles, S. (2013). Crash Prediction Results for Resource Allocation. http://www.ce.memphis.edu/smishra/Publications/CrashPredictionResults.pdf

Data Assumptions

Five hypothetical safety alternatives (Table 2) are proposed as the countermeasures for potential reduction in crashes. Also, for demonstration purposes, it has been assumed that a maximum of four alternatives can be applied to each intersection in Table 1. Each alternative is assumed to be mutually exclusive. In reality, these alternatives are developed as a second sequential step of the hazard elimination program and are based upon engineering judgments, and an analysis of the probable causes of the crashes in such a way that the likelihood of future crashes are reduced. Comprehensive design of alternatives is beyond the scope of this paper and hence alternatives in this study are adapted from Michigan Department of Transportation *(25)*.

The capital cost of the proposed alternatives is presented in Table 2 (in increasing order). For simplicity, O&M costs are assumed as 10% of capital costs, and service life for the alternatives is assumed to be proportional to capital costs. Each alternative has been assumed to consist of a set of countermeasures and with crash reduction factors (CRF) for each alternative. Crash reduction factors for each countermeasure, along with their expected service life, can be derived from the literature *(26)*. An alternative may consist of a single or multiple countermeasures. In the latter case, CRF's associated with each countermeasure are combined, following a linear function, to derive a combined CRF. The CRF values listed in Table 2 can be assumed to be associated with each alternative (that may be a combination of countermeasures).

TABLE 1 Input Data for All Locations

County	Intersection	Crash Frequency				Crash Type					
		Total	Fatal	Injury	PDO	Rear-end	Angle	Swipe-same	Swipe-opp.	Head-on	Other
County-1	1	82.2	0.1	17.4	64.7	33.4	24.9	5.7	3.3	9.0	5.9
	2	57.0	0.0	12.0	45.0	25.1	12.8	6.1	1.6	8.9	2.5
	.	.	.	.	.	.	.	.	.	.	.
	.	.	.	.	.	.	.	.	.	.	.
	19	44.0	0.0	11.6	32.4	20.8	8.2	4.9	0.6	7.5	2.0
	20	43.8	0.0	10.7	33.1	14.3	12.5	7.2	1.7	3.0	5.1
County-2	21	68.0	0.0	9.4	58.6	33.2	14.8	11.9	1.2	3.9	3.0
	22	59.2	0.0	10.4	48.8	25.8	21.5	4.1	0.5	4.9	2.4
	.	.	.	.	.	.	.	.	.	.	.
	.	.	.	.	.	.	.	.	.	.	.
	39	29.2	0.1	4.8	24.3	21.1	2.6	4.0	0.4	0.4	0.7
	40	18.7	0.0	4.4	14.3	10.3	1.6	3.2	0.1	0.7	2.8
County-3	41	34.8	0.1	7.8	26.9	18.5	9.2	3.1	0.6	1.1	2.3
	42	32.6	0.0	9.5	23.1	28.0	1.7	1.0	0.5	0.5	0.9
	.	.	.	.	.	.	.	.	.	.	.
	.	.	.	.	.	.	.	.	.	.	.
	59	12.7	0.0	3.6	9.1	2.1	7.5	1.4	0.1	0.5	1.1
	60	9.4	0.0	2.5	6.9	2.9	2.4	1.9	0.1	0.6	1.5
County-4	61	92.5	0.0	16.1	76.4	41.5	20.1	21.1	1.5	3.4	4.9
	62	76.4	0.2	11.7	64.5	29.8	26.2	14.1	2.8	0.5	3.0
	.	.	.	.	.	.	.	.	.	.	.
	.	.	.	.	.	.	.	.	.	.	.
	79	45.4	0.0	10.4	35.0	18.8	12.3	3.9	2.2	5.0	3.2
	80	43.4	0.0	10.3	33.1	21.0	8.7	4.1	1.5	5.1	3.0

In the study an initial annual budget of $1.6 million is considered. The future year budgets are assumed to increase by six percent every alternate year over a five year planning horizon. The rationale behind selecting the above initial budget is discussed in the next section. Information on factors that need to be considered from year to year for all the proposed models: mutually exclusive feature, carry-over factor[2], and year end surplus are tracked internally within the model. The model is applied to a sub-set of locations depicting reality to the extent possible to ensure a connection between the proposed process and its application / practice. An analysis period of five years is assumed for illustrative purposes, but can be increased in the discretion of user.

