Multidimensional resource allocation for freight transportation project planning and decision making

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ABSTRACT: This paper develops and compares four multidimensional resource allocation models aimed to prioritize freight improvement projects for regional, state, and local transportation agencies such that return on investment is maximized. The proposed models are based on economic competitiveness with and without mutual exclusiveness in location, and equity in opportunity and outcome. Multiple dimensions of the models include the transportation mode, performance measures, improvement type, geographic regions, policy criteria, and time. Results from a case study in the State of Tennessee show that project selection based on equity in outcome provides the optimal balance between benefits and their distribution among counties, while project selection based on equity in opportunity results in the lowest total return on investment.

Keywords**:** multidimensional resource allocation; freight planning; economic competitiveness; equity in opportunity; equity in outcome

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1. INTRODUCTION

It is widely accepted that the economic prosperity of a region highly depends on the efficiency of freight movements. According to the Federal Highway Administration (FHWA), freight volume is expected to grow over 60% in the next 25 years (FHWA 2017a). The America's Surface Transportation Act, referred to as *FAST Act*, recommends separate stream of funding to be dedicated to State Departments of Transportation (DOTs) to invest in freight-specific projects to alleviate congestion, improve operational efficiency, and enhance safety (Bahar et al. 2015). Truck has always been a lifeline of the US for a long time however, the technological advancement over some past years has up surged the importance of overall freight system. For example, the internet shopping has risen dramatically thereby increasing the demand of shipping and the businesses are trying to lower the shipping rates to attract more customers. National Cooperative Freight Research Program (2012) discusses the link of the freight transportation in supply chains and economic performance. Improvement in freight transportation efficiency, reliability, and level of service has multiple benefits for production efficiency, proficiency of distribution network, and more options to the consumers at lower price. The improvement in reliability of freight transit times enables the businesses to reduce the inventory levels relying more on just-in-time shipments, thereby reducing the total logistics cost.

The importance of this research can be realized from a couple of facts. The improvement to the freight transportation system is complicated and expensive as it involves an intermodal and multimodal system connecting various regions within and outside the country. The policymakers are always looking to distribute the resources in such a way that all the modes are proportionally improved enhancing the overall freight system and the competitiveness of their economy. But even after the identification of the projects addressing the problematic section in the freight network, there is a need to prioritize the projects in order to generate the maximum benefits (revenue) while maintaining other priorities such as equity. This is because of more projects but limited budget in the real world. Although traditional benefit-cost analysis (BCA) has been serving as an important tool for assessing the benefits of transportation investments, it fails to capture the freight investment, particularly those realized by the shippers, such as faster and more reliable delivery (FHWA 2004). Following the passage of *FAST Act*, State DOTs, in the last few years, have begun a planning process to develop robust ways to utilize, the already, scarce resources in freight improvement projects prioritization. The process consists of three steps: (i) identification of problematic sections (and/or projects) of the multimodal freight network under their jurisdiction; (ii) development of alternatives for each section; and (iii) allocation of the available resources to implement a subset of the projects identified in the former two steps. While the first two steps are (mostly) based on engineering design, the third step can be formulated as a resource allocation model such that optimal prioritization of freight projects is achieved. The state-of-the-practice for project prioritization, however, is based on either expert knowledge (i.e., certain lists provided by senior employees) or heuristic approaches which do not necessarily yield an optimal improvement plan. Furthermore, Sate DOTs' approaches typically miss a holistic view of all modes such that the freight transportation system as a whole is enhanced. Also, their approaches are not capable of incorporating policies such as equity.

To the best of the authors' knowledge, resource allocation for freight improvement projects prioritization is missing from the literature. The resource allocation problem has been researched in various disciplines including transportation, safety, production, energy, etc. (see for example Kim and Hansen (2013), Zargayouna et al. (2016), Wang (2016), Melkote and Daskin (2001), Lambert et al. (2003), Mathew et al. (2010), Mishra et al. (2015), Fang and Li (2015), Oncul et al. (2009), Crainic (1998), Krugler et al. (2007), Pagano et al. (2004), Arora et al. (2010), Li et al. (2016)). Despite the relatively rich literature on resource allocation, no systematic approach has been developed to prioritize freight improvement projects based on the specific dimensions discussed earlier. The literature within the transportation sector focuses only on one specific mode like trucking, water, or air transportation without considering any applied policy such as equity. For example, Churchill and Lovell (2012) present a stochastic programming model to coordinate matching flights to the slots at congested airports. Zargayouna et al. (2016) develop an optimization model for efficient allocation of parking spaces to drivers. Similarly, Wang (2016) considers a containerized cargo transportation problem in which the freight operator allocates uncertain capacities to products to maximize its profit. This paper fills the gap in the literature by developing a set of resource allocation models that explicitly capture various dimensions of freight transportation and considers equity as well as other policies.

The contribution of this paper is thus twofold: (i) development of a multidimensional resource allocation model that takes into consideration various policies that state DOTs may have; and (ii) application of the model using a real-world case study. In this paper we consider six dimensions that are usually encountered by transportation agencies. The first dimension relates to performance measures. State DOTs typically deal with multiple performance measures such as congestion, air quality, safety, and others. The second dimension is multimodality, since any freight network will consist of multiple modes (i.e., truck, rail, air, water, and pipeline) working together and sharing the infrastructure. The third dimension pertains to the improvement projects proposed for the problematic sections of the freight network, and their associated benefits and costs. The fourth dimension revolves around time. Typically, agencies do not plan on a year-by-year basis but rather consider a short-term planning horizon of five to ten years. Time is a critical element as the question of *when* to invest (i.e., now or wait) is critical to the return of their investment. The fifth dimension is the geographic regions under the jurisdiction of the transportation agency that "compete" for the available funds to implement multiple projects belonging to each mode. The sixth dimension is policy considerations. Each state has different policies including economic competitiveness, carryover of surplus to future years, equitable fund allocation, etc.

The rest of the paper is organized as follows. The methodology is put forward in section 2, followed by a description of the case study data in section 3. Results from numerical experiments are discussed in section 4 and the paper concludes with major findings and directions for future research in section 5.

2. METHODOLOGY

In this section, four resource allocation models using four different policies are developed to prioritize freight improvement projects based on specific features of the freight transportation system discussed in the previous section. The main nomenclature used in the models are presented in Table 1. Other notations will be presented as needed. It is assumed that there exists a pre-specified set of projects *I,* in which each project relates to a specific mode, location, improvement type, and time of implementation. The benefits and costs of implementation of each project are assumed to be known. The total benefits are calculated as the present worth (PW) of all the annual benefits over the service life (n) of the project adjusted with an annual interest rate (α), and expected annual growth of benefits with increasing infrastructure users (β) in cash flow. For example, if a project is implemented in year t=5 and we assume a planning horizon of 25 years then the service life of the project is 20 years and total benefits (present work) will be equal to: $B_{i5} = B_{i0}\frac{(1+\beta)^5}{(\alpha-\beta)}\left[1-\left(\frac{1+\beta}{1+\alpha}\right)^{25}\right]\frac{1}{(1+\alpha)^4}$. In this paper we assume that the service life of each project extends to the end of the planning horizon irrespective of the year of implementation. The budget remaining at the end of each year (i.e., surplus budget), is carried over to the successive year. Note that the surplus budget at beginning of the planning horizon is assumed to be equal to zero (i.e., $SP_0 = 0$).

