Consideration of Conflicting Objectives in Highway Safety Resource Allocation

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ABSTRACT

There is increasing awareness among planning agencies to reduce occurrence of traffic crashes to minimize loss of economic and societal cost. This awareness calls for creation of a transportation system free from fatalities, serious injuries, and property damages. Allocating resources to identify specific countermeasures to be implemented in crash location is challenging problem (as number of countermeasures with specific cost and benefit are available) in the era of economic competitiveness and constrained budget. Non-strategic approaches and unavailability of methods for evaluating policies may lead to sub-optimal funding allocation. This paper identified typical performance measures considered by the state planning agencies and quantified them in an optimization modeling framework. Three performance measures considered are: safety benefit, net present cost, and equity. These three measures are considered as unique objective functions subjected to policy and budget constraints. Further all three objective functions are combined in a multi-objective optimization framework. The proposed methodology is analyzed considering selected intersections in four counties in southeast Michigan. Results suggests that when performance measures are analyzed separately they provide specific policy recommendations. When performance measures are analyzed in combination, the results provide an array of solutions to further consider in safety decision making. The proposed methodology and results indicate the need for applicability of strategies and policies to further enhance highway safety resource allocation.

INTRODUCTION

Highway safety is getting increasing attention as the overall goal of Federal Highway Administration (FHWA) in the United States (U.S) is committed to fulfilling the vison of "Towards Zero Death" *(1, 2)*. This vision calls for creation of a transportation system free from fatalities, serious injuries, and property damages. Better geometric design, planning and traffic operations efforts are underway by many public agencies to reduce occurrence of traffic crashes from the transportation infrastructure. Improving the infrastructure to reduce occurrence of crashes is a capital intensive process. In the era of economic competitiveness a number of transportation agencies are facing scarcity of budget and do not have the flexibility to fulfill all deficiencies of the transportation network to achieve reduction of traffic crashes. FHWA developed Highway Safety Improvement Program (HSIP) to provide guidance to public agencies on (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. Resource allocation (third step) is the most critical phase, and any limitations of the analysis tools used, leads to suboptimal funding allocation with reduced safety benefits and long-term capital loss.

While reduction in number of crashes is the primary objective of many transportation agencies when considering highway safety resource allocation, literature shows that a number of other objectives are also considered *(3, 4)*. Minimization of investment cost while achieving a certain safety benefit is also considered by some agencies. Typically planning agencies administer a number of smaller jurisdictions (such as counties). Equity in resource allocation among the jurisdiction to collectively reduce occurrence of crashes is also considered by some agencies. Benefits, costs, and equity are various performance measures with unique mathematical construct that leads to different selection of safety projects by a planning agencies in the resource allocation process. Literature does not show that these conflicting objectives are considered in combination to allow the planning agencies to strengthen the highway safety resource allocation and decision making process.

The research question remains when the objectives of highway safety resource allocation are different how to optimally allocate funding within a state planning agencies for implementation of safety countermeasures at locations with existing crash history within budget, planning period and strategic/policy constraints. This paper proposes how to (1) consider unique set of objectives considered by planning agencies, (2) quantify the objectives and develop of an optimization modeling approach for safety resource allocation, (3) apply the optimization model to solve a real world case study, and (4) combine the all the objective functions in a multi-objective optimization framework to further strengthen decision making.

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

LITERATURE REVIEW

The literature review is presented four sub-sections: (1) objectives considered in highway safety resource allocation, (2) consideration of road user cost, (3) use of optimization methods, and (4) equity in transportation planning. This section is concluded with a summary of literature review and contribution of this paper to the literature.

Objectives Considered

Monetary savings or societal cost in prevention of occurrence of crashes is considered as one of the primary objectives by transportation planning agencies in highway safety resource allocation *(3–7)*. Locations providing higher savings are typically considered for funding as they result in obtaining the objective of benefit maximization. Transportation planning agencies in the United States (U.S) use Highway Safety Manual (HSM) as a resource that provides step-by-step measures and guidelines to facilitate improved decision making based on safety performance at highway intersections and mid-blocks *(5)*. While benefit is of importance to the agencies, it involves higher investment in terms of capital cost and recurring operation and maintenance cost of countermeasures. Some agencies do consider cost as a performance measure because of scarce resources. Consideration of cost minimization subjected to a specific goal of benefit is also identified in the literature *(8–12)*. 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 *(13)*. While benefit and cost objectives are interdependent, they are conflicting in nature when considered as objective functions *(14–19)*. Irrespective of the objective function the decision variables remain as the selection of countermeasures (typically referred as alternatives in the literature).

Consideration of Road User Cost

Implementation of countermeasures on roadways involve interruption of traffic flow leading to increased road user cost. Depending on the type of countermeasure construction period as may vary. For example installation of a mast arm signal may take few hours to a day whereas addition of a lane may take multiple days. Interruption in traffic results in increased road user cost and considered as dis-benefit in a number of transportation planning literature *(20–24)*. When two countermeasures are considered with similar cost and benefit, then road user cost may play a role in selecting an adequate countermeasure in the highway safety resource allocation. In highway safety resource allocation such dis benefits are often ignored.

Use of optimization approaches

Discrete or integer programming approach are typically used in the highway safety resource allocation while use of other optimization techniques are also found in the literature. Optimization usually involves the maximization or minimization of an objective function comprising a set of decision variables, subject to various constraints *(25, 26)*. 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 *(27, 28)*. Resource allocation on highway safety improvements methods include application of mixed integer programming techniques, based on branch and bound algorithm for highway safety projects *(29)*; linear programming techniques to maximize savings resulting from alcohol-crash reduction *(30)*; linear programming to select safety and operational improvement on highway networks *(31)*; integer programing for reduction in crashes *(4, 6, 32)*; integer programming to minimize total number of crashes *(33)*; linear programming for highway safety improvement alternatives ; and linear programming to incorporate uncertainty in safety resource allocation *(34)*. Objective functions in the literature include minimization of total investment cost or maximization of benefits measured in dollars *(35, 36)*.