TABLE 2 Crash Reduction Factors, Cost and Service Life of Alternatives

Alternatives	Crash Reduction Factors			Capital Cost ($)	O&M Cost ($)	Service Life (Years)
	Fatal	Injury	PDO			
I	0.06	0.05	0.04	20,000	2,000	2
II	0.13	0.11	0.09	35,000	3,500	2
III	0.25	0.23	0.18	80,000	8,000	3
IV	0.30	0.29	0.25	100,000	10,000	4
V	0.46	0.45	0.42	150,000	15,000	4

The annual savings measured in monetary terms from the reduction in number of crashes is termed as "benefit", and the savings over the five year planning period is termed as "total benefit". These two terms are used in the following sections as a measure of the monetary savings from reduction in crashes. Surplus is defined as difference between available budget and the amount committed for implementation of alternatives. The terms annual surplus and total surplus are used in the remainder of the paper for unused budget for annual and planning period respectively.

The crash resource allocation model is solved by Integer Programming with Large-Scale SQP Evolutionary algorithm using Premium Solver Platform *(27)*. Table 3 shows one year allocation of projects with minimum budget considering mutually exclusive nature of alternatives. If minimum cost alternative is chosen for 80 locations then budget becomes $1,600,00 and the resulting benefit is $2,980,000 (Table 4). With the proposed optimization the resulted benefit is $6,788,149. The optimization procedure did not allocate projects to all locations, rather to location that needs improvement to result savings in crashes resulting to maximum benefit. A partial demonstration of results in Table 3 shows that no locations in county 2 and 3 received any improvements. From optimization viewpoint this is logical because these locations consists of very low number of crashes and therefore did not warrant any improvements to maximize the total benefit. The optimization model resulted in 11 alternatives (1 alternative IV and 10 alternative V) using the proposed budget as opposed to choosing all 80 locations with minimum budget.

[2] An alternative installed for the first year remains effective for the remainder of its service life.

TABLE 3 Results of Single Year Allocation

County	Intersection	Improvements (Optimized) I	II	III	IV	V	Min Project Cost ($)	Minimum Benefit ($)	Optimized Project Cost ($)	Optimized Benefit ($)
County-1	1	0	0	0	0	1	20,000	76,272	150,000	708,677
	2	0	0	0	0	0	20,000	47,760	0	0
	.	.	.	.	.	.	.			
	.	.	.	.	.	.	.			
	19	0	0	0	1	0	20,000	42,527	100,000	361,415
	20	0	0	0	0	0	20,000	40,282	0	0
County-2	21	0	0	0	0	0	20,000	45,071	0	
	22	0	0	0	0	0	20,000	44,606	0	
	.	.	.	.	.	.	.	.	.	.
	.	.	.	.	.	.	.	.	.	.
	39	0	0	0	0	0	20,000	28,370	0	0
	40	0	0	0	0	0	20,000	16,790	0	0
County-3	41	0	0	0	0	0	20,000	37,473	0	0
	42	0	0	0	0	0	20,000	33,702	0	0
	.	.	.	.	.	.	.	.	.	.
	.	.	.	.	.	.	.	.	.	.
	59	0	0	0	0	0	20,000	12,885	0	0
	60	0	0	0	0	0	20,000	9,138	0	0
County-4	61	0	0	0	0	1	20,000	69,334	150,000	661,597
	62	0	0	0	0	1	20,000	67,731	150,000	622,113
	.	.	.	.	.	.	.	.	.	.
	.	.	.	.	.	.	.	.	.	.
	79	0	0	0	0	0	20,000	40,080	0	0
	80	0	0	0	0	0	20,000	39,182	0	0
Total		**0**	**0**	**0**	**1**	**10**	**1,600,000**	**2,980,006**	**1,600,000**	**6,788,149**

Economic Competitiveness based Model (EC-RAM) Results

Table 4 illustrates results of Economic competitiveness optimization for a planning period of five years. Model resulted in 35 new alternatives in the first year. The capital cost for implementing these alternatives is $1.36 million leaving surplus of $240,000. The O&M cost is zero, as these costs are incurred one year after the alternative is implemented. The optimum benefit for the first year is computed as $2.86 million. In the second year, optimization resulted in the selection of 28 new alternatives with a capital cost of $1.69 million and benefit of $7.05 million. The effect of carry-over alternatives from the previous year is also included in the estimation of the benefits derived. Similar allocations are made for five years. The benefit for the first year resulting from a single year analysis is $2.98 million (Table 3), while the first year benefit from a multi-year analysis is $2.86 million (Table 4). The difference in benefit is simply a reflection of the fact that the model allocates resources over five-year period optimally resulting in a greater a flexibility of investment from year to year. An analysis of one year at a time, on the other hand, is blind to availability of future funds, and may not necessarily result in maximization of total benefit over the five-year period. Also, for the first year the planning period model resulted in a surplus of $240,000 while in a one year analysis total budget was consumed.

