Optimal Funding Allocation Strategies for Safety Improvements on Urban Intersections

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ABSTRACT
Urban intersections crashes cause significant economic loss. The safety management process undertaken by most states in the United States is referred to as Highway Safety Improvement Program and consists of three standardized steps: (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. The literature review underlines the importance of the third step, and the lack of sophisticated tools available to state planning agencies for leveraging information obtained from the first two steps. Further, non-strategic approaches and unavailability of methods for evaluating policies may lead to sub-optimal funding 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. Proposed policy measures based on benefits maximization (economic competitiveness), equitable allocation (equity), and relaxation of mutually exclusiveness (multiple alternatives at one location) produce significantly different alternative and fund allocation. The proposed models are applied to selected intersections in four counties of southeast Michigan. Results reinforce the applicability of the strategies/policies and tools developed in this paper for safety project funding allocation on critical urban intersections.

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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 (USDOT, 2012). MAP-21 sanctioned continuation of the legacy Highway Safety Improvement Program (HSIP) as a core Federal-aid program. HSIP envisions significant reduction in traffic fatalities and serious injuries on the highway system. Under HSIP, State Departments of Transportation, along with the US Department of Transportation (USDOT), spend billions of dollars annually for safety improvements at urban intersections. In addition, the United Nations has named the present decade the "Decade of Action for Road Safety". The target of this campaign is to reduce the number of fatalities by 50%. In the highway safety arena, both national and worldwide goals include reducing the number of fatalities and serious injuries (UN, 2014).

The safety management process undertaken by most states is often referred to as the Highway Safety Improvement Program (HSIP), 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. 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.

Two critical components of a safety improvement program are crash prediction and funding allocation for preventative measures. The crash prediction component models the trajectory of future crashes. The traditional approach in crash prediction ignores randomness and assumes a deterministic growth factor for the number of crashes. This assumption intrinsically may lead to suboptimal allocation of highway safety improvements, and incorporating the random nature of crashes is critical to achieve robust safety alternative allocation. The second component of a safety improvement program is funding allocation. In this component, funds are distributed for implementing safety alternatives at pre-identified hazardous locations. Current state-level fund allocation strategies suffer from short-term planning, and inefficient/sub-optimal resource allocation due to the absence of optimization-based tools. Further, there is lack of: (i) concrete policies that maximize long-term safety benefits and (ii) policy tools to evaluate implementation and safety benefits. In this paper we focus on the second component of a safety improvement program and propose mathematical models that address the following research question:

"How to optimally allocate funding within a state for implementation of safety measures at locations with existing crash history within budget, planning period and strategic/policy constraints?"

To answer this question we propose an approach to optimize safety benefits in a given region by maximizing the dollar value from crash reduction at intersections over a multi-year planning horizon. The primary contributions of the paper are as follows:

- A resource allocation model is developed that assigns safety alternatives to locations based on crash types so the overall crash reduction benefits are maximized subject to budget and policy constraints.

- Three policy options based on federal and state vision plans are proposed and mathematically modeled to represent realistic issues encountered by the planning agencies during fund allocation:
    - The first policy maximizes total economic and safety benefits and is based on federal policy level goal of economic competiveness.
    - The second policy measure is equity consideration in the benefits and allocation of safety measures among counties.
    - The third policy relaxes the mutually-exclusive nature of improvements and allows locations to receive more than one improvement in a given year if doing so maximizes benefits while satisfying specified constraints.

The remainder of the paper is organized as follows: the 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 in the later sections. Finally, the models and results are summarized and recommendations for future research are outlined.

LITERATURE REVIEW

The literature review is organized into three sections: (1) highway safety resource allocation, (2) analytical methods of highway safety resource allocation and (3) equity-based policy measures in transportation planning. The review presented is by no means comprehensive; rather it captures 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 (AASHTO, 2010). Depending on the severity of crashes, investment in capital, operation and maintenance (O&M) costs may vary significantly. The literature contains a number of studies devoted to identifying 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 (Cook et al., 2001; Hauer, 1996; Hossain and Muromachi, 2012; Lambert et al., 2003; Lyon et al., 2007; Tarko and Kanodia, 2004). The key question remains with knowledge of pre-determined hazardous crash locations and available possible countermeasure, 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 maximization or minimization of an objective function comprising a set of decision variables, subject to various constraints (Bonini et al., 1997; Hillier and Lieberman, 2010). 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 (Rao, 1996; Wolsey and Nemhauser, 1999).

Resource allocation in highway safety improvement methods include application of mixed integer programming techniques, based on branch and bound algorithm for highway safety projects (Melachrinoudis and Kozanidis, 2002); linear programming techniques to maximize savings resulting from alcohol-crash reduction (Kar and Datta, 2004); linear programming to select safety and operational improvement on highway networks (Banihashemi, 2007); integer programing for reduction in crashes (Mishra and Khasnabis, 2012); integer programming to minimize total number of crashes (Pal and Sinha, 1998); linear programming for highway safety improvement alternatives (Chowdhury et al., 2000); and linear programming to incorporate uncertainty in safety resource allocation (Persaud and Kazakov, 1994).

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 few attempted multi-year allocations 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 (Melachrinoudis and Kozanidis, 2002). Since optimally considering proposed alternatives is a discrete decision variable, literature recommends application of complex integer programming (Rao, 1996).

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 (Duthie and Waller, 2008), ratio-based (Meng and Yang, 2002), or accessibility measures (Ferguson et al., 2012). This literature makes a sharp distinction between “equality of outputs” and “equality of outcomes” (Ferguson et al., 2012). “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.

MODEL FRAMEWORK

Figure 1 illustrates the conceptual methodology of the resource allocation model consisting of three steps: (1) crash prediction, (2) resource allocation, and (3) policy analysis. The crash prediction component consists of several sub-steps. The first task is to identify hazardous crash locations based on crash frequency and severity. Then, for each location, predominant crash patterns are derived. Further, appropriate countermeasures are designed based on these crash patterns. These steps leverage the information from the first two phases of the hazard elimination program (i.e. identification of hazardous locations and design of countermeasures) in modeling. Typically, crash prediction models are based on highway geometry, traffic, and roadside feature data. Readers should note that this research employ existing crash prediction models (not develop) and have included them in Figure 1 (as a precursor to step-2) for comprehensive representation.

Next, the resource allocation component involves mathematical modeling based approach to allocate improvements (proposed alternatives or countermeasures to reduce crashes) subject to budget and other constraints. In this step, the overall objective of resource allocation and policy constraints are finalized. Input data is fed into the optimization model and integrated with the crash prediction model. The next step is a policy analysis tool that involves a set of realistic scenarios and alternative ways to allocate resources. Both step-2 and step-3 are discussed in detail in the remaining sections of the paper.

<<Figure 1 Here>>

ECONOMIC COMPETITIVENESS-RESOURCE ALLOCATION MODEL (EC-RAM)

Economic competitiveness and safety are two of the five major goals of USDOT's strategic plan (USDOT 2012). Both of these goals can form the basis for policy options under a safety improvement program. The 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 crashes, injuries, and fatalities that is another way to measure the importance of prevention work. The average economic cost of crashes in 2011 is \$1,420,000/death for fatal crash, \$78,700/injury for nonfatal disabling injury and \$9,100/crash for property damage crash (including non-disabling injuries) (NSC 2011).

Hence, 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 I locations by implementing selected treatments from a set of J alternatives, over the proposed planning period of N years. Next we present the notation that will be used throughout the paper followed by the mathematical formulation of EC-RAM. Additional notations will be presented as needed.

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
$r_{ij}^{f,n}, r_{ij}^{m,n} r_{ij}^{p,n}$	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

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

$x_{ij}^n = \{0,1\}$	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)

The problem can then be formulated as follows:

EC-RAM: ***max*** $Z = \sum_{i,j,n} \left((\mu_i^{f,n} r_{ij}^f c^f + \mu_i^{m,n} r_{ij}^m c^m + \mu_i^{p,n} r_{ij}^p c^p) \sum_{n \geq k > n-l_j} x_{ij}^k \right)$ Equation 1

$\sum_{j \in J} x_{ij}^n \leq \gamma_i^n, \forall i \in I, n \in N$ Equation 2

$x_{ij}^n + \sum_{n-l_j < k < n} x_{ij}^k \leq 1, \forall i \in I, j \in J, n \in N$ Equation 3

$x_{ij}^n + \sum_{d \neq j \in J, n-l_d < k \leq n} x_{id}^k \leq \delta_i^n, \forall i \in I, j \in J, n \in N$ Equation 4

$\sum_{i \in I, j \in J} \left(x_{ij}^n \pi_{ij}^n + \rho_{ij}^n \sum_{n-l_j < k < n \in N} x_{ij}^k \right) \leq b^n, n \in N$ Equation 5

$x_{ij}^n = \{0,1\}, \forall i \in I, j \in J, n \in N$ Equation 6

with the convention that summation terms involving years are zero if the index is "out of range" (referring to a year not in *N*).

Equation 1 maximizes the total benefits from the reduction of crashes. Equation 2 ensures that at most γ alternatives can be implemented each year at a location. Equation 3 ensures the same alternative will not be active more than once during any given year. Equation 4 ensures that no more than δ alternatives will be active during any given year. Figure 2 presents a graphical illustration of equations 3 and 4. Figure 2 shows that during the planning period, a location is eligible to receive funding for either the same existing alternative, or a different alternative. Considering the mutually exclusive nature of alternatives, two alternatives (same or different) cannot be simultaneously implemented at the same location. Equation-3 suggests that when an alternative is active in a location, the same alternative cannot be implemented till the end of effective service life of the same alternative. Graphically, in the upper part of Figure 2 it is shown that an alternative *j* of four years of service life ($l_j=4$) when implemented in the year *n-4*, it remains effective till year *n*, and no new alternative cannot be implemented during this four year of service life. In the year *n*, when the service life of the alternative is completed, the location is eligible for re-implementation of the same alternative. Equation 4 suggests that 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. Equation 4 is illustrated in the lower part of Figure 2. When an alternative *d* of service life three years ($l_d=3$) is implemented in year *n - 3*, then it remains active till year *n* and no other alternative can be implemented between the time period *n -*

3 and *n* years. But in the year *n*, the location is eligible to receive a different alternative *j*, with a service life of 4 years ($l_j=4$). From year *n* to $n + 4$ years no other alternative can be implemented. Figure 2 demonstrate the underlying concept presented in equation 3 and 4 by taking examples of two alternatives (*j* and *d*) of service life of four and three years ($l_j=4; l_d=3$) respectively. Equation 5 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. Finally, equation 6 defines the decision variable as binary.

<<Figure 2 Here>>

Equity in outcome

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. Because equity is a largely subjective measure, we introduce two formulations expressing different ways to quantify equity in outcome:

> ***EPC1-RAM:*** In this model formulation, the objective is unchanged but constraints are added restricting the maximum difference in benefits the decision maker wishes to allow. For example, the decision maker would like to keep the difference in benefits from various jurisdictions (example counties) to be minimum. Then EPC1-RAM allows the decision maker to provide an *a priori* value to ensure the level of equity.
>
> ***EPC2-RAM:*** This model formulation does not depend on any *a priori* value from the decision maker. Rather, the model objective function is now designed provide equity in outcome distribution of benefits. The advantage of EPC2-RAM is that it is free from assumption of equity parameter.