Equity in Transportation Planning

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, Duthie et al., 2007, or Forkenbrock and Sheeley, 2004). 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 *(39)*, ratio-based *(40)*, or accessibility measures *(41)*. This literature makes a sharp distinction between "equality of outputs" and "equality of outcomes" *(41)*. "Equality of outputs" refers to an equal allocation of resources (a.k.a. equity in opportunity), such as funding, while "equality of outcomes" refers to an equal allocation of benefits (a.k.a. equity in outcome). In this paper we propose mathematical formulations that address both policies in highway safety resource allocation.

The literature clearly suggests that more research is needed to consider various performance measures as objectives to assist planning agencies in highway safety resource allocation. A number of persistent studies including development of as a combined effort from FHWA, AASHTO and special TRB taskforce development for over a decade show the importance of highway safety resource allocation. In this paper, optimization techniques are proposed by considering three performance measures as objective functions. These objectives are: benefit, net present cost, and equity (each of these terms are described in the methodology section). Methodological framework to consider these objectives individually and simultaneously is presented next.

METHODOLOGY

In the methodology section, four models are presented. For each model, the objective function and constraints are shown first followed by a discussion of their interpretation. The notations used throughout the paper is shown next.

Notation

Sets

I	candidate locations for safety treatments
J	alternative safety treatments which can be applied
N	years within the analysis period
Parameters	
$\mu_i^{f,n}, \mu_i^{m,n}, \mu_i^{p,n}$	expected number of fatal, injury, and property damage only crashes at year *n* at location *i*
$r_{i,j}^f, r_{i,j}^m, r_{i,j}^p$	crash reduction factors for fatal, injury and property damage only crashes if alternative *j* is implemented at location *i* in year *n*
$c^f, c^m. c^p$	cost of fatal, injury and property only damage crashes
π_{ij}^n, ρ_{ij}^n	capital and O&M cost at year *n* for alternative *j* implemented at location *i*
b^n	available budget at year *n*
$t_{i,j}^n$	duration of construction for alternative *j*, at location *i*, in year *n*
u_i^n	user cost at location *i*, in year *n*
d_i^n	delay cost per user at location *i*, in year *n*
l_j	duration (in years) of effectiveness of alternative *j*
δ	maximum number of active alternatives at any location at a given year
γ	maximum number of active alternatives at a location at a given year
Decision variables	
$x_{i,j}^n$	1 if alternative *j* is implemented at location *i* in year *n* and zero otherwise (even though the alternative is active for l_j years, this variable is only equal to 1 in the year of implementation)

Safety Benefits Model (SBM)

Safety benefit refers to societal gain in preventing occurrence of fatal, injury and property damage crashes. The benefit also considers reduction in user benefits during construction of the proposed countermeasure alternative. Because implementation of countermeasure will require the roadway facility to be prevented from normal traffic flow. The objective function presented in Equation 1 maximizes the total benefits from the reduction of crashes. The four terms are: savings from fatal, injury, property damage, and dis benefit resulted from road user cost. Equation 2 ensures that each year implementation costs for a new alternative and O&M costs of an existing one (i.e. an alternative implemented during a previous year) will not exceed the current yearly budget. Equation 3 ensures that at most γ alternatives can be implemented each year at a location. Equation 4 ensures the same alternative will not be active more than once during any given year.

Equation 5 ensures that no more than δ alternatives will be active during any given year and no other alternative will be considered till the end of service life of current alternative. But after the end of service life, the location is eligible to receive a new alternative. Finally, equation 6 defines the decision variable as binary.

$$Max.\ Z_1 = \sum_{n\in N}\sum_{j\in J}\sum_{i\in I}\left[\left(\mu_i^{f,n} r_{i,j}^{f} c^{f} + \mu_i^{m,n} r_{i,j}^{m} c^{m} + \mu_i^{p,n} r_{i,j}^{p} c^{p} - \pi_{i,j}^{n} t_{i,j}^{n} u_i^{n} d_i^{n}\right)\sum_{n-l_j<k<n} x_{i,j}^{k}\right] \quad (1)$$

Subject to:

$$\sum_{j\in J}\sum_{i\in I}\left[x_{i,j}^{n}\pi_{i,j}^{n} + \rho_{i,j}^{n}\sum_{n-l_j<k<n} x_{i,j}^{k}\right] \le b^{n},\ n\in N \quad (2)$$

$$\sum_{j\in J} x_{i,j}^{n} \le \gamma_{i,j}^{n} \quad \forall\ i\in I, n\in N \quad (3)$$

$$x_{i,j}^{n} + \sum_{n-l_j<k<n} x_{i,j}^{k} \le 1 \quad \forall\ i\in I, j\in J, n\in N \quad (4)$$

$$x_{i,j}^{n} + \sum_{d\neq j\in J, n-l_d<k<n} x_{i,d}^{k} \le \delta_i^{n} \quad (5)$$

$$x_{i,j}^{n} = \{0,1\},\quad \forall\ i\in I, j\in J, n\in N \quad (6)$$

Net Present Cost Model (NPCM)

NPC is defined as the cost when converted to present monetary value using appropriate interest rate for the future. Equation (7) shows the objective function as minimizing NPC, with θ being the interest rate. Since the objective function is minimization constraint (8) ensures that the remaining amount left during the planning period is less than the minimum cost (ϵ) defined by the user. Constraint (3) through (6) ensure the mutually exclusiveness and non-negativity features of the NPC minimization problem.