Table 1: Nomenclature

Type	Component	Description
Sets	I, i	Set and index of projects
	J, j	Set and index of counties
	T, t	Set and index of time periods in planning horizon
	L, l	Set and index of locations

	$B_{it=0}$	Annual benefits from project i at time t =0
	$B_{Ti=0} = B_{it=0} \frac{(1+\beta)^t}{(\alpha-\beta)} \left[1 - \left(\frac{1+\beta}{1+\alpha}\right)^n\right] \frac{1}{(1+\alpha)^{t-1}}$	Total benefits from project i at time t =0
	$K_{it=0}$	Construction cost of project i calculated at time t =0
Parameters	γ	Cost annual growth rate (expected)
	$K_{it} = K_{it=0} * (1+\gamma)^{t-1}$	Construction cost of project i at time t
	g_{ij}	Binary parameter indicating if project i lies in county j
	h_{il}	Binary parameter indicating if project i lies on location l
	$d_{j\hat{j}} = \left\lvert \sum_i (g_{ij} - g_{i\hat{j}}) \right\rvert, j \neq \hat{j} \in J$	Number of candidate projects difference between two counties
	$\mathscr{E}$	Equity in opportunity parameter
	P_t	Budget for all improvement projects at time t
	e	Equity in outcome parameter
	$X_{it} \in \{0,1\}$	=1 if project i is chosen at time t and zero otherwise
Variables	$SP_{t-1} \in \mathbb{R}$	Carry over budget from year t-1 to year t
	$R \in \mathbb{R}^+$	Maximum benefits that can be allocated to any county
	$S \in \mathbb{R}^+$	Minimum benefits that can be allocated to any county

In this paper we also consider a model that is commonly used by transportation agencies (from now on referred to as ***M0***) where project selection is based on a heuristic sorting algorithm. The algorithm sorts the candidate projects in I in a descending order based on benefits at time t=0. The projects with the highest benefits, and within the available budget for year one, are selected and removed from set I. Any remaining budget from year one is added to the budget of the year two and the process is repeated for all the years in the planning horizon (sequentially in increasing order) or until the set I is empty (whichever comes first). We now present the four resource allocation models.

M1: Economic Competitiveness (I)

The first model (***M1*** shown in 1.1-1.4) maximizes economic competitiveness which is one of the major goals of USDOT's strategic plan (USDOT 2012). In ***M1,*** total benefits are maximized subject to budgetary constraints. Constraint set (1.2) ensures that the project selection does not exceed the available budget of each year. Constraint set (1.3) ensures that each project is selected only once while constraint set (1.4) carries over any unspent portion of the budget from time period t to $t+1$.

$$\boldsymbol{M1}: max \sum_{i,t} B_{Ti=0} X_{it} \tag{1.1}$$

Subject to

$$\textstyle\sum_i K_{it} X_{it} \leq P_t + SP_{t-1} \qquad \forall t \in T \tag{1.2}$$

$$\sum_t X_{it} \leq 1 \qquad \forall\, i \in I \tag{1.3}$$

$$P_t - \sum_i K_{it} X_{it} + SP_{t-1} = SP_t \qquad \forall t \in T \tag{1.4}$$

***M2*: Economic Competitiveness with Mutual Exclusiveness (II)**

Model ***M2*** ((2.1)-(2.2)) extends ***M1*** by adding a mutual exclusiveness constraint (constraint set 2.2) to ensure that a location cannot be assigned more than one project over the planning horizon. The rationale for introducing this constraint is to (indirectly) maximize the total number of locations that receive funding as compared to ***M1***. In theory, it may be possible that there are very few unique locations with multiple projects overlapped at the same location. In that scenario, the model might end up selecting very few projects with a huge leftover budget.

$$\boldsymbol{M2}: max \sum_{i,t} B_{Ti=0} X_{it} \tag{2.1}$$

Subject to

(1.2)-(1.4)

$$\sum_{i,t} X_{it} h_{il} \leq 1 \qquad \forall\, l \in L \tag{2.2}$$

***M3*: Economic Competitiveness with Equity in Opportunity**

Model ***M3*** is introduced to distribute the available funds in a fair manner among the sub-regions in the area under study (e.g., counties within the state). Fairness (i.e., equity) is introduced via constraint sets (3.2) and (3.3) that bound the difference of projects selected between any two counties to a fixed number. Constraint set (3.2) ensures that at least one project is selected in each county while constraint set (3.3) bounds the difference in the number of projects selected between any two counties to an upper limit. This bound is calculated as a percentage (i.e., an equity in opportunity parameter $\mathcal{E}_{j\hat{j}}$) of the difference of candidate projects for each county pair ($d_{j\hat{j}}$). For example, if two counties have three and ten candidate projects respectively, then the difference between the number of selected projects between these counties cannot exceed (10-3)×$\mathcal{E}_{j\hat{j}}$ *or* 7$\mathcal{E}_{j\hat{j}}$). Without loss of generality, we assume that the equity in opportunity parameter for any county pair to be the same (i.e., $\mathcal{E}_{j\hat{j}} = \mathcal{E}_{k\hat{k}} \forall\, j, \hat{j}, k, \hat{k} \in J | j \neq \hat{j}, k \neq \hat{k}$). Values of $\mathcal{E}_{j\hat{j}}$ can be estimated as (weighted) ratios of population, income, or other socioeconomic characteristics (Lee and Wong 2004; Talen 1998; Talen and Anselin 1998; Welch and Mishra 2013).

$$\boldsymbol{M3}: max \sum_{i,t} B_{Ti=0} X_{it} \tag{3.1}$$

Subject to

(1.2)-(1.4), (2.2)

$$\sum_{i,t} X_{it}\, g_{ij} \geq 1 \qquad \forall\, j \in J \tag{3.2}$$

$$\left| \sum_{i,t} X_{it}\, g_{ij} - \sum_{i,t} X_{it}\, g_{i\hat{j}} \right| \leq \mathcal{E}_{j\hat{j}} d_{j\hat{j}} \qquad \forall\, j, \hat{j} \in J | j \neq \hat{j} \tag{3.3}$$

***M4*: Economic Competitiveness with Equity in Outcome**

M3 distributes the available resources across counties in a fair manner with regards to the total portion of the available funding allocated but does not ensure an equitable distribution of benefits (i.e., outcomes). For example, two counties may receive the same amount of funding but the benefits from these projects may vary significantly. To account for the equity in outcome, constraints (4.2)-(4.3) are added to ***M2*** and the resulting model is termed model ***M4***. Constraint set (4.2) bounds the benefits of each county between the upper (R) and lower bounds (S) where R and S are determined within constraints set (4.3). Constraint set (4.3) ensures that the difference between R and S is less than a pre-specified percentage (i.e., equity in outcome parameter e) of the total benefits. Constraints (4.2) and (4.3), try to minimize the difference in benefits between any two counties in an effort to obtain an equitable benefits allocation.

$$\boldsymbol{M4}: max \sum_{i,t} B_{Ti=0} X_{it} \quad (4.1)$$

Subject to
(1.2)-(1.4), (2.2)

$$R \geq \sum_{i,t} B_{Ti=0} X_{it} g_{ij} \ \geq \ S \qquad \forall \ j \in J \quad (4.2)$$

$$R - S \ \leq e \sum_{i,t} B_{Ti=0} X_{it} \quad (4.3)$$

3. MODEL APPLICATION

3.1 Study Area

The models formulated in Section 2 are applied to the freight network in the State of Tennessee which consists of over 28,413 miles of functionally classified roadways, over 1,200 miles of railway lines, 949 miles of navigable waterways, and 3,360 miles of pipelines (TDOT 2016; USDOE 2016). Because of unavailability of data, truck and rail are the only modes considered for the model application. A total of 2,238 candidate projects in 51 counties, over a 10-year planning horizon were available.

3.2 Data Preparation

In this subsection, the data collection, analysis, and identification of projects are presented. Potential locations to be improved are identified based on three performance measures including congestion reduction, operational improvement, and safety enhancement. For rail, and due to data unavailability, only the safety performance measure is used for identification of potential locations.

3.2.1 Data Collection

Three major sources of data have been used in this paper: (i) the Statewide Travel Demand Model (S-TDM), (ii) the National Performance Management Research Data Set (NPMRDS), and (iii) the Enhanced Tennessee Roadway Information Management System (ETRIMS). S-TDM provides future year truck volume on various facility types including interstates, freeways, expressways, and principal arterials. Future year truck volumes are used to identify potential growth locations. NPMRDS provides the average travel time observations of trucks in seconds for each five-minute epoch throughout the day and month, on national highway system. ETRIMS is a map-centric, web based, and integrated system that includes state and local roadways, pavements, traffic, roadway crash, railroad-highway crossings crash, etc. Roadway inventory and crash data for all public roads, including the roads crossings railroad, are provided in this application. The roadway safety data is combined with crash data to better identify and understand the problems, prioritize locations for treatment, apply effective countermeasures, and evaluate the effectiveness of those countermeasures (Scopatz et al. 2014). Several types of crashes over the last 15 years are identified along the interstates and expressways as well as railroad-highway crossings.