To address equity in outcome policy let the sets S_h partition I (that is, $S_1 \cup S_2 \cup S_3 \cup .. \cup S_h .... \cup S_l = I, S_k \cup S_h = \varnothing \forall S_k, S_h$ †). Also let H and R be nonnegative real variables. To simultaneously maximizes total benefits received by all locations while accounting for equity in outcome we introduce equations 7 through 10 to EC-RAM (from now we refer to this new formulation as EPC1-RAM).

$$H \geq \sum_{i \in S_h, j, n} \left[(\mu_i^{f,n} r_{ij}^f c^f + \mu_i^{m,n} r_{ij}^m c^m + \mu_i^{p,n} r_{ij}^p c^p) \sum_{n \geq k > n - l_j} x_{ij}^k \right] \forall S_h \qquad \text{Equation 7}$$

$$R \leq \sum_{i \in S_h, j, n} \left[(\mu_i^{f,n} r_{ij}^f c^f + \mu_i^{m,n} r_{ij}^m c^m + \mu_i^{p,n} r_{ij}^p c^p) \sum_{n \geq k > n - l_j} x_{ij}^k \right] \forall S_h \qquad \text{Equation 8}$$

$$H - R \leq a \sum_{i, j, n} \left[(\mu_i^{f,n} r_{ij}^f c^f + \mu_i^{m,n} r_{ij}^m c^m + \mu_i^{p,n} r_{ij}^p c^p) \sum_{n \geq k > n - l_j} x_{ij}^k \right] \qquad \text{Equation 9}$$

$$H, R \geq 0 \qquad \text{Equation 10}$$

† From a practical standpoint these might represent the locations corresponding to counties or districts within a state

Equations (7) and (8) estimate the benefits of the subset of locations with the maximum and minimum benefits respectively. Equation (9) restricts the difference of the benefits of these two subsets to a percentage of the total benefits received by all locations (right hand side of equation 9). Equation (10) defines variables *H* and *R* as nonnegative real variables. Parameter *a* acts as a uniformity coefficient. As $a \to 1$ the solution of EPC1-RAM approaches the solution of EC-RAM‡ (when *a*=1 EPC1-RAM is equivalent to EC-RAM as equation (9) is redundant i.e. both models have the same feasible region and objective function). The smaller the value of *a*, the more uniform is the distribution of benefits among the different subsets of locations (e.g. if *a*=0 then all subsets of locations will receive the same benefits) and the smaller the total benefits as compared to EC-RAM policy. The proposed formulation is always feasible for any *a≥0* because of the trivial solution $x_{ij}^{n} = 0, \forall i \in I, j \in J, n \in N$.

One of the issues of EPC1-RAM is to provide the decision maker with an *a priori* lower bound for *a* so that, at least, a nontrivial solution also exists. To address this issue we propose a second formulation that does not require the use of *a*. The new formulation maximizes the benefits of the subset of locations receiving the least benefits and is formulated as a max-min problem (from now on referred to as EPC2-RAM). As will be seen in the model application section, EPC2-RAM provides the most equitable solution. EPC2-RAM, which is equivalent to EPC1-RAM when $a \cong 0$ and a nontrivial feasible solution exists, can be formulated as follows:

EPC2-RAM: $$\max\left(\min_{S_h} \sum_{i \in S_h, j, n} \left[(\mu_i^{f,n} r_{ij}^{f} c^{f} + \mu_i^{m,n} r_{ij}^{m} c^{m} + \mu_i^{p,n} r_{ij}^{p} c^{p}) \sum_{n \geq k > n - l_j} x_{ij}^{k} \right]\right)$$ Equation 11

s.t.
Equations (2)-(6)

To avoid the complexity of the max-min objective function we introduce a positive variable Ω (equation 12) and constraints set shown in equation (13).

$$\Omega \geq 0$$ Equation 12

$$\Omega \leq \sum_{i \in S_h, j, n} \left((\mu_i^{f,n} r_{ij}^{f} c^{f} + \mu_i^{m,n} r_{ij}^{m} c^{m} + \mu_i^{p,n} r_{ij}^{p} c^{p}) \sum_{n \geq k > n - l_j} x_{ij}^{k} \right), \forall S_h \in I$$ Equation 13

EPC2-RAM is then reformulated as follows:

EPC2-RAM: $$\max(\Omega)$$ Equation 14

s.t.
Equations (2)-(6) & (12)-(13)

Equity in opportunity

EPC1-RAM and EPC2-RAM address equity in opportunity indirectly (and in the authors opinion effectively). However, political, administrative, or other constraints may require equity in

‡ EPC1-RAM may provide the same solution as EC-RAM for *a*<1 depending on the input data. Irrespective of the input data when *a*=1 both models provide the same assignment and objective function value

opportunity (i.e. pre-allocation of specific funds per subset of locations) to be more explicitly modeled. Next, we present a model that accomplishes this goal.

The equity in opportunity policy model is derived from EC-RAM by defining a minimum budget for a subset of locations through equation (15) where $\beta_{S_h}^n, \varepsilon_{S_h}^n$ are the minimum amounts which must be spent in year n for capital and operating costs at the subset of locations S_h, respectively. For the new problem formulation (referred to as EOC-RAM) to be feasible, equations (16) and (17) must hold true. Unlike equation (15), the latter two equations are not part of the optimization model but rather a pre-modeling process. The rationale behind equations (16) and (17) is to guarantee sufficient funding allocation to a subset of locations so that at least one alternative is implemented at a year n and maintained for its lifespan; otherwise any funds allocated at that year will be unused.

$$\sum_{i \in S_h, j} \left(x_{ij}^n \pi_{ij}^n + \rho_{ij}^n \sum_{n-l_j < k < n \in N} x_{ij}^k \right) \geq \beta_{S_h}^n + \varepsilon_{S_h}^n, \forall n \in N \qquad \text{Equation 15}$$

$$\beta_{S_h}^n \geq \min_{i \in S_h, j} \pi_{ij}^n, \forall S_h, n \in N \qquad \text{Equation 16}$$

$$\varepsilon_{S_h}^{n+k} \geq \min_{i \in S_h, j} \rho_{ij}^k, \forall S_h, n \in N : l_j + n > k > n \qquad \text{Equation 17}$$

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 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[§] cost of crash savings is presented in Figure 3 (SEMCOG 2008) for each intersection, sub-grouped by county. Figure 3 show that locations in Oakland County have the highest and St. Clair County the least probable cost of crash savings.

<<Figure 3 Here>>

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

[§] The term probable is used as crash predictions and crash reduction factors are derived from probabilistic models 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 (Khasnabis et al., 2006).

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 (Bahar et al., 2008). 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[**], 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 Here>>

RESULTS

Results from the model application are presented in a series of tables. 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. Alternative allocation and total benefits by county is presented in Table 4 and 5 respectively. Budget allocation by county is shown in Table 6. Lastly, equity in opportunity results are presented in Table A1 through A3.

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

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

are used in the remainder of the paper for unused budget for the annual and planning periods, respectively.

Table 2 summarizes results of the three proposed models in order: EC-RAM; EPC2-RAM, and EPC1-RAM. For each model results are shown (1) when alternatives are mutually exclusive (δ=γ=1), and (2) when each location is eligible to receive up to two alternatives (δ=γ=2).

When alternatives are mutually exclusive (δ=γ=1) EC-RAM resulted in probable cost of total crash cost saving of $72.24 million. Wayne County received $24.89 million, Washtenaw County received $4 million, Oakland County received $43.34 million, and St. Clair received no funding. The potential for Oakland County to receive higher benefits was known prior to the optimization. The model resulted in confirming SEMCOG's intuition in allocating higher cost to Oakland County. For EPC2-RAM to total benefits is $52.44 million. The total benefit received in EPC2-RAM is much less than EC-RAM. As per the formulation EPC2-RAM it is expected to have equitable allocation of resources with objective of maximizing total benefit. All the counties received little over $13 million benefits in the planning period. In contrast, allocation for EPC1-RAM will vary with chosen weights (*a*). 20 solutions for EPC1-RAM is presented in Table 2. When the value of the weight is 0.05 the benefit resulted is $52.09 million and allocation is nearly equitable. With increasing value of the weight total benefits increased. When the value of the weight is close to one the solution resembled with EC-RAM.

<<Table 2 Here>>

When the mutually exclusive nature of alternative allocation is relaxed (δ=γ=2) EC-RAM resulted in total benefit of $79.56 million (versus $72.24 million when mutually exclusiveness of alternative is considered). A $7.32 million of higher benefits are accrued with relaxation of mutually exclusiveness. It is noticed that benefits are increased for Oakland County and decreased for Wayne and Washtenaw, while St. Clair has not received any benefits. Increase in benefits for EPC2-RAM and EPC1- RAM is observed for when δ=γ=2.

Table 3(a) shows detailed annualized allocations and type of alternatives chosen for EC-RAM when alternatives are mutually exclusive. In the first year 11 alternatives are allocated. Out of these 10 "V" and one "IV" alternative are chosen. Total benefit received is $6.68 million at the expense of $1.6 million leaving no surplus. For EC-RAM overall 50 alternatives were chosen yielding benefit of $72.24 million with capital and operation cost as $7.0 and $1.29 million respectively leaving a surplus of $22,500. The surplus suggests that the optimization model did not find an optimal combination of alternatives any better to make the surplus to be zero in a planning period of five years. It should be noted that the optimization model is solved with an annual budget constraint, and each year the surplus is less than the least cost of an alternative. For EPC2-RAM the allocation is different in a number of ways. The total number of alternatives allocated is 53, leading to a benefit of $52.44 million. The capital and O&M cost and surplus is very similar to EC-RAM. For EPC1-RAM only four solutions are presented for *a = 0.1, 0.25, 0.5, and 0.75*. One noticeable pattern observed in EPC1-RAM is that total number of alternatives, capital cost, O&M cost and surplus remained same with different values of "*a*". The reason is the optimization model obtained different allocation strategies among various counties but could do little to the alternative allocation because of the budget constraint. For a lower value of "*a*" the benefit distribution among counties are more equitable and vice versa.

<<Table 3(a) and 3(b) Here>>

Similar pattern is observed in Table 3(b) when the mutually exclusive nature of the alternatives is relaxed. Some noticeable differences include (1) higher benefits for all individual years, (2) higher capital and O&M cost, (3) lesser remaining surplus for EC-RAM and EPC2-RAM, (4) unequal surplus for EPC1-RAM with variation of "*a*", and (5) increased number of alternatives allocated in each model.

Table 4(a) shows number of alternatives allocated to each county b year when $\delta=\gamma=1$. In the first year Wayne and Oakland counties have received three and eight alternatives respectively. From Table 3(a) 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 models in Table 4(a). Table 4(b) shows allocation of alternatives when $\delta=\gamma=2$. The pattern in this case is similar to Table 4(a).