$$Min.\ Z_2 = \sum_{n\in N}\left[\sum_{j\in J}\sum_{i\in I}\left(x_{i,j}^{n}\pi_{i,j}^{n} + \rho_{i,j}^{n}\sum_{n-l_j<k<n} x_{i,j}^{k}\right)(1+\theta)^{-n}\right] \quad (7)$$

Subject to:

$$\sum_{n\in N}\left[\sum_{j\in J}\sum_{i\in I}\left(x_{i,j}^{n}\pi_{i,j}^{n}+\rho_{i,j}^{n}\sum_{n-l_j<k<n}x_{i,j}^{k}\right)-b^{n}\right]\leq \epsilon \quad (8)$$

Equations (3) through (6)

Equity in Outcome Model (EIOM)

Equity in outcome is the idea that all sub-regions within a larger region should receive an equal share of economic and safety benefits. This is distinct from the idea that sub-regions should receive an equal share of funding, because the effectiveness of safety improvements may differ across sub-regions. For analyzing equity let the sub-regions represent sets S_z partitions of I (such that is, $S_1 \cup\ S_1 \cup S_1 \cup \ldots\ldots S_t \cup\ \ldots \cup S_z = I, and\ S_t \cap S_z = \emptyset\ \forall\ S_t, and\ S_z$). Equation (9), and (10) show benefits received by sub-region S_t and S_z respectively.

$$B_t^n=\sum_{i\in S_y}\sum_{j\in J}\left[\left(\mu_i^{f,n}r_{i,j}^{f}c^{f}+\mu_i^{m,n}r_{i,j}^{m}c^{m}+\mu_i^{p,n}r_{i,j}^{p}c^{p}-\pi_{i,j}^{n}t_{i,j}^{n}u_{i,j}^{n}d_{i,j}^{n}\right)\sum_{n-l_j<k<n}x_{i,j}^{k}\right]\ \forall S_t \quad (9)$$

$$B_z^n=\sum_{i\in S_z}\sum_{j\in J}\left[\left(\mu_i^{f,n}r_{i,j}^{f}c^{f}+\mu_i^{m,n}r_{i,j}^{m}c^{m}+\mu_i^{p,n}r_{i,j}^{p}c^{p}-\pi_{i,j}^{n}t_{i,j}^{n}u_{i,j}^{n}d_{i,j}^{n}\right)\sum_{n-l_j<k<n}x_{i,j}^{k}\right]\ \forall S_z \quad (10)$$

The objective function of shows minimum inequitable distribution between all S_t and S_z pairs within the set I. The objective function includes pairwise comparison of all sub-regions once. To avoid the difference to be negative, constraint in equation (12) ensures that the difference is always positive. To further make the search region bound, constraint (8) ensures that all the available budget is utilized, and the remaining surplus available at the end of the planning period is very small. The question remains how to decide on pairwise comparison between S_t and S_z. S_t can be considered as the sub-region with higher number of crashes with higher economic value when compared to S_z. Equation (11), and (12) in combination ensure that equity in outcome is achieved.

$$Min. Z_3=\sum_{n\in N}(B_t^n-B_z^n)\ \forall\ S_t, S_z\in S\ \ and\ S_t\cap\ S_z=\phi \quad (11)$$

Subject to:

$$(B_t^n-B_z^n)>0 \quad (12)$$

Equations (2), (3), (4), (5), (6), and (8).

Multiple Objectives Based Model (MOBM)

Often agencies plan to consider multiple objective functions simultaneously in the decision making process. Such a problem can be analyzed in a multi objective optimization framework. Equation (13) shows consideration of all objectives, where individual objective functions are weighted and normalized. Since safety benefit is maximized, other two objective functions are minimized, to make the optimization a maximization problem, negative signs are used for NPC and equity. Equation (14) shows that the total weight is between 0, and 1. All other constrains considered in the individual optimization problem is also considered.

$$Max. Z_4 = \omega_1 Z_1 - \omega_2 Z_2 - (1 - \omega_1 - \omega_2) Z_3 \quad (13)$$

Subject to:

$$\omega_1 + \omega_2 \leq 1 \quad (14)$$

Equations (2) – (6), (8), and (12).

MODEL APPLICATION

A number of data sources are critical prior to highway safety resource allocation process including (1) identification of hazardous locations by considering frequency and severity of crashes, (2) classification of various crash types, (3) association of highway geometry and traffic operation characteristics to individual crashes (4) drawing of 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 reduction factor (CRF), 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 *(6, 32, 36)*. For example, crash data usually is available for United States by cities, counties, and metropolitan planning organizations (MPOs) or state DOTs *(42)*. 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 a database suitable for highway safety resource allocation.

The resource allocation model for highway safety improvements is applied to a set of intersections in the Southeast Michigan region comprising of four counties (Wayne, Washtenaw, St. Clair, and Oakland). 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 for demonstration purpose in this paper.

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) was compiled from the website of the Southeast Michigan Council of Governments (SEMCOG). The probable[1] cost of crash savings is presented in Figure 1 (SEMCOG 2008) for each intersection, sub-grouped by county. Figure 1 show that locations in Oakland County have the highest and St. Clair County the least probable cost of crash savings.

Data Assumptions

A number of parameters used in the methodology are assumed for the model application. For example ϵ is considered to be \$50,000. Interest rate is assumed to be six percent. The duration of construction is assumed to be a function of construction cost. Czarnigowskaa and Sobotka *(43)* provide the relationship by analyzing number of construction projects. The user cost is assumed to be \$14/hour. AADT

[1] The term probable is used as crash predictions and crash reduction factors are derived from probabilistic models

in combination with construction duration and user cost is used to obtain the dis benefit because of delay caused during implementation of countermeasure at a specific location.