3.2.2 Projects Identification

In this paper, candidate project locations were selected based on the following criteria:

i. **Congestion performance**: Any roadway segment with volume to capacity ratio (VCR) equal to or greater than 0.8 and truck volume to total volume percentage (TP) equal to or greater than 20%. VCR and TP are computed from S-TDM. Note that the VCR threshold of 0.8 aims to include segments with the level of service of lower than D where traffic operations are unstable.

ii. **Operational performance**: Any roadway segment where the ratio of the average morning and evening peak period speed to the speed limit is over 0.75 (as computed from NPMRDS). Similar to VCR threshold the delay threshold of speed representing unstable traffic operations is considered as a measure to represent congested segments.

iii. **Safety performance**: Any roadway segment having a fatal crash rate greater than 1 per mile or where the economic cost of non-fatal crashes is greater than that of the fatal crash. To capture segments critical from safety viewpoint, a two-way approach is considered. All segments with at least one fatal crash or where the sum of crash cost is more than cost of one fatal crash. Fatal, injury, property damage only, and total crashes on roadway and railroad-highway crossings are obtained from ETRIMS. Similarly, the vulnerable railroad crossing segments are identified from the accident probability given in the dataset.

The improvements corresponding to each of the three performance measures are as follows:

i. **Congestion performance:** Capacity expansion projects (one and two-lane addition) are proposed.

ii. **Operational performance**: Increase in the speed limit is proposed with projects such as patching and rehabilitation, and asphalt overlays.

iii. **Safety performance**: For roadway links, countermeasures recommended in the Highway safety manual are proposed. Similarly, three types of countermeasures (flashing lights, median, and gates) are used as safety countermeasures for railroad-highway crossings (Konur et al. 2013; Volmer et al. 2006).

3.2.3 Estimation of Project Benefits

Benefits from capacity expansion and operational improvement projects were computed as travel time savings using the Bureau of Public Roads (BPR) function and a value of time of \$33.8/hour (Belenky 2011).[†] Safety project benefits were estimated as savings from the reduction in crashes. The average costs of fatal, injury, and PDO crashes are obtained from the Highway Safety Manual (HSM) and are shown in Table 2. Table 2 also shows the crash reduction factors used in this study, taken from multiple references.

3.2.4 Projects Summary

Expected annual benefits, construction costs, and the service life of each project were estimated based on engineering design and are not presented in this paper for brevity. A sample of the input data is shown in Table 3. Project costs (construction) and benefits across all modes and improvement types are summarized in Table 4, assuming all projects get selected in the first year. It can be observed that the number of projects as well as a significant portion of the benefits, fall under the category of operational improvements. We also note that project construction time is not considered in this paper (i.e., projects start producing benefits the year they are selected for implementation). Construction time can be added to all models presented in this paper in a straightforward manner (i.e., setting $B_{Ti=0} = \frac{B_{it=0} * (1+\beta)^{t+ct_i}}{(\alpha-\beta)} \left[1 - \left(\frac{1+\beta}{1+\alpha}\right)^{n}\right] * \frac{1}{(1+\alpha)^{t-1+ct_i}}$, where ct_i is the construction time of project *i*) but this is left as future research.

Table 2: Parameter values used in case study

Parameters	Value	Unit	Reference

[†] The estimate in Belenky (2011) was inflated to 2017 values assuming an annual rate of 4%

Fatal	4,008,900	$/crash	Herbel et al. (2010)
Injury	113,300	$/crash	
PDO	7,400	$/crash	
Crash reduction factor (Signs)	0.35	Per crash	Bahar et al. (2008) and Scopatz et al. (2014)
Crash reduction factor (Pavement Friction)	0.75	Per crash	
Crash reduction factor (Flashing Lights)	Single track-0.9, multiple track-0.65	Per crash	
Crash reduction factor (Gates)	Single track-0.7, multiple track-0.65	Per crash	
Crash reduction factor (Median)	0.8	Per crash	

Table 3: Sample data of candidate project details

Project ID	Annual Benefits ($ million)	Costs ($ million)	Improvement Type	County	Location	Mode	Service Life
1	1.390	1.602	Capacity expansion	Knox	I-275 between I-75 & I-40	Truck	20
2	0.12	0.49	Capacity expansion	Knox	I-40 between Western Ave & 17th street	Truck	20
3	2.683	3.381	Capacity expansion	Bradley	I-75 between US 64 & TN 317	Truck	20
4	0.742	1.391	Capacity expansion	Hamilton	I-24 at S Seminole Dr.	Truck	20
5	1.570	1.923	Capacity expansion	Hamilton	I-24 between Germantown Rd & Belvoir Ave	Truck	20
…	…	…	…	…	…	…	…
2238	0.029	0.125	Safety	Shelby	Patterson at Southern Ave	Rail	25

Table 4: Candidate projects benefits, costs and number by mode and improvement type

Improvement Type	Benefits ($ billion)		Costs ($ million)		Number of Projects	
	Truck	Rail	Truck	Rail	Truck	Rail
Capacity	2.944 (11.3%)	-	420.413 (15.4%)	-	719	-
Operation	18.076 (69.7%)	-	2,254.299 (82.7%)	-	1,254	-
Safety	4.821 (18.6%)	0.075 (0.3%)	22.479 (0.8%)	29.072 (1.1%)	102	163
Total	25.841	0.075	2,697.191	29.072	2,075	163
Grand Total	25.916		2,726.263		2,238	

In this paper, we assume four different budget scenarios of $86.20, $95.78, $105.36, and $115.896 million over the planning horizon respectively. These budgets reflect PW and have been abbreviated as B1, B2, B3, and B4 respectively. B2 is estimated using the assumption that $10 million are available in year 1 and an annual increase of 3% over the ten years planning horizon. The remaining three budgets are estimated by assuming a 10% decrease/increase for B1 and B3 respectively and a 20% increase for B4 with respect to the budget available for B2. We also consider five values (0, 0.25, 0.5, 0.75, and 1) for the equity in opportunity and outcome parameters ($\mathscr{E}$ and e respectively). These values were estimated from a sensitivity analysis that is presented in subsection 4.5.2. The annual interest rate (α), expected annual growth of benefits (β), and expected annual growth of costs (γ) in cash flow are assumed to be 4%, 2% and 3% respectively.

4. RESULTS

This section presents results from a number of numerical experiments conducted to evaluate and compare the four policies. All four models are solved using IBM ILOG CPLEX Optimizer V12.7 on a personal computer with Intel Core i7-3770 3.4 GHz CPU and 16 GB of RAM. The optimality gap is set equal to 1.0 $\times 10^{-10}$. The maximum solution time of any model was approximately 17 minutes which is acceptable considering the planning nature of the problem.

4.1 Total Benefits

Figure 1 shows the total benefits and the total number of projects selected for the four different budgets and different values of the equity parameters. Figure 2 shows the same information in terms of percentage of ***M1***. From these figures, we observe the following:

i) As expected, the total benefits (but not the number of selected projects) from ***M1*** are higher than all other models for all four budgets;

ii) The addition of mutual exclusiveness constraint in ***M2*** decreases the objective function value (i.e., total benefits) but increases the total number of projects for all budgets. This is a tradeoff that a decision maker should consider;

iii) As expected, the higher the total budget the higher the total benefits excluding model ***M0***. The unpredictable behavior of ***M0*** (with respect to the total benefits and number of project selected when the budget increases) is not surprising due to the heuristic nature of the project selection process (discussed more in section 4.5.1);

iv) When the equity parameter value is set to zero, we obtain the most equitable distribution among all models, improvement types, and counties with the lowest total benefits for both ***M3*** and ***M4***;

v) By increasing the equity parameter value, equity constraint sets 3-3 and 4-3 start to relax; As a result, the benefit distribution becomes less equitable, and the total benefits increase. This pattern is observed across all four budgets for both ***M3*** and ***M4***.