<<Table 4(a) and 4(b) Here>>

Table 5(a) shows benefit distribution across counties by individual year when $\delta=\gamma=1$. For EC-RAM in the first year Oakland and Wayne received \$5.15 and \$1.53 million respectively. In the second year, Oakland and Wayne received \$7.94 and \$3.64 million respectively in the form of new projects. First year benefits were carried over to the second year (as the alternatives chosen for implementation has service life of four years). At the end of second year total cumulative benefits is \$18.27 million. Similarly benefits for other years can be interpreted. For EPC2-RAM the optimization model allocated resources in such a way that at the end of the planning period each county has received equitable benefits. However, allocation is not equitable in each year (as it was not objective of the model). For EPC1-RAM the allocation is more or less equitable but the equity depends on the user defined parameter "*a*". With a lower value of "*a*", the distribution is more equitable and vice versa. Table 5(b) shows benefit distribution across counties by individual year when $\delta=\gamma=2$. The allocation pattern in Table 5(b) is similar to Table 5(a) with some differences: (1) the total benefit received is higher, (2) counties with more potential to produce more benefit received higher benefits when $\delta=\gamma=2$, and (3) the marginal benefits are higher in the later years of the planning period than the initial years.

<<Table 5(a) and 5(b) Here>>

Equity in opportunity

To evaluate the effectiveness of EPC1-RAM and EPC2-RAM in addressing the equity in opportunity policy we compared their budget allocation to an assignment with the optimal equity in opportunity. To estimate the latter we modified EPC2-RAM (from now on referred to as EOC2-RAM) where equation (13) was replaced with equation (18):

$$\Omega \leq \left(\sum_{i,j} \left(x_{ij}^{n} \pi_{ij}^{n} + \rho_{ij}^{n} \sum_{n-l_j<k<n\in N} x_{ij}^{k} \right) \right), \forall S_h \in I \qquad \text{Equation 18}$$

EOC2-RAM (similar to EPC2-RAM) maximizes the budget allocated to the subset of locations receiving the least budget (but does not consider benefits). Budget assignment results from all the models are shown in tables 6a and 6b where we observe that results from EPC2-RAM and EPC1-RAM with low values of α are close to the results from EOC-RAM. On the other hand the total benefits obtained from EOC-RAM where roughly $48 million (detailed results similar to those presented in tables 4 through 6 are shown in Appendix A).

<<**Tables 6a and 6b Here**>>

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.

DISCUSSION

To use quantitative resource allocation models such as these, transportation planning agencies should maintain a complete and reliable crash database. The database should be prepared for each year would ideally include (a) annual frequency of crashes each location on the highway system (both intersections and mid-blocks) and severity of each crash, (b) predominant type of crashes, (c) condition diagram, (d) collision diagram, (e) design of probable countermeasures as alternatives, (f) crash reduction factors of alternatives, (g) capital and operation maintenance cost of each designed alternative, (h) service life of alternatives, (i) traffic volume classification, and (j) signal timings. A comprehensive database will enable the planning agencies to efficiently design probable countermeasures and utilize appropriate resource allocation models in a multi-year framework to prioritize locations." A discussion on proposed model transferability, flexibility, and policy implications are presented below.

Transferability

The models presented in the paper are generic and can be applied to any geographic area types (urban, suburban, and rural). The case study presented in the paper is based on a set of location in an urban area. However, if the models are to be applied for other area types then alternatives may change. For example, an urban signalized intersection experiencing pedestrian crashes, a pedestrian countdown signal may be an alternative (with heavy volume of non-motorized transport). In contrast, at a rural intersection experiencing read-end or angle crashes, improving horizontal and vertical clearances should be considered as an alternative. Alternatives are typically developed based upon engineering judgment, an analysis of the probable causes of the crashes, such that the likelihood of future crashes, (or severe injuries resulting from future crashes) is reduced. Once the alternatives are well designed for any area typologies, and their respective capital cost, operation and maintenance cost, and service life are determined, then the models presented in this paper can be applied for both urban and non-urban areas.

Flexibility

In this paper, a set of 80 locations are analyzed, where each location has up to five probable countermeasures (alternatives) that can potentially be implemented. The analysis period is five years. The total number of decision variables for one model is 2000 (80×5×5). The optimization problem is implemented in GAMS and MATLAB, on a 3.4 GHz Intel Core i7-3770 desktop computer, with 24 GB of memory, and running 64-bit Windows 7 operating system. The average CPU time was less than two minutes per problem instance. Flexibility analysis was conducted and a number of scenarios are developed with the available data. The flexibility analysis includes three tests to analyze the robustness of the algorithm: (1) with varying planning periods, (2) with varying number of locations, (3) with varying budgets. Table 7 shows variation in planning periods with different budgets. With one year planning period and $1.6 million budget the optimal benefit received is $22.02 million. Capital, operation and maintenance cost are $1.23 and $0.36 million respectively. The number of alternatives implemented is nine and the remaining surplus is $1,500. Table 7 shows that the benefits increases with increasing number of years and budget and so as all other outputs of the model (capital cost, O&M cost, and number of alternatives). The surplus does not follow any specific trend as the number of alternatives allocated is different for various planning periods (and cost of the allocated alternatives is different).

<<**Tables 7 Here**>>

Table 8 shows flexibility analysis based on number of locations. For all cases in Table 8 a constant five years of planning period and budget of $8.32 million is considered. The distribution of number of locations is uniform among all the four counties. As expected, the benefits decrease with lesser number of locations. For example, when eight locations are considered benefits received is $9.27 million and 10 alternatives are implemented during the five years of planning period.

<<**Tables 8 Here**>>

Flexibility of budget is shown in Figure 4. Variation in budget, corresponding safety benefits and number of selected alternatives is presented in Figure 4(a). The relationship between three measures is not linear. Each observation in Figure 4(a) represents a model run. For the same budget scenarios capital cost and surplus is shown in Figure 4(b). Surplus does not follow a specific trend as the number of alternatives (and their respective capital and O&M cost) is different for each budget optimization scenario.

<<**Figure 4**>>

Crash Prediction Models

In multi-year resource allocation models, prediction of crashes are done for use in the analysis in the future years. Typically future year crashes are obtained from crash prediction models (CPM) and are crucial for determining effectiveness of results. CPM are based on probability theory and potential limitations of these models exists based on various assumptions such as estimation procedure, functional form of crashes, variables included in the model estimation, vehicle exposure, traffic conditions, and data uncertainties due to sampling errors (Lord and Mannering, 2010; Miaou and Lum, 1993; Washington et al., 2011). Inputs from CPM are crucial to the accuracy of the models results and should be carefully developed for real life applications. However, results from CPM were exogenous to the optimization model. So any error from the CPM may vary the specific results of the case study presented in the paper but not the effectiveness and applicability of the overall methodology. The proposed model is a decision tool for investment given inputs for the CPM. Improvement of CPM will improve the accuracy of the predictions (i.e. objective function value) from the model but not the solution (i.e. given the input data the decision produced will always be optimal). In real life applications, CPM should be developed accurately in conjunction with an efficient resource allocation model for distributing available budget effectively in a multi-year planning period.

Policy Implications

The models proposed in this paper address efficient resource allocation of safety alternatives to locations in such a way that the total benefits received from economic value from crash reduction are maximized. The four counties considered in this paper are part of the seven county area in south east Michigan, USA. The results of EC-RAM 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 EPC1-RAM and EPC2-RAM as equity becomes another constraint. Available budget is another critical component of the safety resource allocation process. Depending on the available budget there is a likelihood that EC-RAM 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 (EPC1-RAM, and EPC2-RAM). 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.

CONCLUSION

This paper presents set of policies and an analysis tool, founded on integrated highway safety resource allocation model. The basic optimization based resource/fund allocation model is based on economic competitiveness of crash locations thereby allowing improvements to be implemented at locations producing maximum benefits. 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 working of the proposed model is demonstrated using signalized urban intersection data from four counties in Southeast Michigan, USA. Four types of models are proposed and demonstrated: (1) economic competitiveness (EC-RAM), (2) equity in outcome model-1 (EPC1-RAM), (3) equity in outcome model-2 (EPC2-RAM), and (4) equity in opportunity (EOC2-RAM). The objective of all models was to maximize benefits received from prevention of crashes. Two variants of above four models are discussed; where alternatives were mutually exclusive; and where there is relaxation to mutually exclusiveness nature of alternatives. The economic competitiveness model also addresses crash severity which leads to optimal alternative distribution to critical crash locations. EC-RAM resulted in highest benefit in the planning period but resulted in inequitable distribution of number of improvements and benefits to the counties. However, such policy results in low benefits and relatively unequal allocation of alternatives to certain counties or subset of locations. To address the inequity, equity in outcome and equity in opportunity policies are proposed that allows equitable distribution of alternatives and benefits respectively. The first equity in outcome model, EPC1-RAM provides flexibility to the decision maker to a set of achieve equitable distribution of benefits based on a desired parameter. The flexibility of EPC1-RAM provides the decision maker to choose between multiple solutions. EPC2-RAM provides the most equitable resource allocation possible given the budget and policy constraints. Both EPC1-RAM and EPC2-RAM address equity in opportunity indirectly as well. Lastly, EOC2-RAM, provides equity in opportunity by providing similar budgets to the counties in an expectation to maximize safety benefits. EOC2-RAM produced least amount of benefit among all models. The approach and policy measures presented in this paper allow a state or regional agency to allocate resources efficiently within policy constraints.

The contribution of this study to research and practice is threefold. First, the development of an integrated model that mutually selects exclusive alternatives, through an optimization process, satisfying budgetary and other constraints. Second, a policy constraint application that allows not only analysis of one base case but also explores various policy options (equity in outcome and opportunity and relaxation of mutually exclusiveness nature of alternatives). 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, and to consider equity and benefit in a multi-objective modeling framework.