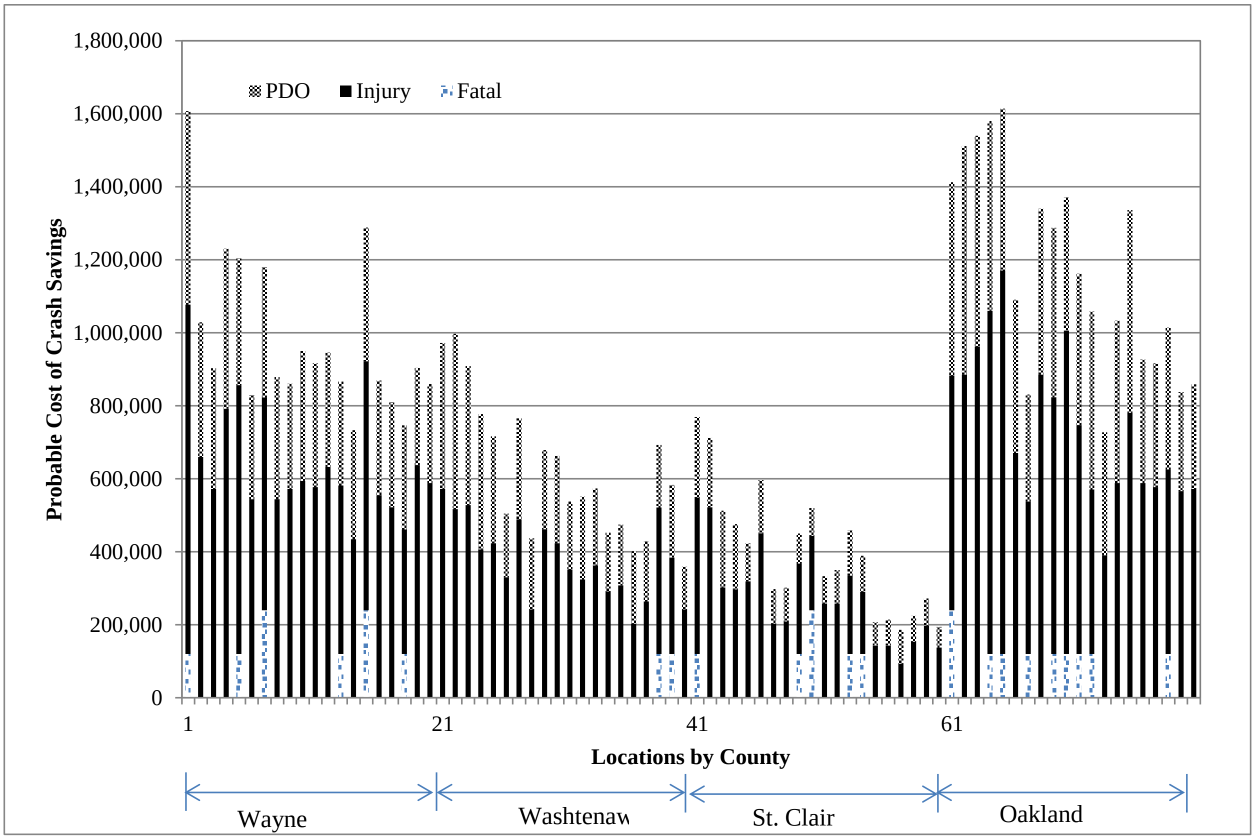


FIGURE 1 Probable Cost of Crash Savings for all locations.

Data Assumptions

Five hypothetical safety alternatives (Table 1) are proposed as countermeasures for potential reduction in crashes. 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 an earlier study for the Michigan Department of Transportation *(44)*.

The capital costs of the proposed alternatives are presented in Table 1 (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. Also, each alternative is assumed to consist of a set of countermeasures with crash reduction factors (CRF) for each alternative. Crash reduction factors for each countermeasure, along with their expected service life, are derived from the literature *(45)*. 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 1 can be assumed to be associated with each alternative.

In the study a first year budget of $1.6 million is considered. The expense for the least cost alternative is $20,000 (Alternative I, see Table 1). If a minimum cost alternative is chosen for 80 locations then budget becomes $1,600,000. However, the initial budget can be changed by the preference of the user. The future year budgets are assumed to increase by six percent every alternate year over a five year planning horizon. 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 using real life data 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 1 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

RESULTS

Case study analysis results are presented in a series of tables and figures. A brief description of the arrangement of tables is presented here. Summary of results for all models is shown in Table 2, Annual summary of allocation is provided in Table 3. County specific total alternative allocation, alternatives by type, total benefits distribution, and allocation of cost is presented in Table 4 through 7. Lastly, multi objective optimization results are shown in Figure 8 and 9.

Single Objective Optimization

Table 2 shows optimized and estimated objective function values for safety benefit, NPC, and equity. The first row shows that the optimal value of SBM is $62.73 million. Similarly, the optimal value for NPCM, and EIOM is $6.94 million and $0.52 million respectively (in second and third row). When the SBM optimal value is $68.73 million, NPC and equity are estimated to be $6.97 and $109.44 million respectively. Please note that higher equity value refers to non-uniform distribution of benefit and vice versa. Similarly, when NPCM optimal value is $6.94 million the benefit and equity is estimated to be $41.86, and $45.47 million respectively. At optimal value of EIOM $0.52 million, safety benefit, and NPC is estimated as $32.08, and $6.95 million respectively. Column wise observation shows that the optimal value is maximum for SBM and minimum for NPCM and EIOM.

TABLE 2 Single Objective Results

	SBM ($)	NPCM ($)	EIOM ($)
SBM ($)	**68,731,289***	6,973,758	109,440,742
NPCM ($)	41,862,228	**6,943,240***	45,476,396
EIOM ($)	32,087,876	6,952,315	**521,806***

Note: *Objective function in corresponding row or column

In Table 3 optimization results for each year is presented. In SBM the annual savings measured in monetary terms from the reduction in number of crashes is termed the “benefit”, and the savings over the five-year planning period is termed the “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 the 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 the annual and planning periods, respectively.