TABLE 4 Summary of Allocation for a Five Year Planning Period For Proposed Policies

Model	Year	Number of Alternatives Allocated						Benefit ($)	Allocated ($)	O&M Cost ($)	Budget ($)	Surplus ($)	Cumulative ($)
		I	II	III	IV	V	Total						
Economic Competitiveness	1	19	8	5	3	0	35	2,864,987	1,360,000	0	1,600,000	240,000	240,000
	2	8	7	8	2	3	28	7,052,356	1,695,000	136,000	1,600,000	-231,000	9,000
	3	4	7	5	3	2	21	7,441,855	1,325,000	123,500	1,680,000	231,500	240,500
	4	6	5	5	6	3	25	6,325,140	1,745,000	159,000	1,680,000	-224,000	16,500
	5	5	5	6	7	1	24	6,947,227	1,605,000	165,000	1,764,000	-6,000	10,500
	Total	**42**	**32**	**29**	**21**	**9**	**133**	**30,631,565**	**7,730,000**	**583,500**	**8,324,000**	**10,500**	
Relative Urgency	1	14	6	4	3	0	27	2,551,145	1,110,000	0	1,600,000	490,000	490,000
	2	14	5	2	3	3	27	6,610,720	1,365,000	111,000	1,600,000	124,000	614,000
	3	11	3	3	1	0	18	5,653,538	665,000	112,500	1,680,000	902,500	1,516,500
	4	8	1	5	8	0	22	4,809,617	1,395,000	106,000	1,680,000	179,000	1,695,500
	5	7	8	6	6	12	39	9,147,599	3,300,000	109,000	1,764,000	-1,645,000	50,500
	Total	**54**	**23**	**20**	**21**	**15**	**133**	**28,772,619**	**7,835,000**	**438,500**	**8,324,000**	**50,500**	
Equity in Outcome	1	17	3	1	2	0	23	1,044,359	725,000	0	1,600,000	875,000	875,000
	2	9	4	6	8	1	28	4,781,175	1,750,000	72,500	1,600,000	-222,500	652,500
	3	6	10	2	6	1	25	6,956,618	1,380,000	76,000	1,680,000	224,000	876,500
	4	5	2	8	5	2	22	6,255,674	1,610,000	163,000	1,680,000	-93,000	783,500
	5	10	4	6	5	2	27	6,382,044	1,620,000	186,000	1,764,000	-42,000	741,500
	Total	**47**	**23**	**23**	**26**	**6**	**125**	**25,419,870**	**7,085,000**	**497,500**	**8,324,000**	**741,500**	
Pure Dominance	1	7	5	6	2	1	21	2,978,220	1,145,000	0	1,600,000	455,000	455,000
	2	13	10	6	7	1	37	8,625,034	1,940,000	114,500	1,600,000	-454,500	500
	3	17	6	5	0	1	29	8,178,797	1,100,000	119,500	1,680,000	460,500	461,000
	4	15	2	8	6	3	34	8,571,476	2,060,000	48,000	1,680,000	-428,000	33,000
	5	15	11	4	0	2	32	8,653,869	1,305,000	20,000	1,764,000	439,000	472,000
	Total	**67**	**34**	**29**	**15**	**8**	**153**	**37,007,396**	**7,550,000**	**302,000**	**8,324,000**	**472,000**	

Table 4 also shows that a total of 133 new alternatives are selected in the five year planning period for economic competitiveness. The total benefit achieved is worth $30.63 million at an expense of $7.73 million of capital cost and $583,500 of O&M cost, leaving a surplus of $10, 500. While the model maximizes total benefit over the five-year period, it does not guarantee that all the locations will receive at least one alternative during the planning cycle, as this condition was not explicitly incorporated in the model formulation.

Table 5 shows that for economic competitiveness case in the first year, eight alternatives are allocated to County-1, nine to County-2, six to County-3, and 12 to County-4. The first year alternatives are carried over to the second year because of multiple year service life of alternatives. For the second year, eight alternatives are allocated to County-1, seven to County-2, five to County-3, and eight to County-4. Similar allocation of projects by county for the economic competitiveness case is shown in Table 5.

RESOURCE ALLOCATION POLICIES

While the economic competitiveness case represented allocation of alternatives with the objective of maximizing benefits when subjected to budget and other constraints. A number of policies are also presented which could be beneficial to the analyst. Four policies analysed are (1) Relative Urgency, (2) Equity in Outcome and (3) Pure dominance. Each of the policies is discussed below.