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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

Table 2: Summary of Probable Cost of Crash Savings in Multi-year Planning Period

	δ=γ=1						
Instance	Model	Weights	Wayne	Washtenaw	St. Clair	Oakland	All Locations
1	EC-RAM	Not Applicable	$24,891,117	$4,004,758	$-	$43,347,611	$72,243,487
2	EPC2-RAM	Not Applicable	$13,111,554	$13,104,344	$13,105,102	$13,124,181	$52,445,182
3	EPC1-RAM	0.05	$15,021,261	$12,731,122	$12,292,858	$15,044,809	$55,090,050
4		0.1	$17,174,190	$11,938,341	$11,407,884	$17,175,151	$57,695,566
5		0.15	$19,499,625	$10,744,724	$10,480,338	$19,515,117	$60,239,803
6		0.2	$21,551,503	$10,426,513	$9,054,938	$21,576,751	$62,609,704
7		0.25	$24,066,682	$8,969,043	$7,852,260	$24,098,337	$64,986,323
8		0.3	$26,393,124	$7,925,512	$6,296,173	$26,381,653	$66,996,461
9		0.35	$28,855,576	$6,329,034	$4,822,979	$28,961,234	$68,968,822
10		0.4	$30,832,888	$5,388,676	$3,000,639	$31,123,085	$70,345,288
11		0.45	$30,437,045	$5,608,257	$1,567,935	$33,605,618	$71,218,855
12		0.5	$28,615,494	$4,881,999	$1,215,368	$37,077,749	$71,790,610
13		0.55	$26,976,029	$4,447,959	$525,108	$40,196,398	$72,145,494
14		0.6	$24,812,031	$4,004,758	$78,765	$43,347,611	$72,243,165
15		0.65	$24,891,117	$4,004,758	$-	$43,347,611	$72,243,487
16		0.7	$24,891,117	$4,004,758	$-	$43,347,611	$72,243,487
17		0.75	$24,871,463	$4,004,758	$-	$43,365,902	$72,242,123
18		0.8	$24,891,117	$4,004,758	$-	$43,347,611	$72,243,487
19		0.85	$24,871,463	$4,004,758	$-	$43,365,902	$72,242,123
20		0.9	$24,891,117	$4,004,758	$-	$43,347,611	$72,243,487
21		0.95	$24,891,117	$4,004,758	$-	$43,347,611	$72,243,487
22		1	$24,891,117	$4,004,758	$-	$43,347,611	$72,243,487
	δ=γ=2						
Instance	Model	Weights	Wayne	Washtenaw	St. Clair	Oakland	All Locations
1	EC-RAM	Not Applicable	$23,339,493	$2,270,282	$-	$53,960,218	$79,569,994
2	EPC2-RAM	Not Applicable	$14,362,221	$14,350,945	$14,357,167	$14,469,895	$57,540,228
3	EPC1-RAM	0.05	$16,392,078	$13,584,583	$13,438,440	$16,428,661	$59,843,762
4		0.1	$18,689,808	$12,519,766	$12,477,069	$18,665,987	$62,352,629
5		0.15	$21,039,941	$11,460,612	$11,320,922	$21,046,064	$64,867,539
6		0.2	$23,472,532	$10,180,979	$10,044,379	$23,458,553	$67,156,443
7		0.25	$26,072,664	$8,805,134	$8,678,652	$26,064,028	$69,620,478
8		0.3	$28,504,255	$7,860,104	$6,975,878	$28,525,183	$71,865,421
9		0.35	$30,826,028	$6,977,134	$5,103,014	$30,941,083	$73,847,259
10		0.4	$33,315,355	$5,437,062	$3,228,083	$33,363,816	$75,344,317
11		0.45	$32,895,678	$5,023,189	$2,098,618	$36,530,121	$76,547,606
12		0.5	$31,687,974	$4,588,210	$1,264,480	$40,001,707	$77,542,370
13		0.55	$28,848,327	$4,662,895	$911,912	$43,971,672	$78,394,806
14		0.6	$28,137,469	$3,363,037	$78,765	$47,483,559	$79,062,831
15		0.65	$25,127,819	$2,722,318	$-	$51,594,972	$79,445,108
16		0.7	$22,523,416	$2,150,403	$-	$54,902,374	$79,576,193
17		0.75	$23,199,249	$2,270,282	$-	$54,109,543	$79,579,074
18		0.8	$23,339,493	$2,270,282	$-	$53,965,236	$79,575,011
19		0.85	$23,339,493	$2,270,282	$-	$53,960,218	$79,569,994
20		0.9	$23,021,186	$2,058,165	$-	$54,471,438	$79,550,788
21		0.95	$22,632,793	$2,058,165	$-	$54,891,016	$79,581,974
22		1	$22,396,969	$2,270,282	$-	$54,907,331	$79,574,582

Table 3a: Summary of Allocation for a Five Year Planning Period for Proposed Policies ($\delta=\gamma=1$)

EC-RAM												
	Alternative											
Year	I	II	III	IV	V	Total	Benefit($)	Allocated($)	O&MCost($)	Budget($)	Surplus($)	Cumulative($)
1	0	0	0	1	10	11	$6,682,835	$1,600,000	$-	$1,600,000	$-	$-
2	0	0	1	0	9	10	$11,591,440	$1,430,000	$160,000	$1,600,000	$10,000	$10,000
3	1	0	0	0	9	10	$15,759,287	$1,370,000	$303,000	$1,680,000	$7,000	$17,000
4	0	1	0	0	8	9	$19,441,599	$1,235,000	$440,000	$1,680,000	$5,000	$22,000
5	1	0	0	0	9	10	$18,768,326	$1,370,000	$393,500	$1,764,000	$500	$22,500
Total	2	1	1	1	45	50	$72,243,487	$7,005,000	$1,296,500	$8,324,000	$22,500	
EPC2-RAM												
1	0	0	0	1	10	11	$3,403,639	$1,600,000	$-	$1,600,000	$-	$-
2	0	0	1	0	9	10	$6,776,171	$1,430,000	$160,000	$1,600,000	$10,000	$10,000
3	1	0	0	0	9	10	$11,430,027	$1,370,000	$303,000	$1,680,000	$7,000	$17,000
4	0	5	0	0	7	12	$15,556,848	$1,225,000	$440,000	$1,680,000	$15,000	$32,000
5	1	0	0	0	9	10	$15,278,497	$1,370,000	$392,500	$1,764,000	$1,500	$33,500
Total	2	5	1	1	44	53	$52,445,182	$6,995,000	$1,295,500	$8,324,000	$33,500	
EPC1-RAM, *a*=0.1												
1	0	0	0	1	10	11	$3,901,792	$1,600,000	$-	$1,600,000	$-	$-
2	0	0	1	0	9	10	$8,546,834	$1,430,000	$160,000	$1,600,000	$10,000	$10,000
3	1	0	0	0	9	10	$12,796,916	$1,370,000	$303,000	$1,680,000	$7,000	$17,000
4	0	1	0	0	8	9	$16,511,638	$1,235,000	$440,000	$1,680,000	$5,000	$22,000
5	1	0	0	0	9	10	$15,938,387	$1,370,000	$393,500	$1,764,000	$500	$22,500
Total	2	1	1	1	45	50	$57,695,566	$7,005,000	$1,296,500	$8,324,000	$22,500	
EPC1-RAM, *a*=0.25												
1	0	0	0	1	10	11	$5,318,622	$1,600,000	$-	$1,600,000	$-	$-
2	0	0	1	0	9	10	$10,216,402	$1,430,000	$160,000	$1,600,000	$10,000	$10,000
3	1	0	0	0	9	10	$14,295,835	$1,370,000	$303,000	$1,680,000	$7,000	$17,000
4	0	1	0	0	8	9	$17,885,927	$1,235,000	$440,000	$1,680,000	$5,000	$22,000
5	1	0	0	0	9	10	$17,269,537	$1,370,000	$393,500	$1,764,000	$500	$22,500
Total	2	1	1	1	45	50	$64,986,323	$7,005,000	$1,296,500	$8,324,000	$22,500	
EPC1-RAM, *a*=0.5												
1	0	0	0	1	10	11	$6,551,214	$1,600,000	$-	$1,600,000	$-	$-
2	0	0	1	0	9	10	$11,499,847	$1,430,000	$160,000	$1,600,000	$10,000	$10,000
3	1	0	0	0	9	10	$15,709,950	$1,370,000	$303,000	$1,680,000	$7,000	$17,000
4	0	1	0	0	8	9	$19,342,920	$1,235,000	$440,000	$1,680,000	$5,000	$22,000
5	1	0	0	0	9	10	$18,686,678	$1,370,000	$393,500	$1,764,000	$500	$22,500
Total	2	1	1	1	45	50	$71,790,610	$7,005,000	$1,296,500	$8,324,000	$22,500	
EPC1-RAM,*a*=0.75												
1	0	0	0	1	10	11	$6,678,174	$1,600,000	$-	$1,600,000	$-	$-
2	0	0	1	0	9	10	$11,591,440	$1,430,000	$160,000	$1,600,000	$10,000	$10,000
3	1	0	0	0	9	10	$15,759,287	$1,370,000	$303,000	$1,680,000	$7,000	$17,000
4	0	1	0	0	8	9	$19,441,599	$1,235,000	$440,000	$1,680,000	$5,000	$22,000
5	1	0	0	0	9	10	$18,771,623	$1,370,000	$393,500	$1,764,000	$500	$22,500
Total	2	1	1	1	45	50	$72,242,123	$7,005,000	$1,296,500	$8,324,000	$22,500	

Table 3b: Summary of Allocation for a Five Year Planning Period for Proposed Policies (δ=γ=2)

EC-RAM												
	Alternative											
Year	I	II	III	IV	V	Total	Benefit ($)	Allocated ($)	O&M Cost ($)	Budget ($)	Surplus ($)	Cumulative ($)
1	0	0	0	7	6	13	$6,982,269	$1,600,000	$-	$1,600,000	$-	$-
2	0	1	0	5	6	12	$12,621,438	$1,435,000	$160,000	$1,600,000	$5,000	$5,000
3	1	0	0	3	7	11	$17,490,544	$1,370,000	$303,500	$1,680,000	$6,500	$11,500
4	0	6	1	2	5	14	$21,534,595	$1,240,000	$437,000	$1,680,000	$3,000	$14,500
5	0	1	1	5	5	12	$20,941,148	$1,365,000	$399,000	$1,764,000	$-	$14,500
Total	1	8	2	22	29	62	$79,569,994	$7,010,000	$1,299,500	$8,324,000	$14,500	
EPC2-RAM												
1	0	0	0	7	6	13	$4,076,116	$1,600,000	$-	$1,600,000	$-	$-
2	0	1	0	2	8	11	$8,265,544	$1,435,000	$160,000	$1,600,000	$5,000	$5,000
3	1	0	0	3	7	11	$12,837,438	$1,370,000	$303,500	$1,680,000	$6,500	$11,500
4	0	16	1	0	4	21	$16,347,895	$1,240,000	$437,000	$1,680,000	$3,000	$14,500
5	1	1	0	4	6	12	$16,013,234	$1,355,000	$399,000	$1,764,000	$10,000	$24,500
Total	2	18	1	16	31	68	$57,540,228	$7,000,000	$1,299,500	$8,324,000	$24,500	
EPC1-RAM, *a*=0.1												
1	0	0	0	7	6	13	$4,300,196	$1,600,000	$-	$1,600,000	$-	$-
2	0	1	0	2	8	11	$9,321,106	$1,435,000	$160,000	$1,600,000	$5,000	$5,000
3	0	0	2	3	6	11	$13,716,430	$1,360,000	$303,500	$1,680,000	$16,500	$21,500
4	0	6	1	2	5	14	$17,622,292	$1,240,000	$436,000	$1,680,000	$4,000	$25,500
5	1	4	0	3	6	14	$17,352,562	$1,360,000	$400,000	$1,764,000	$4,000	$29,500
Total	1	11	3	17	31	63	$62,312,587	$6,995,000	$1,299,500	$8,324,000	$29,500	
EPC1-RAM, *a*=0.25												
1	0	0	0	4	8	12	$5,379,413	$1,600,000	$-	$1,600,000	$0	$0
2	0	0	0	5	6	11	$10,473,689	$1,400,000	$160,000	$1,600,000	$40,000	$40,000
3	0	0	1	4	6	11	$15,476,408	$1,380,000	$300,000	$1,680,000	$0	$40,000
4	0	11	0	1	5	17	$19,390,949	$1,235,000	$438,000	$1,680,000	$7,000	$47,000
5	0	3	0	2	7	12	$18,819,432	$1,355,000	$401,500	$1,764,000	$7,500	$54,500
Total	0	14	1	16	32	63	$69,539,890	$6,970,000	$1,299,500	$8,324,000	$54,500	
EPC1-RAM, *a*=0.5												
1	0	0	0	4	8	12	$6,375,071	$1,600,000	$-	$1,600,000	$-	$-
2	0	1	0	5	6	12	$12,379,750	$1,435,000	$160,000	$1,600,000	$5,000	$5,000
3	1	0	0	6	5	12	$17,092,129	$1,370,000	$303,500	$1,680,000	$6,500	$11,500
4	0	4	0	2	6	12	$21,093,279	$1,240,000	$437,000	$1,680,000	$3,000	$14,500
5	0	1	1	2	7	11	$20,668,145	$1,365,000	$399,000	$1,764,000	$-	$14,500
Total	1	6	1	19	32	59	$77,608,374	$7,010,000	$1,299,500	$8,324,000	$14,500	
EPC1-RAM, *a*=0.75												
1	0	0	0	7	6	13	$6,967,433	$1,600,000	$-	$1,600,000	$-	$-
2	0	1	0	5	6	12	$12,621,438	$1,435,000	$160,000	$1,600,000	$5,000	$5,000
3	1	0	0	3	7	11	$17,495,537	$1,370,000	$303,500	$1,680,000	$6,500	$11,500
4	0	4	0	2	6	12	$21,536,688	$1,240,000	$437,000	$1,680,000	$3,000	$14,500
5	0	1	1	5	5	12	$20,950,207	$1,365,000	$399,000	$1,764,000	$-	$14,500
Total	1	6	1	22	30	60	$79,571,302	$7,010,000	$1,299,500	$8,324,000	$14,500	