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

TABLE 3 Annual Distribution of Alternatives, Benefits, Costs, and Objective Function Values

SBM													
Year	I	II	III	IV	V	Total	Benefit	NPC	Inequity	Capital Cost	O&M Cost	Budget	Surplus
1	0	0	0	1	10	11	5,880,650	1,509,434	9,745,562	1,600,000	0	1,600,000	0
2	0	0	1	0	9	10	10,888,818	1,423,994	19,268,086	1,430,000	160,000	1,600,000	10,000
3	1	0	0	0	9	10	15,088,948	1,410,560	23,622,642	1,370,000	303,000	1,680,000	7,000
4	0	1	0	0	8	9	18,803,072	1,330,717	32,316,096	1,235,000	440,000	1,680,000	5,000
5	1	0	0	0	9	10	18,069,801	1,318,163	29,800,322	1,370,000	393,500	1,764,000	500
Total	*2*	*1*	*1*	*1*	*45*	*50*	*68,731,289*	*6,992,869*	*114,752,709*	*7,005,000*	*1,296,500*	*8,324,000*	*22,500*
NPCM													
1	1	0	5	1	7	14	2,431,807	1,471,698	1,899,671	1,560,000	0	1,600,000	40,000
2	2	8	6	2	3	21	5,964,591	1,423,994	3,940,569	1,444,000	156,000	1,600,000	0
3	4	3	0	12	0	19	10,057,284	1,410,560	8,697,935	1,381,600	298,400	1,680,000	0
4	1	1	0	11	1	14	11,770,689	1,318,836	14,024,917	1,300,440	379,560	1,680,000	0
5	3	0	3	7	3	16	11,637,857	1,318,151	16,913,304	1,450,000	313,984	1,764,000	16
Total	*11*	*12*	*14*	*33*	*14*	*84*	*41,862,228*	*6,943,240*	*45,476,396*	*7,136,040*	*1,147,944*	*8,324,000*	*40,016*
EIOM													
1	9	10	3	2	4	28	2,108,752	1,481,132	129,997	1,570,000	0	1,600,000	30,000
2	3	9	2	6	2	22	5,590,729	1,416,874	61,558	1,435,000	157,000	1,600,000	8,000
3	7	8	2	4	3	24	7,178,518	1,408,461	181,457	1,430,000	247,500	1,680,000	2,500
4	1	2	2	5	4	14	8,575,340	1,329,925	104,833	1,350,000	329,000	1,680,000	1,000
5	5	5	2	4	4	20	8,634,537	1,315,922	43,962	1,435,000	326,000	1,764,000	3,000
Total	*25*	*34*	*11*	*21*	*17*	*108*	*32,087,876*	*6,952,315*	*521,806*	*7,220,000*	*1,059,500*	*8,324,000*	*44,500*

Note:
(1) Benefit is the performance measure for SBM
(2) NPC is the performance measure for NPCM
(3) Equity is the performance measure for EIOM

In Table 3, NPC is the net present cost with interest rate of six percent. Equity is the sum of pairwise benefit difference between two counties. A higher value of equity represents that the distribution of funds is not even between counties, and vice versa for a lower value.

When SBM is considered as the objective function, the model resulted in the objective function value of $68.73 million (Table 3). Safety benefits received increased with later years. This is because safety benefits are received in the future year when the alternative is already implemented in the past years. A total of 50 alternatives are selected with 45 alternatives are of type "V". Majority of alternatives selected are of type "V" is justified in this case because the objective was to maximize the total safety benefits. Capital cost spent was $7.005 million, and operation and maintenance cost is $1.29 million. In the five year planning period $22,500 was the remaining surplus.

Similarly, when NPCM is considered as the objective function, a total of 84 alternatives are selected. The distribution of alternatives are very different than the safety benefit case. Out of 84 alternatives, 33 type "IV", 14 type "V", and 14 type "III" were selected. Since the goal is to minimize NPC, but at the same time all the funds needs to be spent, the model resulted in selection of larger number of lower cost alternatives. The surplus remaining was $40,016. When Inequity is considered as the objective function, a total of 108 alternatives were selected. Out of these 34 type "II", 25 type "I", and 21 type "V". In EIOM, number of alternatives were reasonably spread out among various types compared to other two objective functions. The total surplus remained was $44, 500.

Table 4 shows number of alternatives allocated to each county when individual objective functions are considered. In the first year Wayne and Oakland counties have received three and eight alternatives respectively. From Table 3 it is clear that out of 11 alternatives 10 were type "V", and one was type "IV". Both "IV" and "V" type alternatives have four years of service life. For the second year these alternatives will remain active and provide benefits but with little expense such as O&M cost. Similar observation can be seen for other objective functions. For the EIOM it is clear that all counties received similar number of alternatives. The number of alternatives effective for each county is more or less same at any given time. This is expected as the objective of EIOM is to allocate alternatives in such a way that the difference in benefit received by all counties is minimized.

TABLE 4 County wise distribution of alternatives by year

SBM										
	New					Cumulative				
Year	Wayne	Washtenaw	St.Clair	Oakland	Total	Wayne	Washtenaw	St.Clair	Oakland	Total
1	3	0	0	8	11	3	0	0	8	11
2	5	0	0	5	10	8	0	0	13	21
3	4	3	0	3	10	12	3	0	16	31
4	6	0	0	3	9	18	3	0	19	40
5	2	0	0	8	10	20	3	0	27	50
NPCM										
1	3	6	4	1	14	3	6	4	1	14
2	4	4	5	8	21	7	10	9	9	35
3	4	2	4	9	19	11	12	13	18	54
4	7	6	1	0	14	18	18	14	18	68
5	2	6	2	6	16	20	24	16	24	84
EIOM										
1	7	6	7	8	28	7	6	7	8	28
2	4	10	6	2	22	11	16	13	10	50
3	9	4	4	7	24	20	20	17	17	74
4	1	6	5	2	14	21	26	22	19	88
5	2	4	8	6	20	23	30	30	25	108

Table 5 shows the type and number of alternatives received by each county for individual objective functions (also categorized by year). As expected, Wayne and Oakland counties received higher cost alternatives throughout the planning period when SBM is considered as the objective function. The distribution of type of alternative is quite different for both NPCM, and EIOM. Specifically, for EIOM case the distribution of benefits are equally spread out among the counties and also between types of alternative.