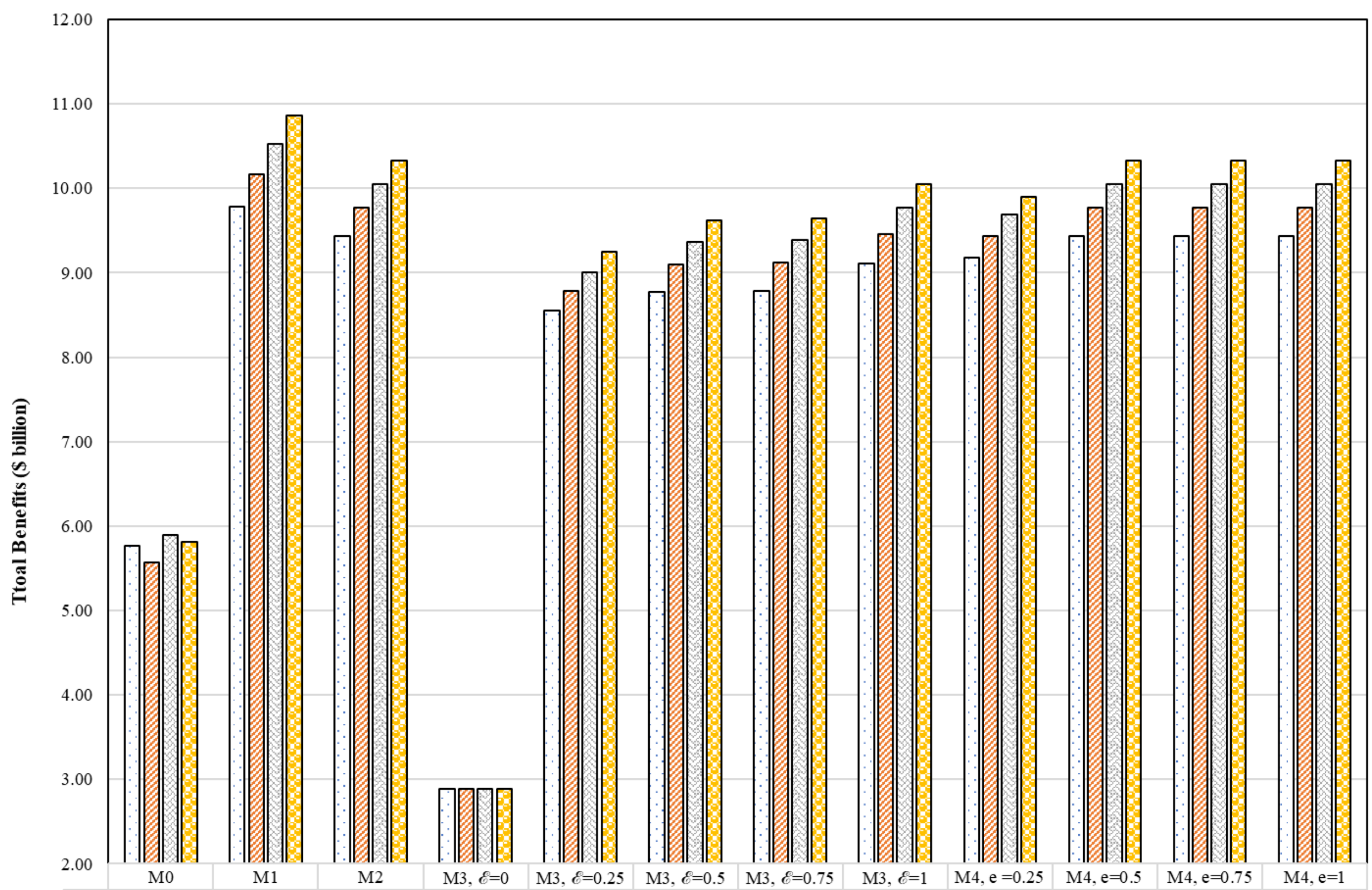
vi) For values of e greater than 0.5, ***M4*** produces the same total benefits as ***M2*** which means that constraint set 3.3 becomes inactive when $e \geq 0.5$.[‡] The effects of the equity parameters values to the total benefits will be discussed in detail in subsection 4.5.2.

vii) Model ***M3*** results in the least total benefits, compared to the other models, suggesting that equity in opportunity policy should be very carefully analyzed before implementation;

viii) As the budget increases the percentage of total benefits for models ***M0***, and ***M2*** through ***M4*** as compared to ***M1*** decrease. A similar (but not consistent) pattern is observed for the number of projects.

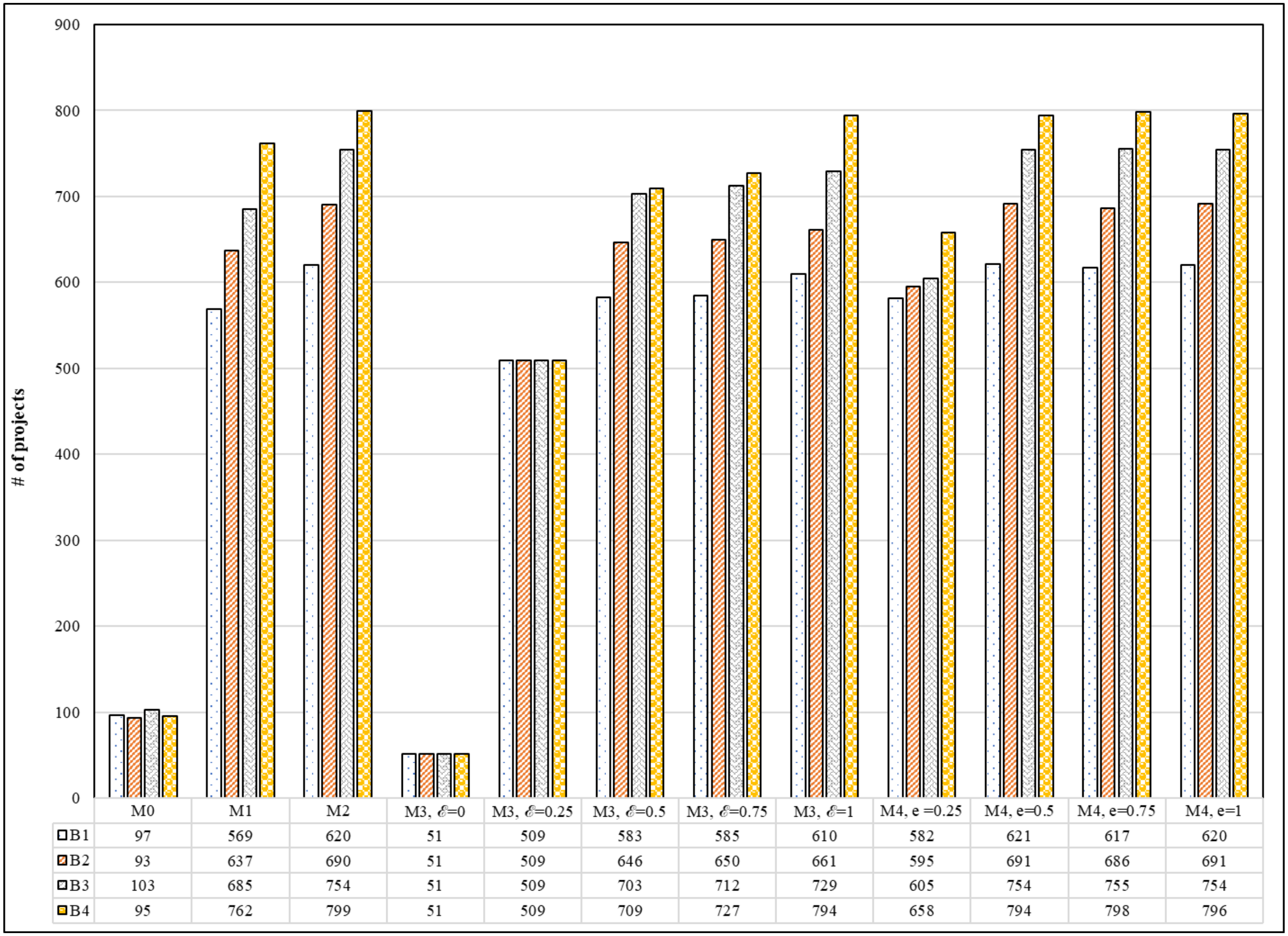
It should be noted that for $e = 0$, the only feasible solution to the problem is $X_{it} = 0, \forall i \in I, t \in T$. Even though generalization of this result cannot be made it is highly unlikely that any other solution to ***M4*** (when e=0) will exist (for real world input data) such that the minimum and maximum benefits received by all counties is equal to the same value.