Relative Urgency

In this policy measure priorities are assigned to locations with crashes of higher severity. Relative urgency of a location can be expressed by means of a relative score (equation 8), which consists of weighting factors for fatal and injury crashes (equation 9). A scenario to represent relative urgency for locations having higher severe crashes is analyzed. The relative score (s_i^n) of a location can be determined as;

$$s_i^n = \left[\omega^f f_i^n + \omega^m m_i^n + p_i^n\right] \tag{8}$$

where,

$$\omega^f = \frac{c^f}{c^p}, and\ \omega^m = \frac{c^m}{c^p} \tag{9}$$

A threshold value of the relative urgency ϑ^n is estimated as the mean of relative scores of all the locations in year *n*, i.e. $\frac{\sum_{i=1}^{I} s_i^n}{\sum_{i=1}^{I} i}$. A binary variable is defined based on the threshold value ϑ^n for each location to incorporate its relative urgency, which is defined as follows (expression 10):

$$\gamma_i^n = 0\ \forall i, n : \vartheta^n \geq s_i^n \tag{10}$$

In the allocation for relative urgency case, locations are prioritized based on their relative scores. The threshold value for relative urgency is determined as the mean relative score of all locations. For the first year, the mean relative score (or the threshold value, ϑ^n in equation 13) is 61.14. Locations with higher relative scores (than the threshold value) receive priority in funding allocation in such a way that the total benefit is maximized, subject to budget and other constraints.

Table 4 shows that total benefits achieved from relative urgency are comparatively lesser than economic competitiveness. Since the objective of relative urgency is to allocate alternatives at locations that has higher number of fatal/severe crashes. It can be observed although the numbers of alternatives that are allocated are same; the expenditure for relative urgency is higher compared to economic competitiveness. However, relative urgency provides the decision maker one more policy option to explore allocation process when crash severity is one of the criteria to consider.

Further, Table 5 shows a high variance among allocated alternatives at all counties, for example in the first year eight alternatives are allocated to County-1, 2, and 4, and three alternatives are allocated to County-3. Similarly at the end of second year, only three alternatives are allocated to County-3, whereas County-1, 2, and 4 received 20, 13, and 18 alternatives respectively. The variance can also be seen in terms of benefits to these counties. Hence, it can be observed that Economic Competitiveness and Relative Urgency based policies lead to inequitable distribution of benefits and alternatives among counties. Most federal and state policies consider equity as an equally important factor in resource allocation. Thus, the next proposed policy measure for fund allocation is based on Equity.

TABLE 5 Allocation of Alternatives to Counties by Proposed Strategies[3]

Model	Year	New					Carry-Over					Total				
		County 1	County 2	County 3	County 4	Total	County 1	County 2	County 3	County 4	Total	County 1	County 2	County 3	County 4	Total
Economic Competitiveness	1	8	9	6	12	35	0	0	0	0	0	8	9	6	12	35
	2	8	7	5	8	28	8	9	6	12	35	16	16	11	20	63
	3	8	6	3	4	21	11	10	6	9	36	19	16	9	13	57
	4	5	8	6	6	25	12	8	8	9	37	17	16	14	15	62
	5	7	4	3	10	24	9	11	10	9	39	16	15	13	19	63
	Total	**36**	**34**	**23**	**40**	**133**	**40**	**38**	**30**	**39**	**147**	**76**	**72**	**53**	**79**	**280**
Relative Urgency	1	8	8	3	8	27	0	0	0	0	0	8	8	3	8	27
	2	12	5	0	10	27	8	8	3	8	27	20	13	3	18	54
	3	5	4	3	6	18	13	8	1	12	34	18	12	4	18	52
	4	10	5	1	6	22	8	7	4	10	29	18	12	5	16	51
	5	7	12	10	10	39	12	7	1	11	31	19	19	11	21	70
	Total	**42**	**34**	**17**	**40**	**133**	**41**	**30**	**9**	**41**	**121**	**83**	**64**	**26**	**81**	**254**
Equity in Outcome	1	5	6	7	5	23	0	0	0	0	0	5	6	7	5	23
	2	7	7	7	7	28	5	6	7	5	23	12	13	14	12	51
	3	5	7	7	6	25	7	8	9	7	31	12	15	16	13	56
	4	5	6	5	6	22	10	11	12	9	42	15	17	17	15	64
	5	5	9	7	6	27	11	7	11	11	40	16	16	18	17	67
	Total	**27**	**35**	**33**	**30**	**125**	**33**	**32**	**39**	**32**	**136**	**60**	**67**	**72**	**62**	**261**

Equity in Outcome

This policy is based on the assertion that all counties should receive benefits in an equitable manner. Equity in outcome is a critical measure that guarantees equal benefits, hence justifies investments in preventative measures. Let I_δ denote the intersections in county δ, I_ε denote the intersections in county ε, and τ be a constant greater than or equal to 1. Following constraint is incorporated in EC-RAM, as it ensures benefits from the alternatives allocated to a particular county, are within a reasonable limit as compared to other counties

$$\sum_{n=1}^{N}\sum_{j=1}^{J}\sum_{i\in I_\delta}^{I}\sum_{n'=1}^{N}\left[f_i^n r_{i,j}^f c^f + m_i^n r_{i,j}^m c^m + p_i^n r_{i,j}^p c^p\right] y_{i,j}^{n,n'} \le \tau \sum_{n=1}^{N}\sum_{j=1}^{J}\sum_{i\in I_\varepsilon}^{I}\sum_{n'=1}^{N}\left[f_i^n r_{i,j}^f c^f + m_i^n r_{i,j}^m c^m + p_i^n r_{i,j}^p c^p\right] y_{i,j}^{n,n'} \tag{11}$$