TABLE 5 Type of alternatives distribution by county and year

Year	County	SBM						NPCM						EIOM					
		I	II	III	IV	V	*Total*	I	II	III	IV	V	*Total*	I	II	III	IV	V	*Total*
1	Wayne	0	0	0	1	2	*3*	0	0	0	1	2	*3*	1	6	0	0	0	*7*
	Washtenaw	0	0	0	0	0	*0*	1	0	4	0	1	*6*	2	2	1	0	1	*6*
	St.Clair	0	0	0	0	0	*0*	0	0	1	0	3	*4*	1	0	1	2	3	*7*
	Oakland	0	0	0	0	8	*8*	0	0	0	0	1	*1*	5	2	1	0	0	*8*
2	Wayne	0	0	1	0	4	*5*	1	1	0	2	0	*4*	1	0	0	3	0	*4*
	Washtenaw	0	0	0	0	0	*0*	0	3	0	0	1	*4*	1	6	0	2	1	*10*
	St.Clair	0	0	0	0	0	*0*	0	2	2	0	1	*5*	1	3	1	0	1	*6*
	Oakland	0	0	0	0	5	*5*	1	2	4	0	1	*8*	0	0	1	1	0	*2*
3	Wayne	1	0	0	0	3	*4*	0	0	0	4	0	*4*	4	3	0	2	0	*9*
	Washtenaw	0	0	0	0	3	*3*	0	2	0	0	0	*2*	0	2	1	1	0	*4*
	St.Clair	0	0	0	0	0	*0*	3	0	0	1	0	*4*	0	1	0	1	2	*4*
	Oakland	0	0	0	0	3	*3*	1	1	0	7	0	*9*	3	2	1	0	1	*7*
4	Wayne	0	0	0	0	6	*6*	0	0	0	6	1	*7*	0	0	0	1	0	*1*
	Washtenaw	0	0	0	0	0	*0*	1	1	0	4	0	*6*	1	0	1	2	2	*6*
	St.Clair	0	0	0	0	0	*0*	0	0	0	1	0	*1*	0	1	0	2	2	*5*
	Oakland	0	1	0	0	2	*3*	0	0	0	0	0	*0*	0	1	1	0	0	*2*
5	Wayne	1	0	0	0	1	*2*	0	0	0	1	1	*2*	0	1	0	1	0	*2*
	Washtenaw	0	0	0	0	0	*0*	0	0	2	4	0	*6*	1	1	1	1	0	*4*
	St.Clair	0	0	0	0	0	*0*	2	0	0	0	0	*2*	0	3	0	1	4	*8*
	Oakland	0	0	0	0	8	*8*	1	0	1	2	2	*6*	4	0	1	1	0	*6*
Total		*2*	*1*	*1*	*1*	*45*	*50*	*11*	*12*	*14*	*33*	*14*	*84*	*25*	*34*	*11*	*21*	*17*	*108*

Distribution of benefits is shown in Table 6. When SBM is considered as the objective function, Wayne and Oakland counties have received majority of funding while St. Clair has not received any funding at all. Washtenaw has received only a small portion of funding. In the case of NPCM, still majority of the funding is devoted to Wayne and Oakland, other counties have also received some funding. This is because of the nature of different objective functions. When EIOM is considered, all counties have received nearly equal funding for all years within the planning period.

Allocation of costs is shown in Table 7. Similar to distribution of benefits, allocation of costs exhibit similar pattern for all objective functions considered. One of the clear distinction of allocation of cost is between EIOM and others. Allocation of funds for EIOM clearly suggests that reasonable distribution of funds between all counties is obtained. But this distribution has also made the SBM and NPCM objective worse. So there exists a trade-off stating that no objective function can be made better without lessening the effect of other conflicting objective function. To examine the result when all objective functions are considered simultaneously, the next section discusses result of multi objective optimization.

TABLE 6 Distribution of Benefits

	Annual				Cumulative				
Year	Wayne	Washtenaw	St.Clair	Oakland	Wayne	Washtenaw	St.Clair	Oakland	Total
SBM									
1	1,456,159	0	0	4,549,832	1,456,159	0	0	4,549,832	6,005,991
2	3,490,229	0	0	7,398,589	4,946,388	0	0	11,948,421	16,894,809
3	4,996,262	1,082,877	0	9,009,809	4,996,262	1,082,877	0	9,009,809	31,983,758
4	7,330,352	1,334,662	0	10,138,058	12,326,614	2,417,539	0	19,147,867	50,661,488
5	6,797,948	1,361,355	0	9,910,497	19,124,562	3,778,894	0	29,058,365	68,731,289
NPCM									
1	1,015,609	608,399	386,776	621,570	1,015,609	608,399	386,776	621,570	2,632,353
2	1,832,253	1,090,056	877,104	2,165,177	2,847,862	1,698,455	1,263,880	2,786,747	8,596,944
3	2,990,766	1,282,822	1,193,809	4,589,887	2,990,766	1,282,822	1,193,809	4,589,887	18,654,228
4	4,666,943	1,113,418	1,213,205	4,777,122	7,657,709	2,396,241	2,407,015	9,367,009	29,823,299
5	5,022,809	1,819,129	383,246	4,813,746	12,680,517	4,215,369	2,790,261	14,180,755	41,862,228
EIOM									
1	579,072	548,627	543,127	570,788	579,072	548,627	543,127	570,788	2,241,613
2	1,404,757	1,396,309	1,386,517	1,403,147	1,983,829	1,944,936	1,929,643	1,973,935	7,832,343
3	1,818,569	1,793,837	1,761,632	1,804,481	1,818,569	1,793,837	1,761,632	1,804,481	15,010,861
4	2,167,738	2,137,250	2,132,871	2,137,481	3,986,307	3,931,087	3,894,502	3,941,962	23,453,339
5	2,165,097	2,159,255	2,150,565	2,159,621	6,151,404	6,090,342	6,045,067	6,101,583	32,087,876