[‡] The value of e after which constraint set 3.3 becomes inactive cannot be generalized as it depends on the data used.



	M0	M1	M2	M3, $\mathcal{E}$=0	M3, $\mathcal{E}$=0.25	M3, $\mathcal{E}$=0.5	M3, $\mathcal{E}$=0.75	M3, $\mathcal{E}$=1	M4, e =0.25	M4, e=0.5	M4, e=0.75	M4, e=1
B1	5.76	9.78	9.43	2.89	8.55	8.77	8.79	9.11	9.17	9.43	9.43	9.43
B2	5.57	10.17	9.77	2.89	8.78	9.10	9.12	9.46	9.43	9.77	9.77	9.77
B3	5.90	10.52	10.05	2.89	9.01	9.37	9.39	9.77	9.69	10.05	10.05	10.05
B4	5.82	10.87	10.32	2.89	9.25	9.62	9.65	10.05	9.90	10.32	10.32	10.32

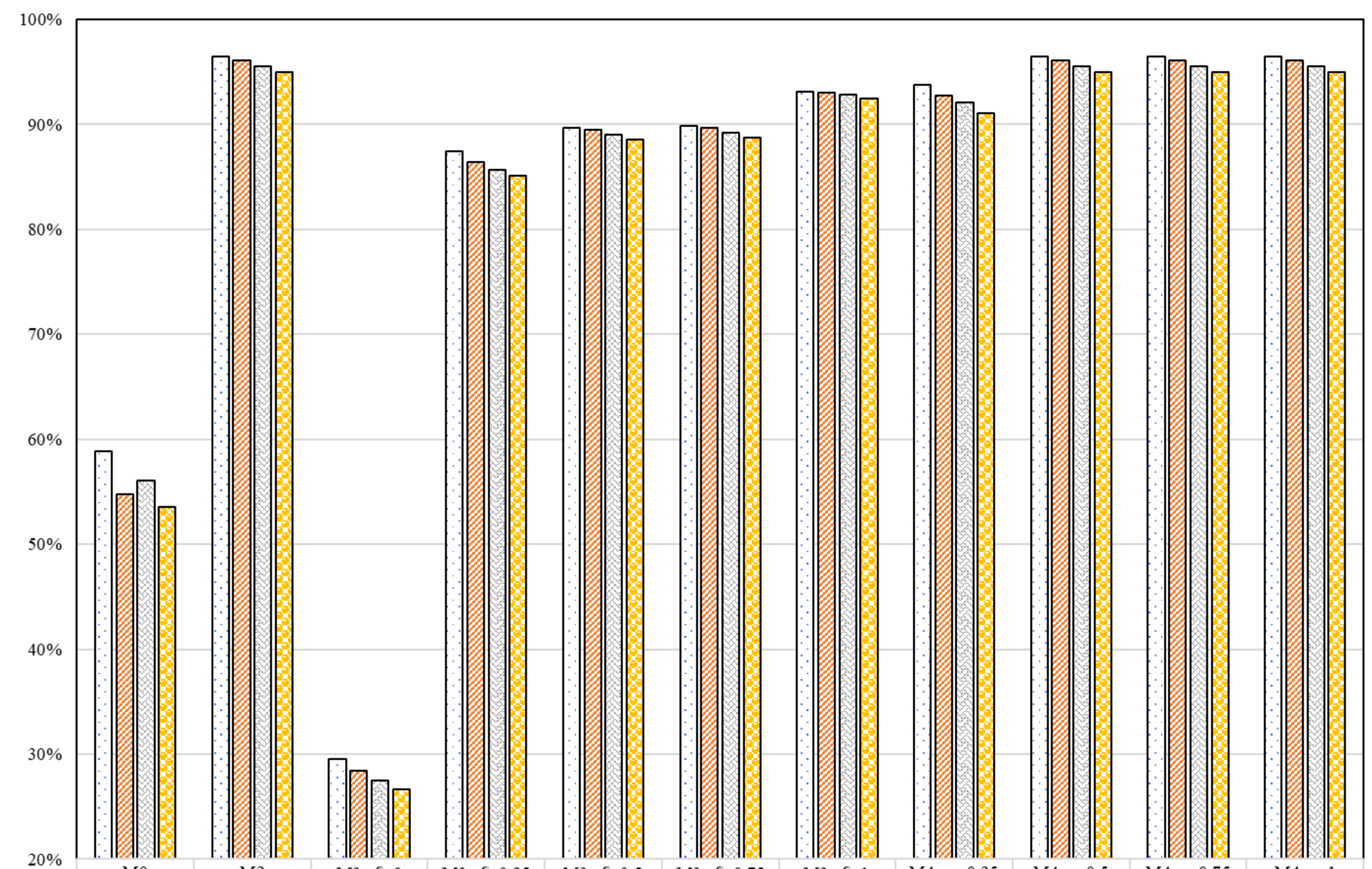
1(a): Total benefits by budget, model and equity



	M0	M1	M2	M3, $\mathcal{E}$=0	M3, $\mathcal{E}$=0.25	M3, $\mathcal{E}$=0.5	M3, $\mathcal{E}$=0.75	M3, $\mathcal{E}$=1	M4, e =0.25	M4, e=0.5	M4, e=0.75	M4, e=1
B1	97	569	620	51	509	583	585	610	582	621	617	620
B2	93	637	690	51	509	646	650	661	595	691	686	691
B3	103	685	754	51	509	703	712	729	605	754	755	754
B4	95	762	799	51	509	709	727	794	658	794	798	796