For analysis, the value of τ is assumed to be three, such that it represents that no county should receive three times more benefit than other counties. The ratio of three is used to account for unequal number of crashes and population densities between counties. Table 4 shows that

[3] Table 5 does not list “Pure Dominance” results as the strategy discounts mutual exclusivity of alternatives and hence is not equivalent in comparison of allocated alternatives to other three strategies.

equity in outcome resulted in $25.41 million with a capital cost of $7.08 million and O&M cost of $497,500. A total of 125 new improvements are implemented in the equity in outcome scenario. Table 5 suggests that all counties received almost similar number of alternatives/projects every year during the planning period. Table 5 shows 136 alternatives are carried over to the future years after implementation. Including new and carried over a total of 261 alternatives were in effect during planning period for this scenario. Table 6 shows benefit distribution across counties over the years.

TABLE 6 Distribution Of Benefits Across Counties According To Proposed Strategies[4]

Model	Year	New (Million $)					Carry-Over (Million $)					Total (Million $)				
		County 1	County 2	County 3	County 4	Total	County 1	County 2	County 3	County 4	Total	County 1	County 2	County 3	County 4	Total
Economic Competitiveness	1	0.90	0.72	0.29	0.96	2.86	0.00	0.00	0.00	0.00	0.00	0.90	0.72	0.29	0.96	2.86
	2	1.12	0.48	0.54	2.05	4.19	0.90	0.72	0.29	0.96	2.86	2.02	1.20	0.83	3.01	7.05
	3	1.66	0.63	0.18	0.78	3.25	1.12	0.48	0.54	2.05	4.19	2.78	1.10	0.73	2.83	7.44
	4	0.54	0.90	0.33	1.63	3.40	1.34	0.63	0.18	0.78	2.93	1.87	1.53	0.51	2.41	6.33
	5	1.08	0.22	0.12	2.13	3.55	0.54	0.90	0.33	1.63	3.40	1.62	1.12	0.45	3.76	6.95
	Total	**5.30**	**2.94**	**1.46**	**7.55**	**17.25**	**3.89**	**2.73**	**1.34**	**5.42**	**13.38**	**9.18**	**5.67**	**2.81**	**12.97**	**30.63**
Relative Urgency	1	0.61	0.91	0.31	0.72	2.55	0.00	0.00	0.00	0.00	0.00	0.61	0.91	0.31	0.72	2.55
	2	1.66	0.61	0.00	1.79	4.06	0.61	0.91	0.31	0.72	2.55	2.27	1.51	0.31	2.51	6.61
	3	0.50	0.18	0.08	0.83	1.59	1.66	0.61	0.00	1.79	4.06	2.16	0.78	0.08	2.62	5.65
	4	1.32	0.50	0.09	1.30	3.22	0.50	0.18	0.08	0.83	1.59	1.82	0.68	0.18	2.13	4.81
	5	0.48	1.46	1.06	2.93	5.93	1.32	0.50	0.09	1.30	3.22	1.80	1.96	1.16	4.23	9.15
	Total	**4.58**	**3.65**	**1.55**	**7.57**	**17.35**	**4.09**	**2.19**	**0.49**	**4.64**	**11.42**	**8.67**	**5.84**	**2.04**	**12.21**	**28.77**
Equity in Outcome	1	0.21	0.27	0.26	0.31	1.04	0.00	0.00	0.00	0.00	0.00	0.21	0.27	0.26	0.31	1.04
	2	1.29	0.78	0.46	1.21	3.74	0.21	0.27	0.26	0.31	1.04	1.50	1.05	0.72	1.52	4.78
	3	0.98	0.38	0.61	1.25	3.22	1.29	0.78	0.46	1.21	3.74	2.27	1.15	1.07	2.46	6.96
	4	1.24	0.70	0.31	0.86	3.11	0.90	0.38	0.61	1.25	3.14	2.14	1.08	0.93	2.11	6.26
	5	0.88	1.04	0.49	0.86	3.27	1.24	0.70	0.31	0.86	3.11	2.13	1.74	0.80	1.71	6.38
	Total	**4.60**	**3.16**	**2.13**	**4.49**	**14.38**	**3.64**	**2.13**	**1.64**	**3.63**	**11.04**	**8.24**	**5.29**	**3.78**	**8.12**	**25.42**

For the economic competitiveness case over the planning period County-1 received $5.3 million and County-4 received $7.55 million benefits. County-2 and 3 received $2.94 million and $1.46 million respectively (Table 6). While looking at the equitable distribution for economic competitiveness case, County-4 received about 5.71 times ($7.55million / $1.46 million) benefits than County-3. Similar observations can be made for such inequitable carry-over and total benefits for County-4 and County-3 for the economic competitiveness case. Table 6 also shows similar inequitable distribution of benefits for both relative urgency policy. Equity in outcome results shows that no county have received benefits more than three times in any given year in the planning period. Such an equitable distribution of benefits is achieved for the equity in outcome scenario but as a trade-off in the total benefits received, i.e. $25.42 million (Table 6).