TABLE 7 Allocation of Costs

	Annual				Cumulative				
Year	Wayne	Washtenaw	St.Clair	Oakland	Wayne	Washtenaw	St.Clair	Oakland	Total
SBM									
1	400,000	0	0	1,200,000	400,000	0	0	1,200,000	1,600,000
2	720,000	0	0	870,000	1,120,000	0	0	2,070,000	3,190,000
3	578,000	450,000	0	645,000	578,000	450,000	0	645,000	4,863,000
4	1,055,000	45,000	0	575,000	1,633,000	495,000	0	1,220,000	6,538,000
5	365,000	45,000	0	1,353,500	1,998,000	540,000	0	2,573,500	8,301,500
NPCM									
1	400,000	480,000	530,000	150,000	400,000	480,000	530,000	150,000	1,560,000
2	289,000	303,000	433,000	575,000	689,000	783,000	963,000	725,000	3,160,000
3	461,500	141,500	251,000	826,000	461,500	141,500	251,000	826,000	4,840,000
4	844,500	491,000	192,000	137,500	1,306,000	632,500	443,000	963,500	6,505,000
5	398,484	620,500	75,000	685,000	1,704,484	1,253,000	518,000	1,648,500	8,283,984
EIOM									
1	230,000	340,000	750,000	250,000	230,000	340,000	750,000	250,000	1,570,000
2	343,000	614,000	430,000	205,000	573,000	954,000	1,180,000	455,000	3,162,000
3	417,000	331,000	543,500	386,000	417,000	331,000	543,500	386,000	4,839,500
4	168,500	675,000	666,500	169,000	585,500	1,006,000	1,210,000	555,000	6,518,500
5	195,000	348,000	913,500	304,500	780,500	1,354,000	2,123,500	859,500	8,279,500

Multi-objective Optimization

The MOBM results are shown in Figure 2. Pairwise comparison of two objectives are made in each of the sub-figure. Pareto front for each pairwise comparison shows the non-dominated and dominated solutions. The multi-objective optimization results shows the tradeoff between two objectives and provides the decision maker an array of solutions. Choice of a specific solution on the pareto front depends on the need and goal of the planning agency.

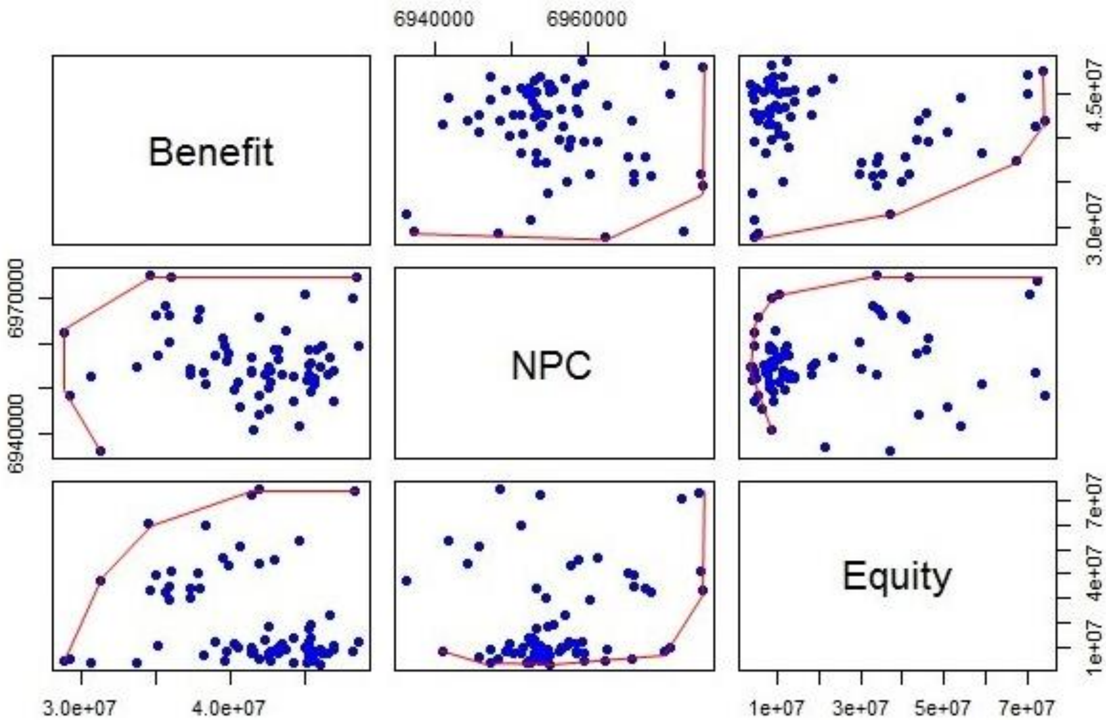
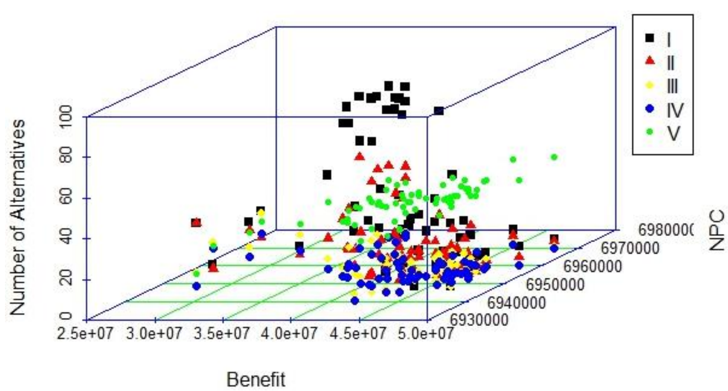
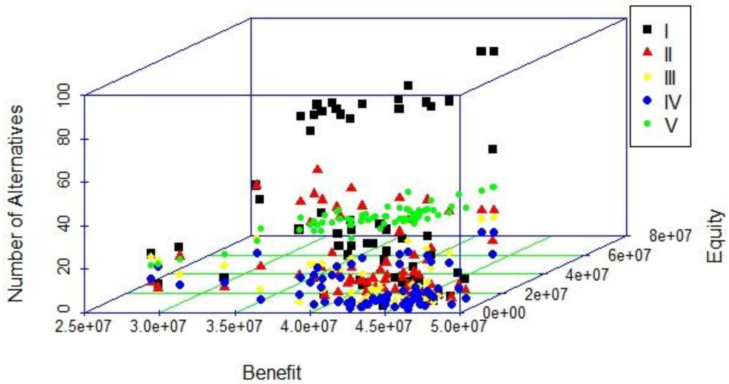