Table 4a: Allocation of Alternatives to Counties by Proposed Strategies (δ=γ=1)

Model	Year	Yearly					Cumulative				
		Wayne	Washtenaw	St. Clair	Oakland	Total	Wayne	Washtenaw	St. Clair	Oakland	Total
EC-RAM	1	3	-	-	8	11	3	-	-	8	11
	2	4	-	-	6	10	7	-	-	14	21
	3	4	3	-	3	10	11	3	-	17	31
	4	7	-	-	2	9	18	3	-	19	40
	5	2	-	-	8	10	20	3	-	27	50
EPC2-RAM	1	1	2	8	-	11	1	2	8	-	11
	2	2	3	4	1	10	3	5	12	1	21
	3	2	4	1	3	10	5	9	13	4	31
	4	3	2	2	5	12	8	11	15	9	43
	5	1	2	7	-	10	9	13	22	9	53
EPC1-RAM, *a*=0.1	1	1	3	6	1	11	1	3	6	1	11
	2	4	-	3	3	10	5	3	9	4	21
	3	2	4	1	3	10	7	7	10	7	31
	4	4	2	1	2	9	11	9	11	9	40
	5	1	3	5	1	10	12	12	16	10	50
EPC1-RAM, *a*=0.25	1	4	2	3	2	11	4	2	3	2	11
	2	3	1	2	4	10	7	3	5	6	21
	3	3	2	2	3	10	10	5	7	9	31
	4	6	1	1	1	9	16	6	8	10	40
	5	4	2	2	2	10	20	8	10	12	50
EPC1-RAM, *a*=0.5	1	5	-	-	6	11	5	-	-	6	11
	2	2	2	1	5	10	7	2	1	11	21
	3	5	1	-	4	10	12	3	1	15	31
	4	6	-	1	2	9	18	3	2	17	40
	5	4	-	-	6	10	22	3	2	23	50
EPC1-RAM, *a*=0.75	1	2	-	-	9	11	2	-	-	9	11
	2	5	-	-	5	10	7	-	-	14	21
	3	4	3	-	3	10	11	3	-	17	31
	4	7	-	-	2	9	18	3	-	19	40
	5	1	-	-	9	10	19	3	-	28	50

Table 4b: Allocation of Alternatives to Counties by Proposed Strategies (δ=γ=2)

Model	Year	Yearly					Cumulative				
		Wayne	Washtenaw	St. Clair	Oakland	Total	Wayne	Washtenaw	St. Clair	Oakland	Total
EC-RAM	1	3	-	-	10	13	3	-	-	10	13
	2	3	-	-	9	12	6	-	-	19	25
	3	5	-	-	6	11	11	-	-	25	36
	4	5	4	-	5	14	16	4	-	30	50
	5	2	-	-	10	12	18	4	-	40	62
EPC2-RAM	1	2	3	8	-	13	2	3	8	-	13
	2	2	4	3	2	11	4	7	11	2	24
	3	2	1	3	5	11	6	8	14	7	35
	4	5	7	5	4	21	11	15	19	11	56
	5	2	3	7	-	12	13	18	26	11	68
EPC1-RAM, *a*=0.1	1	2	5	6	-	13	2	5	6	-	13
	2	5	1	2	3	11	7	6	8	3	24
	3	3	2	3	3	11	10	8	11	6	35
	4	1	3	4	6	14	11	11	15	12	49
	5	2	5	7	-	14	13	16	22	12	63
EPC1-RAM, *a*=0.25	1	6	1	4	1	12	6	1	4	1	12
	2	3	3	1	4	11	9	4	5	5	23
	3	2	1	2	6	11	11	5	7	11	34
	4	5	4	3	5	17	16	9	10	16	51
	5	6	1	4	1	12	22	10	14	17	63
EPC1-RAM, *a*=0.5	1	9	-	-	3	12	9	-	-	3	12
	2	2	-	-	10	12	11	-	-	13	24
	3	3	3	1	5	12	14	3	1	18	36
	4	6	2	1	3	12	20	5	2	21	48
	5	8	-	-	3	11	28	5	2	24	59
EPC1-RAM, *a*=0.75	1	3	-	-	10	13	3	-	-	10	13
	2	3	-	-	9	12	6	-	-	19	25
	3	5	-	-	6	11	11	-	-	25	36
	4	3	4	-	5	12	14	4	-	30	48
	5	2	-	-	10	12	16	4	-	40	60

Table 5a: Distribution of Benefits Across Counties According To Proposed Strategies (δ=γ=1)

Model	Year	Yearly					Cumulative				
		Wayne	Washtenaw	St. Clair	Oakland	Total	Wayne	Washtenaw	St. Clair	Oakland	Total
EC-RAM	1	$1,531,364	$-	$-	$5,151,471	$6,682,835	$1,531,364	$-	$-	$5,151,471	$6,682,835
	2	$3,644,502	$-	$-	$7,946,938	$11,591,440	$5,175,866	$-	$-	$13,098,409	$18,274,275
	3	$5,045,450	$1,308,556	$-	$9,405,281	$15,759,287	$10,221,316	$1,308,556	$-	$22,503,690	$34,033,562
	4	$7,688,900	$1,334,956	$-	$10,417,743	$19,441,599	$17,910,216	$2,643,512	$-	$32,921,433	$53,475,161
	5	$6,980,902	$1,361,247	$-	$10,426,178	$18,768,326	$24,891,117	$4,004,758	$-	$43,347,611	$72,243,487
EPC2-RAM	1	$708,677	$859,936	$1,835,026	$-	$3,403,639	$708,677	$859,936	$1,835,026	$-	$3,403,639
	2	$1,853,454	$1,971,623	$2,646,239	$304,856	$6,776,171	$2,562,130	$2,831,558	$4,481,265	$304,856	$10,179,810
	3	$2,989,732	$3,268,914	$2,709,167	$2,462,214	$11,430,027	$5,551,862	$6,100,473	$7,190,432	$2,767,070	$21,609,837
	4	$3,740,611	$3,468,294	$3,059,526	$5,288,417	$15,556,848	$9,292,473	$9,568,767	$10,249,958	$8,055,487	$37,166,685
	5	$3,819,081	$3,535,577	$2,855,145	$5,068,694	$15,278,497	$13,111,554	$13,104,344	$13,105,102	$13,124,181	$52,445,182
EPC1-RAM, *a*=0.1	1	$708,677	$1,257,682	$1,565,068	$370,365	$3,901,792	$708,677	$1,257,682	$1,565,068	$370,365	$3,901,792
	2	$2,927,041	$1,282,892	$2,217,367	$2,119,534	$8,546,834	$3,635,718	$2,540,573	$3,782,435	$2,489,899	$12,448,625
	3	$3,503,401	$2,655,116	$2,439,669	$4,198,729	$12,796,916	$7,139,119	$5,195,690	$6,222,104	$6,688,628	$25,245,541
	4	$4,988,327	$3,338,831	$2,668,650	$5,515,829	$16,511,638	$12,127,446	$8,534,521	$8,890,754	$12,204,457	$41,757,179
	5	$5,046,744	$3,403,820	$2,517,130	$4,970,694	$15,938,387	$17,174,190	$11,938,341	$11,407,884	$17,175,151	$57,695,566
EPC1-RAM, *a*=0.25	1	$2,353,109	$859,936	$784,055	$1,321,523	$5,318,622	$2,353,109	$859,936	$784,055	$1,321,523	$5,318,622
	2	$3,578,707	$1,282,892	$1,303,472	$4,051,331	$10,216,402	$5,931,816	$2,142,827	$2,087,527	$5,372,854	$15,535,024
	3	$4,562,032	$2,011,034	$1,781,638	$5,941,130	$14,295,835	$10,493,848	$4,153,861	$3,869,166	$11,313,984	$29,830,859
	4	$6,839,814	$2,383,950	$2,041,196	$6,620,967	$17,885,927	$17,333,662	$6,537,811	$5,910,362	$17,934,951	$47,716,786
	5	$6,733,021	$2,431,232	$1,941,898	$6,163,386	$17,269,537	$24,066,682	$8,969,043	$7,852,260	$24,098,337	$64,986,323
EPC1-RAM, *a*=0.5	1	$2,591,629	$-	$-	$3,959,585	$6,551,214	$2,591,629	$-	$-	$3,959,585	$6,551,214
	2	$3,631,283	$877,240	$157,353	$6,833,971	$11,499,847	$6,222,912	$877,240	$157,353	$10,793,555	$18,051,061
	3	$5,820,181	$1,308,556	$160,450	$8,420,763	$15,709,950	$12,043,094	$2,185,796	$317,803	$19,214,318	$33,761,011
	4	$8,330,603	$1,334,956	$527,665	$9,149,696	$19,342,920	$20,373,697	$3,520,752	$845,468	$28,364,014	$53,103,931
	5	$8,241,798	$1,361,247	$369,899	$8,713,735	$18,686,678	$28,615,494	$4,881,999	$1,215,368	$37,077,749	$71,790,610
EPC1-RAM, *a*=0.75	1	$960,117	$-	$-	$5,718,057	$6,678,174	$960,117	$-	$-	$5,718,057	$6,678,174
	2	$3,644,502	$-	$-	$7,946,938	$11,591,440	$4,604,619	$-	$-	$13,664,995	$18,269,614
	3	$5,045,450	$1,308,556	$-	$9,405,281	$15,759,287	$9,650,069	$1,308,556	$-	$23,070,276	$34,028,901
	4	$7,688,900	$1,334,956	$-	$10,417,743	$19,441,599	$17,338,969	$2,643,512	$-	$33,488,019	$53,470,500
	5	$7,532,494	$1,361,247	$-	$9,877,883	$18,771,623	$24,871,463	$4,004,758	$-	$43,365,902	$72,242,123