[4] Table 6 does not list "Pure Dominance" results as the strategy discounts mutual exclusivity of alternatives and hence is not equivalent in disaggregated level comparison to other three strategies in terms of benefits distribution across counties.

Total benefits received for equity in outcome is the least among all scenarios. For some agencies equity in outcome policy may be favorable if the goal is to provide equitable distribution of improvement and benefits.

Pure Dominance

The Economic competitiveness policy, Relative urgency policy, and Equity in outcome policy are based upon allocation of alternatives that are mutually exclusive in nature. High frequency and high severity locations require installation of multiple alternatives in a given year to maximize the benefits. If there are a number of high frequency and high severity locations, it may be necessary to relax the mutually exclusive constraint, thereby allowing the installation of different alternatives during the service life of an existing alternative at a specific location. This feature is termed as "carry-over" in remainder of the paper. Thus, if alternative *j* is installed in the year *n* for location *i*, it has a carry-over effect in the year *n+1* for location *i*, and for subsequent years during the service life of the alternative. Relaxation of the carry-over feature allows installation of another alternative (*j'*) in year *n+1*, while the effect of alternative *j* is carried over from year *n* for location *i*. The relaxation may take on different forms, and will depend upon the specific case. In this paper, the carry-over feature is described as follows:

- A location that has a carry-over effect from an alternative implemented from previous year(s), may receive another alternative.
- However, locations with carry-over effects from two alternatives may not receive another alternative on the year in question.

The objective of this option is to maximize total benefits by allocating a new alternative when a different alternative is already in place. Relaxation of the "carry-over feature" constraint can be implemented by adding equation (12), and (13). Equation (12) relaxes the carry-over effect, thereby installing multiple alternatives in one year, or installing a new alternative while the effect of another alternative installed earlier is still in place. $y_{i,j}^{n,n'}$ is 1, if alternative alternative *j* implemented at location *i* in year *n* is still active in n' year. Equation (13) suggests that a new alternative $y_{i,j}^{n,n'}$ (of similar nature) cannot be installed if another alternative is already in place for location *i* in the year *n*, active in year n'.

$$\gamma_i^n = \begin{cases} y_{i,j}^{n,n'} + y_{i,j'}^{n,n'}; & n' = 1 \\ x_{i,j}^{n'+1,n} + x_{i,j'}^{n'+1,n}; & 1 < n' - n \le l_j \end{cases} \tag{12}$$

$$y_{i,j}^{n,n'} = \begin{cases} 0, \forall\, x_{i,j}^{n'+1,n} = 1 \\ 1, Otherwise \end{cases} \tag{13}$$

The combined CRF for locations with multiple allocations of projects will follow the regular practice of total $CRF_t = 1 - \{(1 - CRF_1)(1 - CRF_2) \ldots . (1 - CRF_n)\}$. This is accomplished by setting the value of γ_i^n to 2 for all intersections and years, rather than 1 as in the prior experiments. Results of relaxation of mutually exclusive policy are shown in Table 4. A total of 21 alternatives are selected for the first year, with an allocated cost and resulting benefit of \$1.14

million and $2.97 million respectively. In the second year, 37 alternatives are selected, and the resulting benefit is $8.62 million (including the carry-over from the first year). The capital and O&M costs are $1.94 million and $114, 500 respectively. The total benefit received is $37.07 million, at a capital cost of $7.75 million, and an O&M cost of $302,000. Relaxation of mutually exclusive policy resulted in a surplus of $472,000 and produced the highest total benefit among all options considered. Since, mutual exclusivity of alternatives is disregarded in this policy (unlike other three policies) the county-wise distribution of alternatives (Table 5) and benefits (Table 6) is not presented for this policy as it is not an equivalent comparison.

Overall, the model output is considered reasonable, and the trends observed followed are logical. These are reflected in various performance factors discussed above, such as: amount committed, total surplus, and number of alternatives funded. The whole methodology is implemented in a VBA based solver platform *(27)*, on an Intel (R) Xeon (R) Core ™ i7-3820, 3.6 GHz, 32GB memory, with Windows 7 operating system. A precision value of 1.0E-6 is used to determine how closely the estimated constraints match with the given values. Each optimization run requires 50,000 iterations to find the optimal value. Single iteration requires 0.09 seconds, and one complete optimization run requires approximately 46 minutes. However, depending upon the type of problem, nature of the objective function and the constraints the computational time may differ.