FIGURE 2 Pairwise Comparison of Objective Functions and Pareto Fronts.

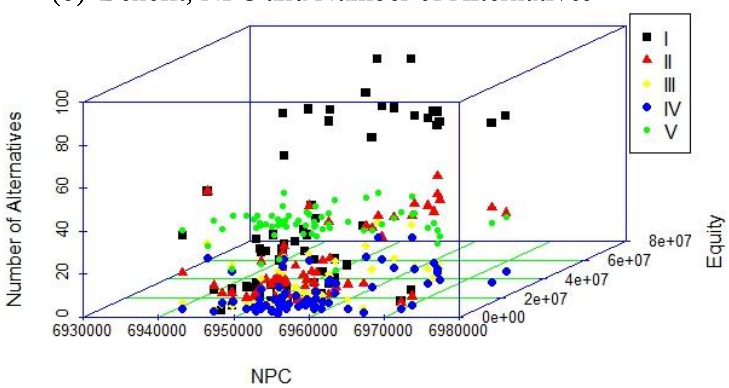
Further, in Figure 3 allocation of type of alternatives with variation of objective functions is presented. The multi-objective optimization results support the earlier findings in single objective optimization such as in case of SBM alternatives of type "IV", and "V" are selected. In case of NPCM more alternative type "I", and "II" are selected. In case of EIOM alternatives "III", "IV" and "V" are selected. Figure 3 presents an array of solutions for the planning agencies to further strengthen the highway safety resource allocation decision making.



(a) Benefit, NPC and Number of Alternatives



(b) Benefit, NPC and Number of Alternatives



(c) Benefit, NPC and Number of Alternatives

FIGURE 3 Sensitivity Analysis of Allocation of Alternatives with Varying Objective Functions.

Policy Implications

The models proposed in this paper address efficient resource allocation of safety alternatives to locations in such a way that optimal values of unique objectives are achieved. The four counties considered in this paper are part of the seven county area in south east Michigan, USA. The results of SBM shows that high cost alternatives are implemented in locations with potential of high economic crash cost savings. These locations may have high crash severity or high crash frequency or combinations of both. However, this trend is not seen in NPCM and EIOM as lower cost and equity becomes constraint in respective models. Available budget is another critical component of the safety resource allocation process. Depending on the available budget there is a likelihood that SBM model may result in inequitable funding allocation of majority of alternatives among counties. Since, economic competitiveness is embedded in the objective function represented by the maximization of safety benefits received from economic savings of crashes. In contrast, this disparity is not observed in the equity based allocation (EIOM). In combination all the models presented in this paper provides a set of optimization models for the decision maker to consider in the safety resource allocation. Further, MOBM model combined all objectives simultaneously to provide an array of solutions and tradeoffs between objective functions.

CONCLUSION

In this paper a set of performance measures typically considered by planning agencies for highway safety resource allocation are analyzed. These performance measures include safety benefit, NPC, and equity. Safety benefit is a quality measure while NPC is a cost measure. Equity is relatively subjective, and planning agencies typically aim to reduce inequality in highway safety resource allocation process. The performance measures are considered as objective functions and analyzed in an optimization modeling framework subject to real world policies, budgets and other constraints. Safety benefit is a maximization function, while NPC, and equity are minimization functions. The proposed model is robust in its formulation as it incorporates the random nature of crashes; 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 application is demonstrated using urban intersection data from four counties in Southeast Michigan, USA. Three types of models are proposed and demonstrated: (1) SBM, (2) NPCM, and (3) EIOM. SBM addresses crash severity which leads to optimal alternative distribution to critical crash locations. NPCM resulted in lowest total present value of allocated cost. EIOM resulted in fair distribution of benefits across counties in the region in such a way that equity in outcome is achieved. Further all objectives are analyzed simultaneously in a MOBM framework and a set of solutions are presented to enhance the flexibility of the decision maker in the event of considering trade-off between two or more objectives. The proposed and policy measures presented in this paper allow a state or regional agency to allocate resources efficiently within policy constraints. Additional research is needed to enhance the resource allocation process by considering other challenging policies considered by planning agencies, and to apply the proposed model for larger case study areas.

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