Table 5b: Distribution of Benefits Across Counties According To Proposed Strategies (δ=γ=2)

Model	Year	Yearly					Cumulative				
		Wayne	Washtenaw	St.Clair	Oakland	Total	Wayne	Washtenaw	St.Clair	Oakland	Total
EC-RAM	1	$1,493,992	$-	$-	$5,488,277	$6,982,269	$1,493,992	$-	$-	$5,488,277	$6,982,269
	2	$3,021,042	$-	$-	$9,600,396	$12,621,438	$4,515,034	$-	$-	$15,088,673	$19,603,707
	3	$5,345,355	$-	$-	$12,145,189	$17,490,544	$9,860,388	$-	$-	$27,233,862	$37,094,251
	4	$6,851,520	$1,124,080	$-	$13,558,994	$21,534,595	$16,711,909	$1,124,080	$-	$40,792,856	$58,628,845
	5	$6,627,585	$1,146,202	$-	$13,167,362	$20,941,148	$23,339,493	$2,270,282	$-	$53,960,218	$79,569,994
EPC2-RAM	1	$1,154,842	$1,129,996	$1,791,279	$-	$4,076,116	$1,154,842	$1,129,996	$1,791,279	$-	$4,076,116
	2	$1,898,051	$2,428,672	$2,501,887	$1,436,933	$8,265,544	$3,052,893	$3,558,668	$4,293,166	$1,436,933	$12,341,660
	3	$3,052,409	$2,827,190	$3,109,174	$3,848,665	$12,837,438	$6,105,303	$6,385,858	$7,402,339	$5,285,599	$25,179,099
	4	$4,234,121	$3,944,286	$3,584,638	$4,584,850	$16,347,895	$10,339,424	$10,330,144	$10,986,978	$9,870,449	$41,526,994
	5	$4,022,797	$4,020,801	$3,370,190	$4,599,446	$16,013,234	$14,362,221	$14,350,945	$14,357,167	$14,469,895	$57,540,228
EPC1-RAM, *a*=0.1	1	$1,154,842	$1,644,361	$1,500,994	$-	$4,300,196	$1,154,842	$1,644,361	$1,500,994	$-	$4,300,196
	2	$3,346,978	$2,083,041	$1,994,329	$1,896,758	$9,321,106	$4,501,819	$3,727,402	$3,495,323	$1,896,758	$13,621,302
	3	$4,586,356	$2,827,190	$2,524,818	$3,778,066	$13,716,430	$9,088,176	$6,554,592	$6,020,141	$5,674,824	$27,337,733
	4	$4,685,905	$3,382,974	$3,177,101	$6,376,313	$17,622,292	$13,774,080	$9,937,566	$9,197,242	$12,051,137	$44,960,025
	5	$4,784,378	$2,916,434	$3,150,140	$6,501,610	$17,352,562	$18,558,459	$12,853,999	$12,347,382	$18,552,747	$62,312,587
EPC1-RAM, *a*=0.25	1	$3,160,689	$434,468	$1,070,010	$714,245	$5,379,413	$3,160,689	$434,468	$1,070,010	$714,245	$5,379,413
	2	$4,430,212	$1,424,008	$1,358,823	$3,260,645	$10,473,689	$7,590,901	$1,858,476	$2,428,833	$3,974,891	$15,853,101
	3	$5,268,034	$1,866,193	$1,802,514	$6,539,667	$15,476,408	$12,858,935	$3,724,669	$4,231,347	$10,514,558	$31,329,509
	4	$6,583,489	$2,693,475	$2,200,848	$7,913,136	$19,390,949	$19,442,424	$6,418,144	$6,432,195	$18,427,694	$50,720,458
	5	$6,480,217	$2,746,782	$2,111,884	$7,480,549	$18,819,432	$25,922,642	$9,164,926	$8,544,080	$25,908,243	$69,539,890
EPC1-RAM, *a*=0.5	1	$4,288,469	$-	$-	$2,086,603	$6,375,071	$4,288,469	$-	$-	$2,086,603	$6,375,071
	2	$5,233,931	$-	$-	$7,145,819	$12,379,750	$9,522,400	$-	$-	$9,232,421	$18,754,821
	3	$6,118,328	$1,175,662	$352,568	$9,445,572	$17,092,129	$15,640,728	$1,175,662	$352,568	$18,677,993	$35,846,950
	4	$8,167,277	$1,903,884	$452,300	$10,569,818	$21,093,279	$23,808,004	$3,079,546	$804,868	$29,247,811	$56,940,229
	5	$7,490,927	$1,941,368	$459,612	$10,776,239	$20,668,145	$31,298,931	$5,020,914	$1,264,480	$40,024,050	$77,608,374
EPC1-RAM, *a*=0.75	1	$1,493,992	$-	$-	$5,473,442	$6,967,433	$1,493,992	$-	$-	$5,473,442	$6,967,433
	2	$3,021,042	$-	$-	$9,600,396	$12,621,438	$4,515,034	$-	$-	$15,073,838	$19,588,871
	3	$5,345,355	$-	$-	$12,150,182	$17,495,537	$9,860,388	$-	$-	$27,224,020	$37,084,408
	4	$6,455,792	$1,124,080	$-	$13,956,816	$21,536,688	$16,316,180	$1,124,080	$-	$41,180,835	$58,621,096
	5	$6,223,841	$1,146,202	$-	$13,580,164	$20,950,207	$22,540,022	$2,270,282	$-	$54,760,999	$79,571,302

Table 6a: Budget Allocation by year and subset of locations (δ=γ=1)

Model	Year	County				
		Wayne	Washtenaw	St. Clair	Oakland	Total
EOC2-RAM	1	$ 1,350,000	$ -	$ 250,000	$ -	$ 1,600,000
	2	$ 135,000	$ -	$ 1,055,000	$ 400,000	$ 1,590,000
	3	$ 135,000	$ 900,000	$ 298,000	$ 340,000	$ 1,673,000
	4	$ 155,000	$ 860,000	$ 445,000	$ 220,000	$ 1,680,000
	5	$ 302,000	$ 317,000	$ 370,000	$ 765,000	$ 1,754,000
	Total	$ 2,077,000	$ 2,077,000	$ 2,418,000	$ 1,725,000	
EC-RAM	1	$ 400,000	$ -	$ -	$ 1,200,000	$ 1,600,000
	2	$ 640,000	$ -	$ -	$ 950,000	$ 1,590,000
	3	$ 570,000	$ 450,000	$ -	$ 653,000	$ 1,673,000
	4	$ 1,082,000	$ 45,000	$ -	$ 548,000	$ 1,675,000
	5	$ 368,500	$ 45,000	$ -	$ 1,350,000	$ 1,763,500
	Total	$ 3,060,500	$ 540,000	$ -	$ 4,701,000	
EPC2-RAM	1	$ 150,000	$ 300,000	$ 1,150,000	$ -	$ 1,600,000
	2	$ 315,000	$ 480,000	$ 715,000	$ 80,000	$ 1,590,000
	3	$ 345,000	$ 675,000	$ 195,000	$ 458,000	$ 1,673,000
	4	$ 295,000	$ 205,000	$ 477,000	$ 688,000	$ 1,665,000
	5	$ 232,000	$ 412,000	$ 1,010,000	$ 108,500	$ 1,762,500
	Total	$ 1,337,000	$ 2,072,000	$ 3,547,000	$ 1,334,500	
EPC1-RAM, *a*=0.1	1	$ 150,000	$ 450,000	$ 900,000	$ 100,000	$ 1,600,000
	2	$ 615,000	$ 45,000	$ 540,000	$ 390,000	$ 1,590,000
	3	$ 245,000	$ 645,000	$ 285,000	$ 498,000	$ 1,673,000
	4	$ 577,000	$ 405,000	$ 300,000	$ 393,000	$ 1,675,000
	5	$ 273,500	$ 540,000	$ 825,000	$ 125,000	$ 1,763,500
	Total	$ 1,860,500	$ 2,085,000	$ 2,850,000	$ 1,506,000	
EPC1-RAM, *a*=0.25	1	$ 600,000	$ 300,000	$ 400,000	$ 300,000	$ 1,600,000
	2	$ 440,000	$ 180,000	$ 340,000	$ 630,000	$ 1,590,000
	3	$ 418,000	$ 345,000	$ 370,000	$ 540,000	$ 1,673,000
	4	$ 915,000	$ 225,000	$ 250,000	$ 285,000	$ 1,675,000
	5	$ 738,500	$ 360,000	$ 375,000	$ 290,000	$ 1,763,500
	Total	$ 3,111,500	$ 1,410,000	$ 1,735,000	$ 2,045,000	
EPC1-RAM, *a*=0.5	1	$ 700,000	$ -	$ -	$ 900,000	$ 1,600,000
	2	$ 370,000	$ 300,000	$ 80,000	$ 840,000	$ 1,590,000
	3	$ 850,000	$ 180,000	$ 8,000	$ 635,000	$ 1,673,000
	4	$ 1,075,000	$ 45,000	$ 158,000	$ 397,000	$ 1,675,000
	5	$ 795,000	$ 45,000	$ 15,000	$ 908,500	$ 1,763,500
	Total	$ 3,790,000	$ 570,000	$ 261,000	$ 3,680,500	
EPC1-RAM, *a*=0.75	1	$ 250,000	$ -	$ -	$ 1,350,000	$ 1,600,000
	2	$ 775,000	$ -	$ -	$ 815,000	$ 1,590,000
	3	$ 570,000	$ 450,000	$ -	$ 653,000	$ 1,673,000
	4	$ 1,082,000	$ 45,000	$ -	$ 548,000	$ 1,675,000
	5	$ 363,500	$ 45,000	$ -	$ 1,355,000	$ 1,763,500
	Total	$ 3,040,500	$ 540,000	$ -	$ 4,721,000	

Table 6b: Budget Allocation by year and subset of locations (δ=γ=2)