CONCLUSION

This paper presents set of innovative and generic policy analysis tools, founded on a highway safety resource allocation model. The resource/fund allocation is performed using an optimization model based on economic competitiveness of crash location thereby allowing improvements to be implemented to locations producing higher benefits. The proposed model is robust in its formulation; and maximizes total benefits from allocation of safety improvement alternatives, within a set of optional policy constraints satisfying budgetary requirements. The model provides flexibility to modify various attributes in four-dimensions: number of counties, planning period (years), policy options and budget (annually or in planning period). The multi-year feature allows the user to effectively utilize the year-end savings in subsequent years, thereby deriving the most benefit from the available resources. Incorporation of policy constraints allows the analyst flexibility of selectively adding required constraints to the resource allocation problem.

The proposed model is demonstrated using signalized urban intersections data from four counties in Southeast Michigan, USA. The economic competitiveness resource allocation model resulted in highest benefit in the planning period but resulted in inequitable distribution of number of improvements to counties. The crash severity is assumed as major factor in relative urgency, which leads to low total benefits and unequal allocation of alternatives. To address the equity feature Equity in Outcome scenario is considered that allows equitable distribution of benefits. However, the resulting total economic benefits from Equity in Outcome scenario were the least among all. Another, policy measure that considers implementation of multiple preventative alternatives at a location is proposed (Pure dominance), that results in highest total benefits. The approach and policy measures presented in this paper allow a state or regional agency to allocate resources efficiently when there are constraints in policies.

The contribution of this study to research and practice is three fold. First, development of an integrated model that simultaneously selects mutually exclusive alternatives in the optimization process satisfying the budgetary and other constraints. Second, the policy constraint application allows not only analysis of one base case but also explores various policy options (relative urgency, equity and relaxation of carry-over). Third, scalability and generic nature of model can be leveraged for seamless application and inclusion of other factors, like advanced crash prediction model or policy constraints. Further, additional research is required to expand the proposed approach by taking more number of alternatives per location, to increase the study area to a state level and to obtain insights on computational performance for larger size problems.

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REFERENCES

1. USDOT. *Moving Ahead for Progress in 21st Century (MAP-21)*. Publication HR.4348. U.S. Department of Transportation, Federal Highway Administration, Washington DC, Jul. 2012, p. 303.
2. AASHTO. *Asset Management Task Force-Strategic Plan*. American Association of State Highway and Transportation Officials, Washington, D.C., 2010, pp. 1–2.
3. Tarko, A., and M. Kanodia. Effective and Fair Identification of Hazardous Locations. *Transportation Research Record*, Vol. 1897, No. 1, Jan. 2004, pp. 64–70.
4. Hauer, E. Identification of Sites with Promise. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1542, No. -1, Jan. 1996, pp. 54–60.
5. Lambert, J. H., J. A. Baker, and K. D. Peterson. Decision aid for allocation of transportation funds to guardrails. *Accident Analysis & Prevention*, Vol. 35, No. 1, Jan. 2003, pp. 47–57.
6. Cook, W. D., A. Kazakov, and B. N. Persaud. Prioritising highway accident sites: a data envelopment analysis model. *Journal of the Operational Research Society*, Vol. 52, No. 3, Feb. 2001, pp. 303–309.
7. Hossain, M., and Y. Muromachi. A Bayesian network based framework for real-time crash prediction on the basic freeway segments of urban expressways. *Accident Analysis & Prevention*, Vol. 45, Mar. 2012, pp. 373–381.
8. Lyon, C., B. Gotts, W. K. F. Wong, and B. Persaud. Comparison of Alternative Methods for Identifying Sites with High Proportion of Specific Accident Types. *Transportation Research Record*, Vol. 2019, No. -1, Dec. 2007, pp. 212–218.
9. Hillier, F. S., and G. J. Lieberman. *Introduction to Operations Research*. McGraw-Hill Higher Education, 2010.
10. Bonini, C. P., W. H. Hausman, H. Bierman, and H. Bierman. *Quantitative analysis for management*. Irwin, Chicago, 1997.
11. Rao, S. S. *Engineering Optimization: Theory and Practice*. Wiley, 1996.
12. Wolsey, L. A., and G. L. Nemhauser. *Integer and Combinatorial Optimization*. Wiley-Interscience, 1999.