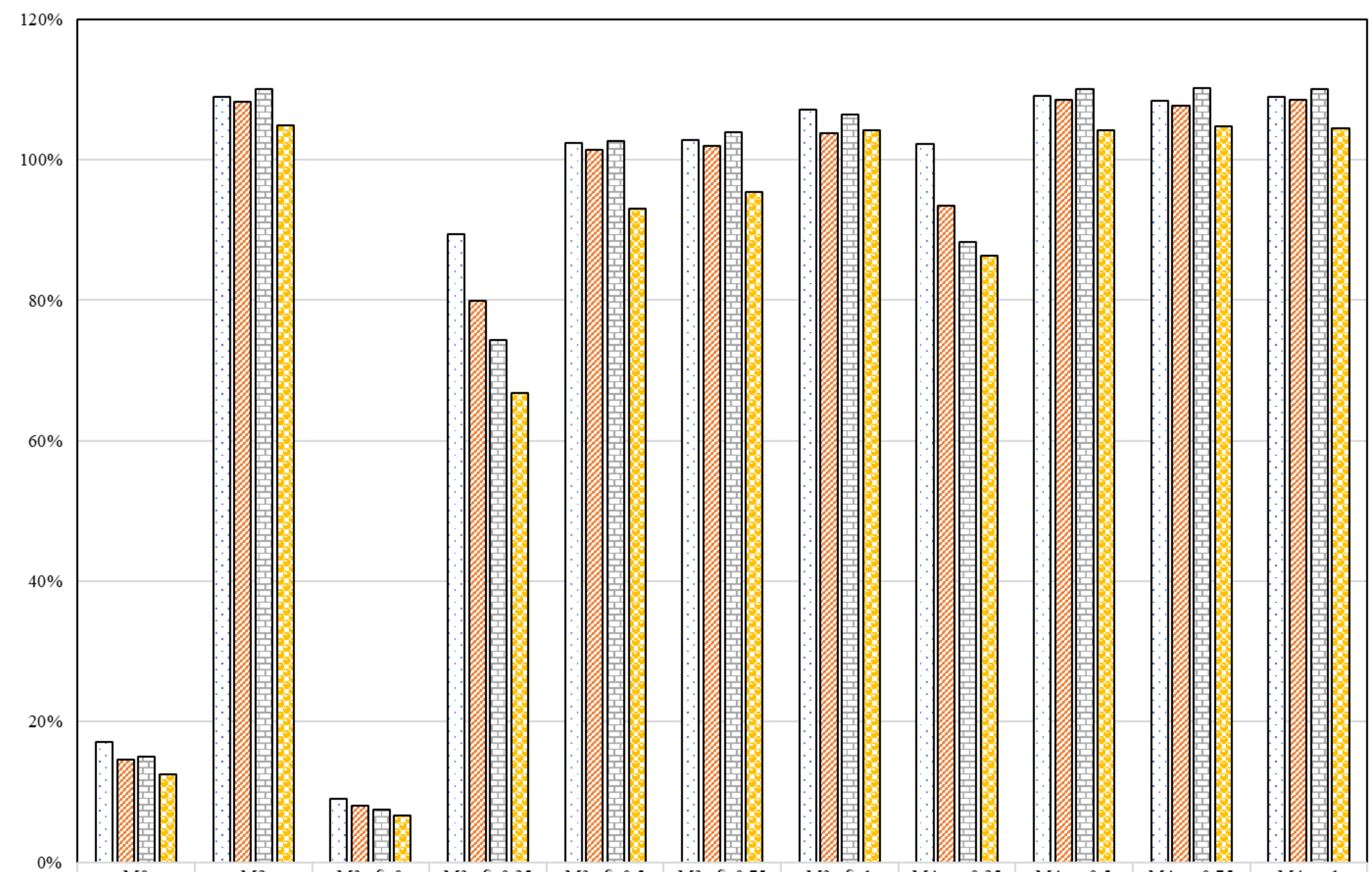
1(b): Total number of selected projects by budget, model and equity

Figure 1: Total benefits and number of selected projects by budget, by model, and by equity



	M0	M2	M3, ℰ=0	M3, ℰ=0.25	M3, ℰ=0.5	M3, ℰ=0.75	M3, ℰ=1	M4, e =0.25	M4, e=0.5	M4, e=0.75	M4, e=1
B1	59%	96%	30%	87%	90%	90%	93%	94%	96%	96%	96%
B2	55%	96%	28%	86%	89%	90%	93%	93%	96%	96%	96%
B3	56%	96%	27%	86%	89%	89%	93%	92%	96%	96%	96%
B4	54%	95%	27%	85%	89%	89%	92%	91%	95%	95%	95%

2(a): Percentage of total benefit of ***M0***, ***M2-M4*** to ***M1***



	M0	M2	M3, $\mathcal{E}$=0	M3, $\mathcal{E}$=0.25	M3, $\mathcal{E}$=0.5	M3, $\mathcal{E}$=0.75	M3, $\mathcal{E}$=1	M4, e =0.25	M4, e=0.5	M4, e=0.75	M4, e=1
B1	17%	109%	9%	89%	102%	103%	107%	102%	109%	108%	109%
B2	15%	108%	8%	80%	101%	102%	104%	93%	108%	108%	108%
B3	15%	110%	7%	74%	103%	104%	106%	88%	110%	110%	110%
B4	12%	105%	7%	67%	93%	95%	104%	86%	104%	105%	104%

2(b): Percentage of number of selected projects of ***M0***, ***M2-M4*** to ***M1***

Figure 2: Percentage of total benefits and number of selected projects of ***M0***, ***M2-M4*** to ***M1***

4.2 Benefits Distribution

Figure 3 and Figure 4 show the benefit distribution by year and budget obtained by each model/budget/equity parameter value. Figure 4 adds the dimension of the equity parameters for models ***M3*** and ***M4***. For all models, annual benefits after 20 years are lumped together (x-axis label "*>20*") as they represent a small percentage of the total benefits. From these figures we observe the following:

i) The benefits distributions, for all models (excluding ***M0*** which is based on a heuristic), budgets, and equity parameter values, follow a bell-shaped curve with a long right-side tail and a maximum value at year five. The bell-shaped curve is attributed to the decrease of the present worth due to the interest rate. In other words, there is a trade-off between the interest rate and the number of projects selected every year;

ii) Most of the benefits are received within the first 15 years (or five years after the end of planning horizon);

iii) Model ***M1*** is the only model with over 1% of the total benefits distributed after year 20;

iv) For models ***M3*** and ***M4***, as expected, relaxation of the equity constraints results in higher yearly benefits;

v) Higher budgets do not necessarily translate into consistently higher yearly benefits (for example, for model ***M2*** and years 9 through 15, budget B1 provides higher yearly benefits than budget B4).