Model	Year	County				
		Wayne	Washtenaw	St. Clair	Oakland	Total
EOC2-RAM	1	$ 920,000	$ -	$ 635,000	$ 35,000	$ 1,590,000
	2	$ 232,000	$ 355,000	$ 463,500	$ 543,500	$ 1,594,000
	3	$ 256,000	$ 205,500	$ 595,000	$ 619,000	$ 1,675,500
	4	$ 325,000	$ 797,000	$ 449,500	$ 101,500	$ 1,673,000
	5	$ 340,000	$ 720,000	$ 301,000	$ 398,000	$ 1,759,000
	Total	$ 2,073,000	$ 2,077,500	$ 2,444,000	$ 1,697,000	
EC-RAM	1	$ 350,000	$ -	$ -	$ 1,250,000	$ 1,600,000
	2	$ 435,000	$ -	$ -	$ 1,160,000	$ 1,595,000
	3	$ 725,000	$ -	$ -	$ 948,500	$ 1,673,500
	4	$ 610,000	$ 370,000	$ -	$ 697,000	$ 1,677,000
	5	$ 402,000	$ 37,000	$ -	$ 1,325,000	$ 1,764,000
	Total	$ 2,522,000	$ 407,000	$ -	$ 5,380,500	
EPC2-RAM	1	$ 250,000	$ 400,000	$ 950,000	$ -	$ 1,600,000
	2	$ 210,000	$ 540,000	$ 545,000	$ 300,000	$ 1,595,000
	3	$ 343,500	$ 240,000	$ 540,000	$ 550,000	$ 1,673,500
	4	$ 405,000	$ 580,000	$ 470,000	$ 222,000	$ 1,677,000
	5	$ 263,500	$ 512,500	$ 884,000	$ 94,000	$ 1,754,000
	Total	$ 1,472,000	$ 2,272,500	$ 3,389,000	$ 1,166,000	
EPC1-RAM, *a*=0.1	1	$ 250,000	$ 600,000	$ 750,000	$ -	$ 1,600,000
	2	$ 610,000	$ 210,000	$ 375,000	$ 400,000	$ 1,595,000
	3	$ 413,500	$ 375,000	$ 435,000	$ 440,000	$ 1,663,500
	4	$ 148,000	$ 325,000	$ 553,000	$ 650,000	$ 1,676,000
	5	$ 341,500	$ 472,000	$ 809,500	$ 137,000	$ 1,760,000
	Total	$ 1,763,000	$ 1,982,000	$ 2,922,500	$ 1,627,000	
EPC1-RAM, *a*=0.25	1	$ 800,000	$ 150,000	$ 500,000	$ 150,000	$ 1,600,000
	2	$ 430,000	$ 365,000	$ 200,000	$ 565,000	$ 1,560,000
	3	$ 345,000	$ 200,000	$ 315,000	$ 820,000	$ 1,680,000
	4	$ 543,000	$ 385,000	$ 310,000	$ 435,000	$ 1,673,000
	5	$ 833,500	$ 232,000	$ 497,000	$ 194,000	$ 1,756,500
	Total	$ 2,951,500	$ 1,332,000	$ 1,822,000	$ 2,164,000	
EPC1-RAM, *a*=0.5	1	$ 1,150,000	$ -	$ -	$ 450,000	$ 1,600,000
	2	$ 365,000	$ -	$ -	$ 1,230,000	$ 1,595,000
	3	$ 410,000	$ 400,000	$ 150,000	$ 713,500	$ 1,673,500
	4	$ 837,000	$ 290,000	$ 50,000	$ 500,000	$ 1,677,000
	5	$ 1,032,000	$ 65,000	$ 18,500	$ 648,500	$ 1,764,000
	Total	$ 3,794,000	$ 755,000	$ 218,500	$ 3,542,000	
EPC1-RAM, *a*=0.75	1	$ 350,000	$ -	$ -	$ 1,250,000	$ 1,600,000
	2	$ 435,000	$ -	$ -	$ 1,160,000	$ 1,595,000
	3	$ 725,000	$ -	$ -	$ 948,500	$ 1,673,500
	4	$ 475,000	$ 370,000	$ -	$ 832,000	$ 1,677,000
	5	$ 388,500	$ 37,000	$ -	$ 1,338,500	$ 1,764,000
	Total	$ 2,373,500	$ 407,000	$ -	$ 5,529,000	

Table 7: Flexibility Analysis with Varying Planning Periods (80 locations)

Planning Period	Budget	Benefit	Capital Cost	O&M Cost	Surplus	# of Alternatives
1 Year	$1,600,000	$22,024,905	$1,235,000	$363,500	$1,500	9
2 Years	$3,200,000	$40,484,200	$2,450,000	$735,000	$15,000	17
3 Years	$4,880,000	$54,389,797	$3,820,000	$1,057,000	$3,000	27
4 Years	$6,560,000	$64,099,721	$5,290,000	$1,270,000	$0	40
5 Years	$8,324,000	$72,245,290	$7,005,000	$1,296,500	$22,500	50

Table 8: Flexibility Analysis with varying locations (five years of planning period)

Number of Locations	Benefit	Capital Cost	O&M Cost	Surplus	# of Alternatives
80	$72,245,290	$7,005,000	$1,296,500	$22,500	50
60	$70,090,675	$7,005,000	$1,296,500	$22,500	50
40	$29,408,267	$4,640,000	$888,500	$2,795,500	34
20	$19,430,951	$3,250,000	$450,000	$4,624,000	22
12	$13,244,687	$2,250,000	$270,000	$5,804,000	15
8	$9,276,307	$1,500,000	$180,000	$6,644,000	10

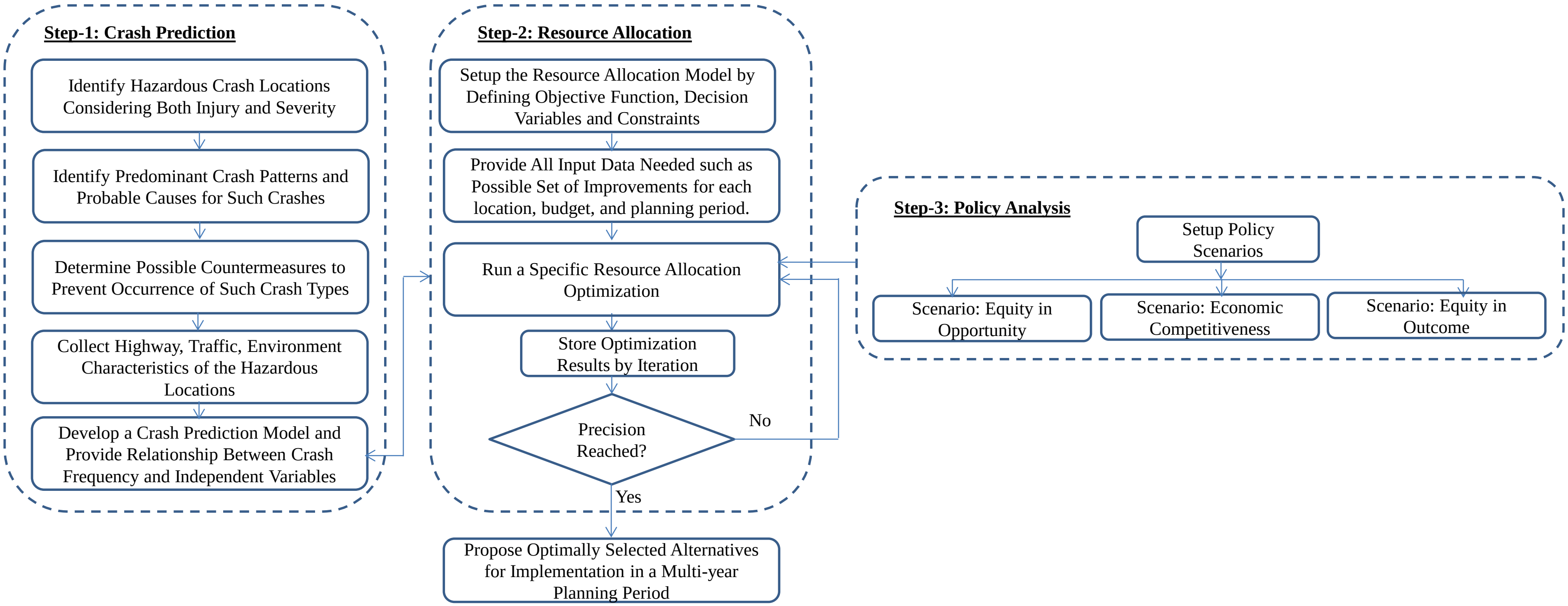


Fig. 1. Proposed Methodology for Resource Allocation
(Note: Step-1 is not discussed or analyzed in this paper but showed in the figure as it is a preliminary process for Step-2)