13. Melachrinoudis, E., and G. Kozanidis. A mixed integer knapsack model for allocating funds to highway safety improvements. *Transportation Research Part A: Policy and Practice*, Vol. 36, No. 9, Nov. 2002, pp. 789–803.
14. Kar, K., and T. Datta. Development of a Safety Resource-Allocation Model in Michigan. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1865, No. -1, Jan. 2004, pp. 64–71.
15. Banihashemi, M. Optimization of Highway Safety and Operation by Using Crash Prediction Models with Accident Modification Factors. *Transportation Research Record*, Vol. 2019, No. -1, Dec. 2007, pp. 108–118.
16. Mishra, S., and S. Khasnabis. Optimization Model for Allocating Resources for Highway Safety Improvement at Urban Intersections. *Journal of Transportation Engineering*, Vol. 138, No. 5, 2012, pp. 535–547.
17. Pal, R., and K. Sinha. Optimization Approach to Highway Safety Improvement Programming. *Transportation Research Record*, Vol. 1640, No. 1, Jan. 1998, pp. 1–9.
18. Chowdhury, M., N. Garber, and D. Li. Multiobjective Methodology for Highway Safety Resource Allocation. *Journal of Infrastructure Systems*, Vol. 6, No. 4, 2000, pp. 138–144.
19. Persaud, B., and A. Kazakov. A procedure for allocating a safety improvement budget among treatment types. *Accident Analysis & Prevention*, Vol. 26, No. 1, 1994, pp. 121–126.
20. Forkenbrock, D. J., and J. Sheeley. *Effective Methods for Environmental Justice Assessment*. Transportation Research Board, 2004.
21. Duthie, J., K. Cervenka, and S. Waller. Environmental Justice Analysis: Challenges for Metropolitan Transportation Planning. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2013, No. -1, Dec. 2007, pp. 8–12.
22. Duthie, J., and S. Waller. Incorporating Environmental Justice Measures into Equilibrium-Based Network Design. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2089, No. -1, Dec. 2008, pp. 58–65.
23. Meng, Q., and H. Yang. Benefit distribution and equity in road network design. *Transportation Research Part B*, Vol. 36, No. 1, 2002, pp. 19–35.
24. Ferguson, E. M., J. Duthie, A. Unnikrishnan, and S. T. Waller. Incorporating equity into the transit frequency-setting problem. *Transportation Research Part A: Policy and Practice*, Vol. 46, No. 1, Jan. 2012, pp. 190–199.
25. Khasnabis, S., C. Safi, and S. Mishra. *Safety improvements for urban arterials*. Michigan Department of Transportation, Detroit, MI, 2006.
26. Bahar, G., M. Masliah, R. Wolf, and P. Park. *Desktop Reference for Crash Reduction Factors*. Publication FHWA-SA-08-011. 2008, pp. 1–112.
27. PSP. 12. *Premium Solver Platform*. Frontline Systems, Nevada, USA, 2013.

APPENDIX: Notations

Variables	Explanation
b_n	Allocated budget ($) in the analysis year *n*
c^f	Cost of fatal crash (*f*)
c^m	Cost of injury crash (*m*)
c^p	Cost of property damage (*p*)
f_i^n	Expected number of fatal crashes for location *i* in analysis period *n*
I_ε	Set of intersections at county ε
l_j	Service life of the alternative *j*
m_i^n	Expected number of injury crashes, *m*, for location *i* in analysis period *n*
$o_{i,j}^n$	Operation and maintenance cost for alternative *j* implemented in location *i* in the analysis year *n*
p_i^n	Expected number of property damage only crashes, for location *i* in analysis period *n*
$r_{i,j}^p$	Crash reduction factor for property damage, *p*, alternative *j* chosen for location *i*
$r_{i,j}^f$	Crash reduction factor for fatality *f*, alternative *j* chosen for location *i*
$r_{i,j}^m$	Crash reduction factor for injury *m*, alternative *j* chosen for location *i*
s_i^n	Relative urgency score for location *i* in the analysis year *n*
$x_{i,j}^n$	A binary decision variable equal to 1 if alternative *j* is implemented at location *i* in year *n*
$y_{i,j}^{n,n'}$	A binary decision variable equal to 1 if alternative *j* implemented at location *i* in year *n* is still active in *n'* year
δ	Subscript used for a county
ϑ^n	A threshold value representing a measure of relative score for year *n*
$\pi_{i,j}^n$	Capital cost for alternative *j* implemented in location *i* in the analysis year *n*
ω^f	Weighting factor for fatal crash
ω^m	Weighting factor for injury crash
i	Location in the study area
I	Total number of locations
I'	A subset of *I*
j	Alternative proposed to be have potential for crash reduction
J	Total number of alternatives
j'	Alternative selected for installation in addition to an existing alternative *j* already in place for
n	Planning period under consideration
N	Total planning period
Z	Objective function, dollar benefit of crashes saved for the analysis period *n*
γ_i^n	Active alternatives at location *i* during the analysis year *n*
τ	Equity in outcome threshold, a constant that ensures maximum economic benefits for a county