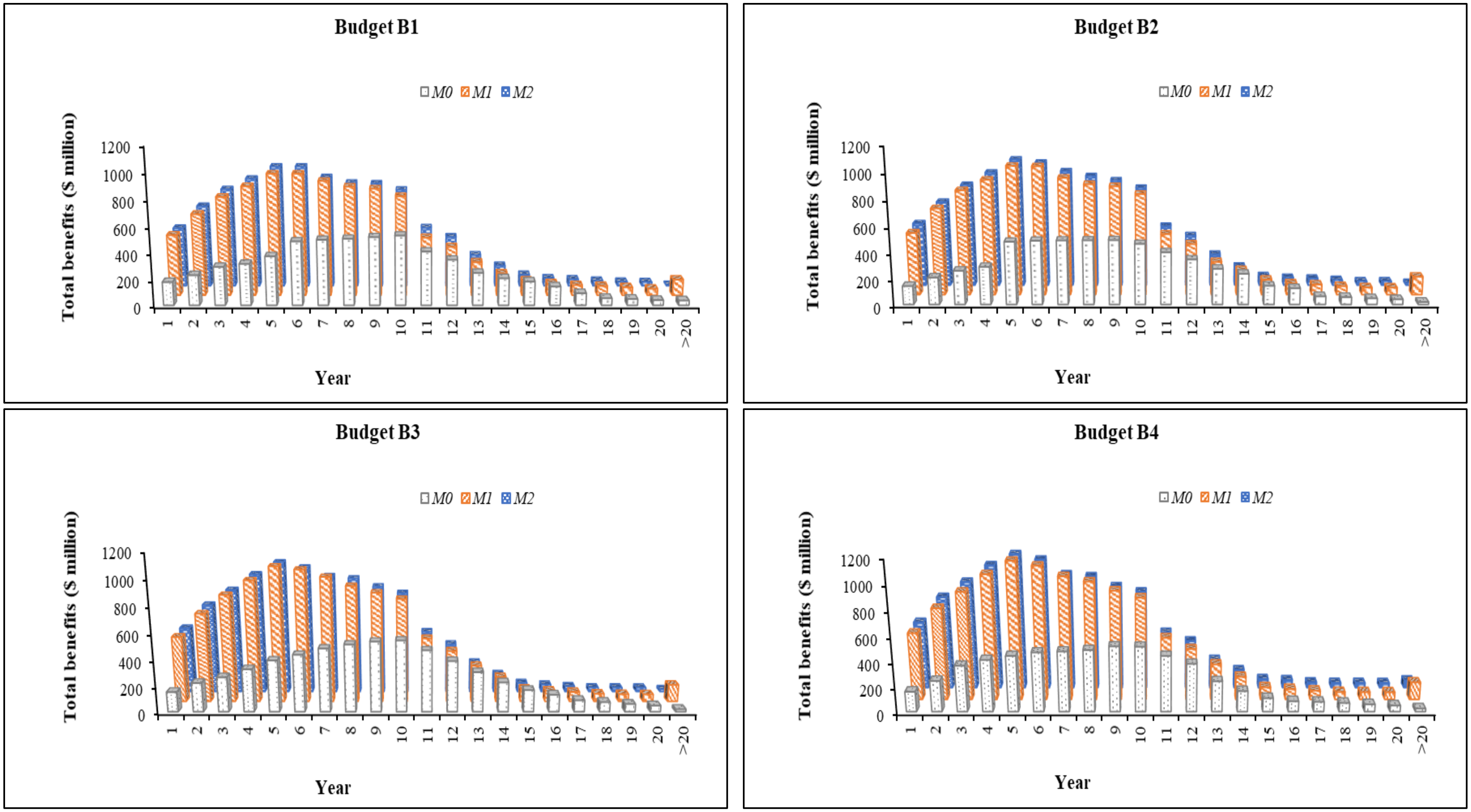
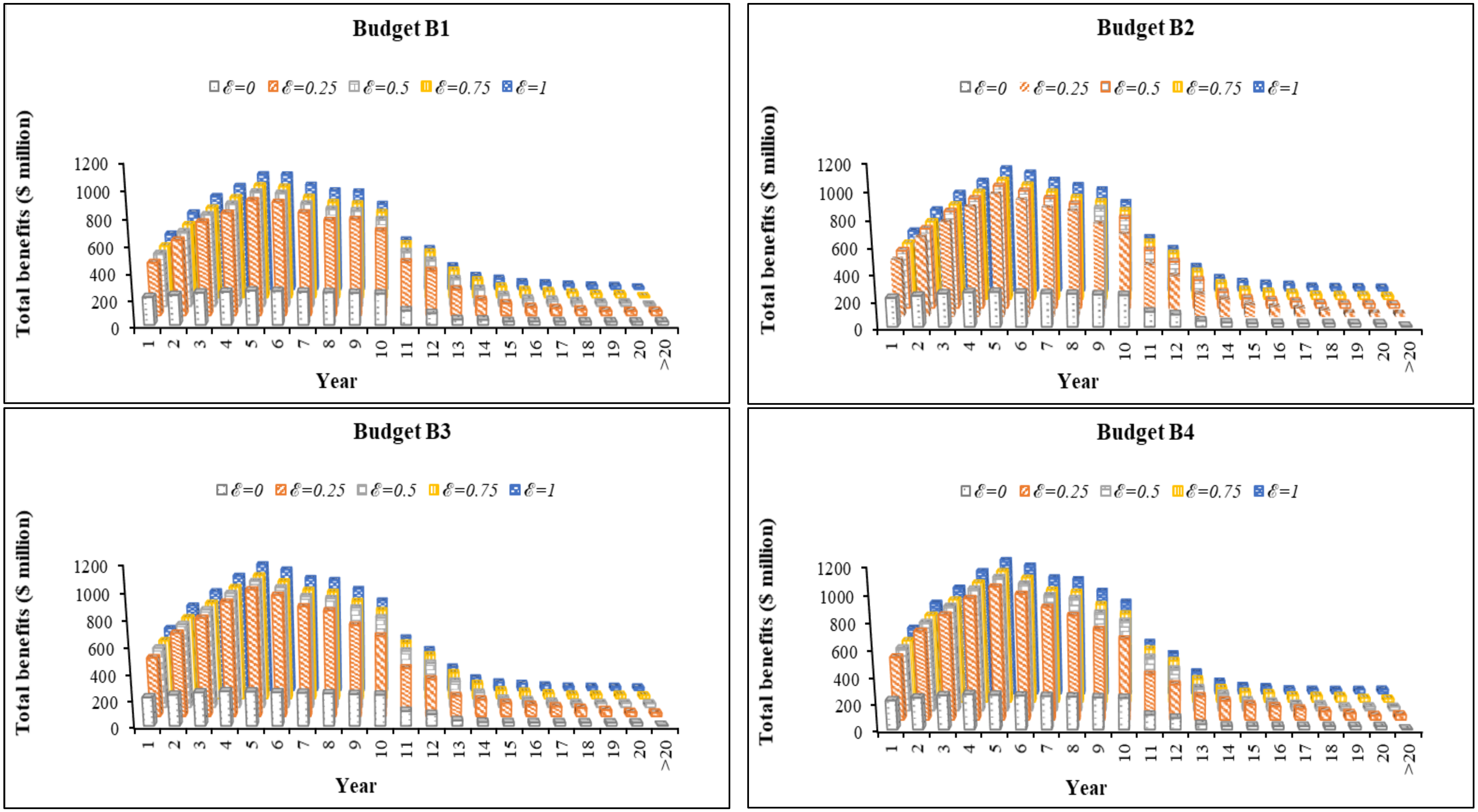
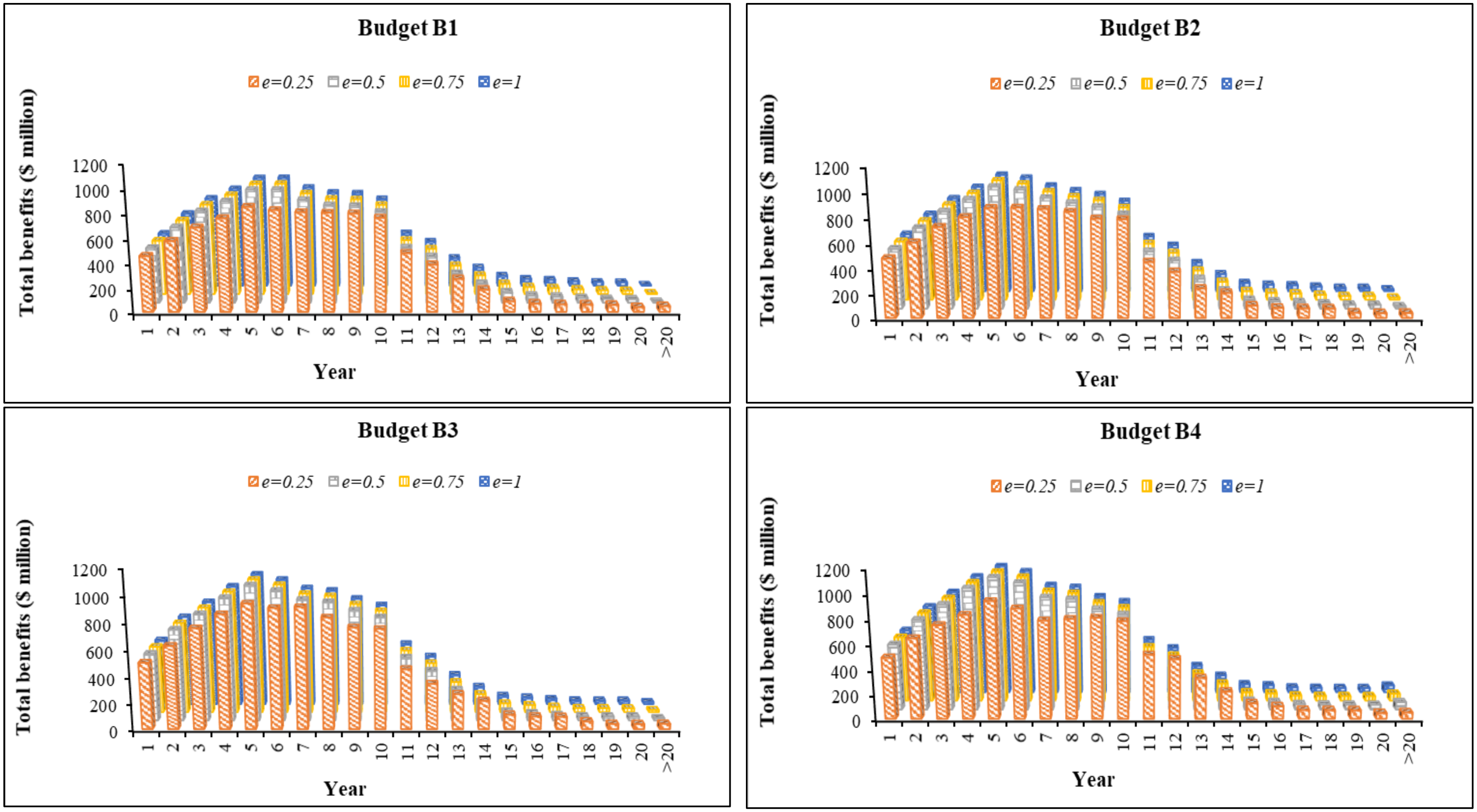