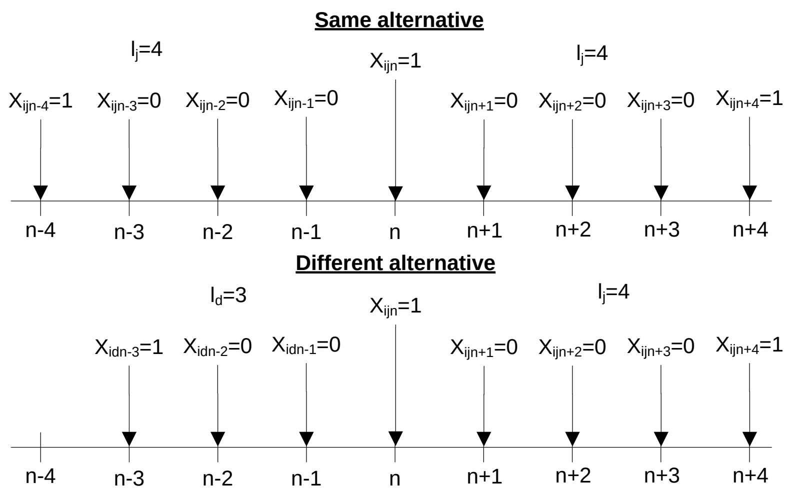


Fig. 2. Schematic example of equations 3 through 6

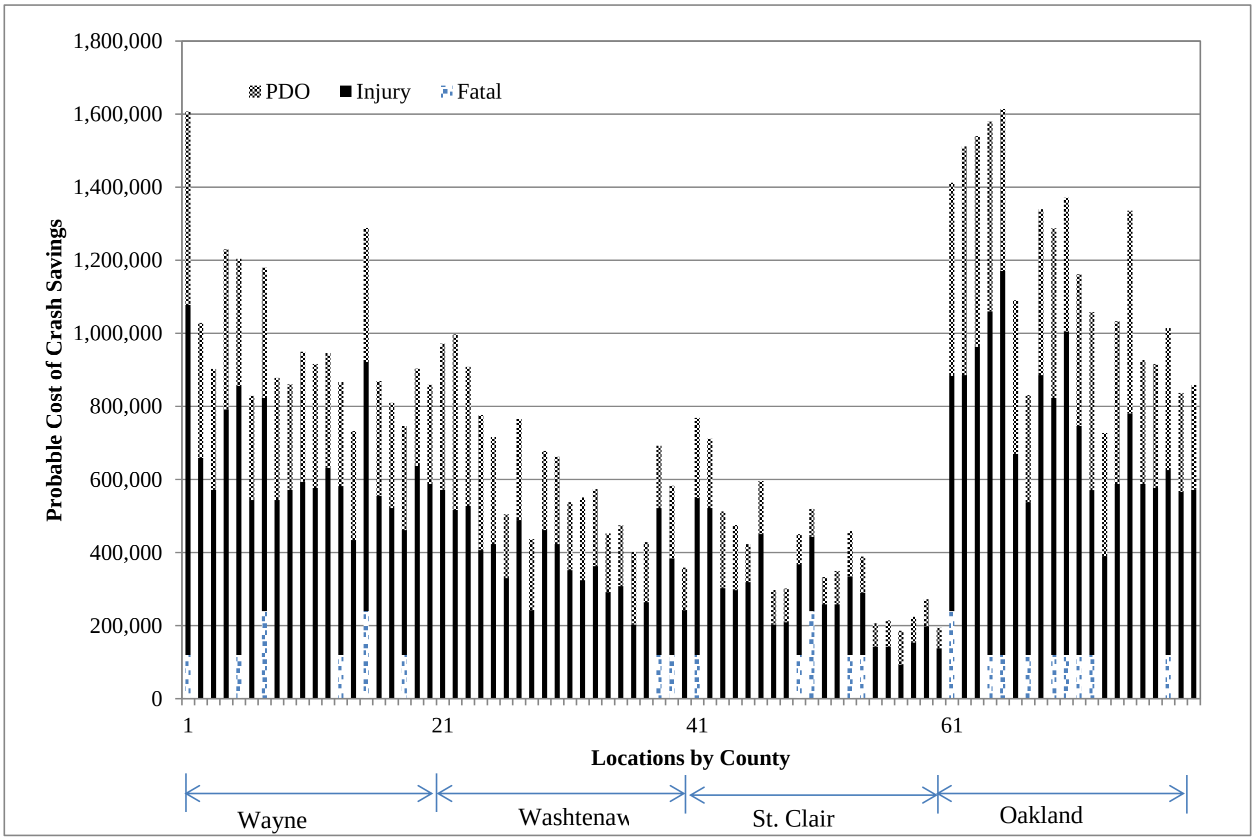
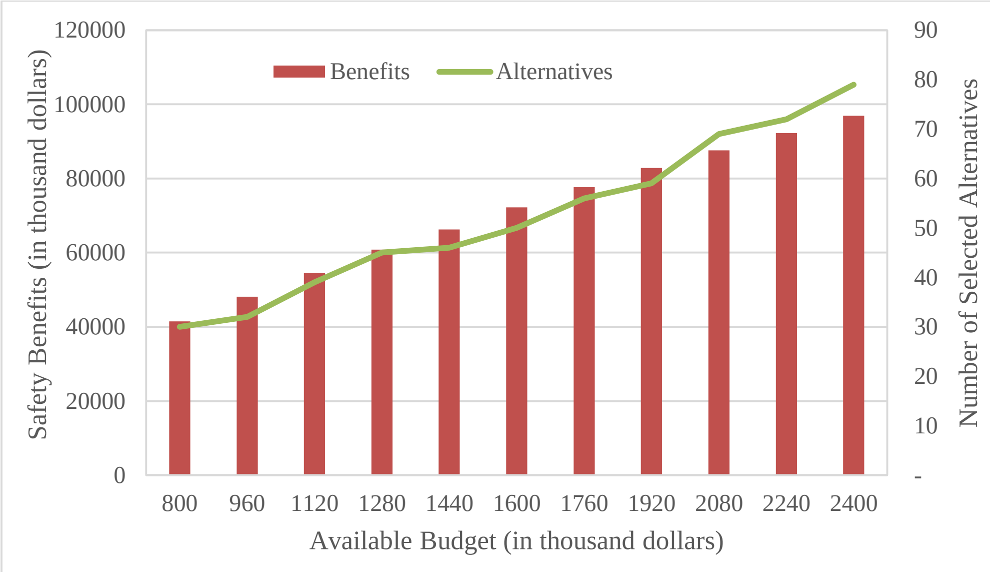
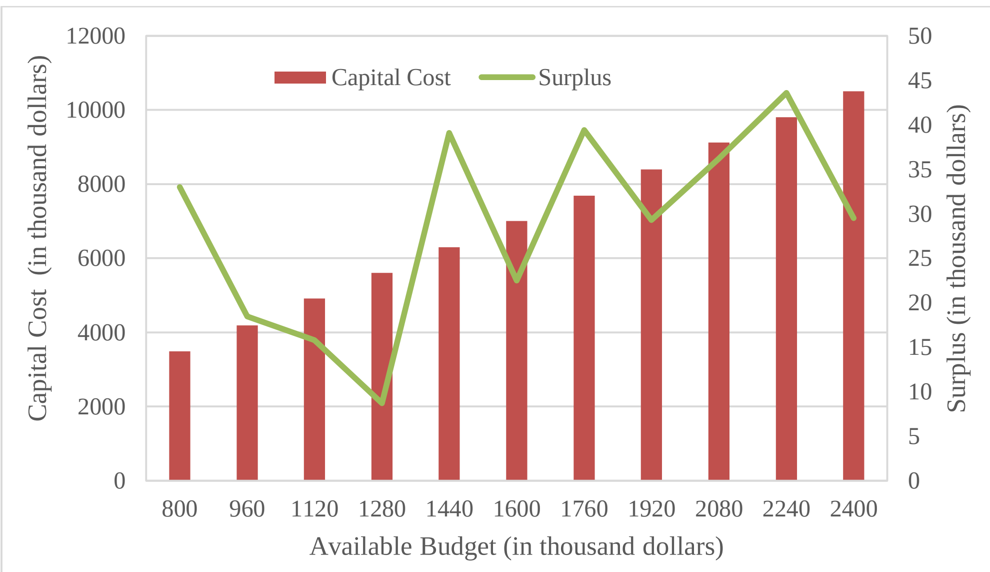


Fig. 3. Probable Cost of Crash Savings for all locations



(a) Budget, safety benefits, and number of alternatives



(b) Budget, capital cost, and surplus

Fig. 4. Budget Sensitivity Analysis

Appendix A

Table A1: Allocation of Alternatives to Counties by Proposed Strategies for Optimal Equity in Opportunity Budget Allocation

δ=γ=1												
EOC2-RAM												
	Alternative											
Year	1	2	3	4	5	Total	Benefit ($)	Allocated ($)	O&M Cost ($)	Budget ($)	Surplus ($)	Cumulative ($)
1	0	0	0	1	10	11	$ 4,568,317	$ 1,600,000	$ -	$ 1,600,000	$ -	$ -
2	0	0	1	3	7	11	$ 7,222,911	$ 1,430,000	$ 160,000	$ 1,600,000	$ 10,000	$ 10,000
3	1	0	0	0	9	10	$ 10,398,787	$ 1,370,000	$ 303,000	$ 1,680,000	$ 7,000	$ 17,000
4	2	0	0	0	8	10	$ 13,482,798	$ 1,240,000	$ 440,000	$ 1,680,000	$ -	$ 17,000
5	0	0	2	0	8	10	$ 13,058,320	$ 1,360,000	$ 394,000	$ 1,764,000	$ 10,000	$ 27,000
Total	3	0	3	4	42	52	$ 48,731,133	$ 7,000,000	$ 1,297,000	$ 8,324,000	$ 27,000	
δ=γ=2												
	Alternative											
Year	1	2	3	4	5	Total	Benefit ($)	Allocated ($)	O&M Cost ($)	Budget ($)	Surplus ($)	Cumulative ($)
1	0	2	4	0	8	14	$ 3,872,174	$ 1,590,000	$ -	$ 1,600,000	$ 10,000	$ 10,000
2	2	7	0	1	7	17	$ 7,482,758	$ 1,435,000	$ 159,000	$ 1,600,000	$ 6,000	$ 16,000
3	1	2	3	0	7	13	$ 11,200,874	$ 1,380,000	$ 295,500	$ 1,680,000	$ 4,500	$ 20,500
4	0	0	0	1	8	9	$ 12,375,837	$ 1,300,000	$ 373,000	$ 1,680,000	$ 7,000	$ 27,500
5	0	1	0	0	9	10	$ 13,344,579	$ 1,385,000	$ 374,000	$ 1,764,000	$ 5,000	$ 32,500
Total	3	12	7	2	39	63	$ 48,276,222	$ 7,090,000	$ 1,201,500	$ 8,324,000	$ 32,500	

Table A2: Allocation of Alternatives to Counties by Proposed Strategies for Optimal Equity in Opportunity Budget Allocation

δ=γ=1

Model	Year	New					Cumulative				
		Wayne	Washtenaw	St. Clair	Oakland	Total	Wayne	Washtenaw	St. Clair	Oakland	Total
EOC2-RAM	1	9	-	2	-	11	9	-	2	-	11
	2	-	-	8	3	10	9	-	10	3	22
	3	-	6	2	2	10	9	6	12	5	32
	4	1	6	2	1	9	10	12	14	6	42
	5	2	1	2	5	10	12	13	16	11	52

δ=γ=2

Model	Year	New					Cumulative				
		Wayne	Washtenaw	St. Clair	Oakland	Total	Wayne	Washtenaw	St. Clair	Oakland	Total
EOC2-RAM	1	8	-	5	1	11	8	-	5	1	14
	2	4	4	3	6	10	12	4	8	7	31
	3	1	2	5	5	10	13	6	13	12	44
	4	2	5	2	-	9	15	11	15	12	53
	5	2	4	2	2	10	17	15	17	14	63

Table A3: Distribution of Benefits Across Counties According To Proposed Strategies for Optimal Equity in Opportunity Budget Allocation

δ=γ=1

Model	Year	Yearly					Cumulative				
		Wayne	Washtenaw	St.Clair	Oakland	Total	Wayne	Washtenaw	St.Clair	Oakland	Total
EOC2-RAM	1	$4,275,813	$-	$292,504	$-	$6,682,835	$4,275,813	$-	$292,504	$-	$4,568,317
	2	$4,357,210	$-	$1,510,516	$1,355,185	$11,591,440	$8,633,023	$-	$1,803,020	$1,355,185	$11,791,228
	3	$4,444,892	$1,971,386	$1,799,251	$2,183,259	$15,759,287	$13,077,915	$1,971,386	$3,602,271	$3,538,444	$22,190,016
	4	$4,583,497	$3,549,896	$2,454,421	$2,894,984	$19,441,599	$17,661,412	$5,521,281	$6,056,692	$6,433,428	$35,672,813
	5	$1,240,834	$3,986,086	$2,230,491	$5,600,909	$18,768,326	$18,902,246	$9,507,368	$8,287,183	$12,034,336	$48,731,133

δ=γ=2

Model	Year	Yearly					Cumulative				
		Wayne	Washtenaw	St.Clair	Oakland	Total	Wayne	Washtenaw	St.Clair	Oakland	Total
EOC2-RAM	1	$2,816,619	$-	$909,635	$145,920	$6,682,835	$2,816,619	$-	$909,635	$145,920	$3,872,174
	2	$3,281,249	$658,188	$1,382,729	$2,160,591	$11,591,440	$6,097,868	$658,188	$2,292,365	$2,306,511	$11,354,932
	3	$3,813,051	$1,035,656	$1,920,544	$4,431,624	$15,759,287	$9,910,919	$1,693,844	$4,212,908	$6,738,134	$22,555,806
	4	$3,228,356	$2,553,812	$2,451,032	$4,142,638	$19,441,599	$13,139,275	$4,247,656	$6,663,940	$10,880,772	$34,931,643
	5	$2,400,272	$3,931,331	$1,882,960	$5,130,016	$18,768,326	$15,539,547	$8,178,987	$8,546,900	$16,010,788	$48,276,222