Figure 3: Benefits distribution by year, by model, and by budget



4(a): Benefits distribution of ***M3*** (Economic Competitiveness with Equity in Opportunity)



4(b): Benefits distribution of ***M4 (***Economic Competitiveness with Equity in Outcome)

Figure 4: Benefits distribution by year, equity parameters ($\mathscr{E}$ and *e*), and budget

4.3 Benefits by mode and improvement type

Table 5 shows the total benefits by mode and improvement type for the four different budgets. All models allocate almost all the benefits to the roadway which is intuitive as only one type of improvement (i.e., safety) is considered for rail. In addition, rail safety projects are less beneficial than roadway safety projects as fatal crashes in railroad-highway crossings are less common (at least in our dataset). Considering that the benefits of reducing PDO crashes are much lower than savings in freight travel time and fatal crashes, all models, excluding ***M3***, never selected any railroad safety projects. Railroad safety projects are selected by ***M3*** in those counties where there is no other type of candidate improvement projects. Another interesting result is that roadway safety projects contribute the maximum portion of total benefits almost in all models as the economic costs from crashes is higher than the freight travel time savings. In addition, highway operational projects are more beneficial than capacity expansion projects mainly because the cost of operational projects are lower and have added benefits (reduction in fatal crashes and emissions) compared to capacity expansion projects (FHWA 2017b).

Table 5: Total benefits in billion dollars by mode, by improvement type, by budget, by model, and by equity parameter

Model & equity parameter	Truck												Rail			
	Capacity expansion				Operational				Safety				Safety			
	B1	B2	B3	B4	B1	B2	B3	B4	B1	B2	B3	B4	B1	B2	B3	B4
M0	0.94	0.92	0.95	0.98	1.26	1.04	1.27	1.23	3.56	3.61	3.68	3.60	0	0	0	0
M1	1.20	1.28	1.28	1.33	3.95	4.24	4.58	4.86	4.64	4.65	4.66	4.67	0	0	0	0
M2	0.71	0.74	0.75	0.91	4.22	4.53	4.79	4.98	4.49	4.50	4.51	4.43	0	0	0	0
M3, $\mathcal{E}$=0	0.55	0.56	0.56	0.56	0.59	0.59	0.59	0.59	1.73	1.73	1.73	1.73	0.01	0.01	0.01	0.01
M3, $\mathcal{E}$=0.25	0.77	0.77	0.78	0.82	3.88	4.11	4.32	4.54	1.73	3.90	3.90	3.88	0.01	0.01	0.01	0.01
M3, $\mathcal{E}$=0.5	0.72	0.75	0.77	0.77	4.05	4.33	4.57	4.82	3.99	4.00	4.01	4.02	0.01	0.01	0.01	0.01
M3, $\mathcal{E}$=0.75	0.72	0.75	0.77	0.77	4.07	4.36	4.60	4.85	3.99	4.00	4.01	4.01	0.01	0.01	0.01	0.01
M3, $\mathcal{E}$=1	0.72	0.74	0.75	0.78	3.93	4.25	4.52	4.76	4.44	4.45	4.47	4.50	0.02	0.02	0.02	0.02
M4, e=0.25	0.92	0.93	0.93	1.01	3.88	4.12	4.37	4.52	4.38	4.38	4.39	4.38	0	0	0	0
M4, e=0.5	0.71	0.74	0.75	0.92	4.22	4.53	4.79	4.98	4.49	4.50	4.51	4.43	0	0	0	0
M4, e=0.75	0.71	0.74	0.75	0.91	4.22	4.53	4.79	4.98	4.49	4.50	4.51	4.43	0	0	0	0
M4, e=1	0.71	0.74	0.75	0.92	4.22	4.53	4.79	4.98	4.49	4.50	4.51	4.43	0	0	0	0

4.4 Benefits by counties

This subsection presents and discusses the results on distribution of benefits across counties. Recall that 51 out of the 95 counties in Tennessee had candidate improvement projects. A summary of the total benefits by county, budget, model, and equity parameter are presented in Table 6. ***M0*** distributes the budget to only 27 out of the 51 counties and, despite having the lowest coefficient of variation (CV) and highest minimum benefits received by a county among the five models, it exhibits the lowest number of counties receiving the benefits. This reinforces the observations from the results presented in the previous subsections, that this model may not be used. ***M1*** distributes projects in 31 counties and ***M2*** across 32 counties as mutual exclusiveness omits the possibility of selecting projects in the same location thereby increasing the possibility of projects belonging to different counties being selected.

M3 allocates benefits across all 51 counties with a very less benefits distributed all over the possible counties (see minimum county benefits in Table 6). This is because of the equity constraints in place making sure that each county receives at least one project in 10 years planning horizon. The pattern of benefit distribution across the counties in ***M3*** is similar for all values of equity with significantly lower benefits in case of 0. Then, only 32 counties are benefitted in ***M4*** where the maximum difference within maximum and minimum benefits between the counties is less than 25%, 50%, 75%, and 100% of total benefits for equity parameters 0.25, 0.5, 0.75, and 1 respectively. When the equity parameter is set 0, the model did not result in selecting any projects to satisfy the constraints. In this model, rather than the selection of more counties, the difference between the benefits received by any two counties is minimized. However, four counties (Knox, Hamilton, Davidson, and Shelby) are the top four benefitted counties regardless of the model and the equity parameter thereby highlighting the beneficial and important projects in these counties which need to be prioritized in the freight resource allocation.

Table 6: Summary statistics of county benefits by budget, by model, and by equity parameter

Model & equity parameter	Number of benefitted county				Min benefits in a county ($ billion)				Max benefits in a county ($ billion)				Coefficient of variation (CV) of benefits in a county ($ billion)			
	B1	B2	B3	B4	B1	B2	B3	B4	B1	B2	B3	B4	B1	B2	B3	B4
M0	27	27	27	27	0.02	0.02	0.02	0.02	1.15	1.04	1.20	1.07	1.35	1.25	1.34	1.29
M1	31	31	31	32	Y	Y	Y	Y	2.81	3.05	3.32	3.54	1.89	1.94	2.00	2.08
M2	31	32	32	32	Y	Y	Y	Y	3.02	3.24	3.39	3.51	2.00	2.09	2.12	2.11
M3, $\mathcal{E}$=0	51	51	51	51	Y	Y	Y	Y	0.38	0.38	0.38	0.38	1.41	1.39	1.39	1.39
M3, $\mathcal{E}$=0.25	51	51	51	51	Y	Y	Y	Y	2.93	3.14	3.18	3.21	2.90	2.97	2.97	2.93
M3, $\mathcal{E}$=0.5	51	51	51	51	Y	Y	Y	Y	3.08	3.28	3.41	3.64	2.90	2.95	2.97	3.04
M3 $\mathcal{E}$=0.75	51	51	51	51	Y	Y	Y	Y	3.08	3.28	3.42	3.49	2.90	2.94	2.98	2.94
M3, $\mathcal{E}$=1	51	51	51	51	Y	Y	Y	Y	2.90	3.18	3.34	3.48	2.67	2.75	2.78	2.82
M4, *e*=0.25	32	32	32	33	Y	Y	Y	Y	2.29	2.36	2.42	2.48	1.82	1.80	1.83	1.87
M4, *e*=0.5	31	32	32	32	Y	Y	Y	Y	3.02	3.24	3.40	3.50	2.00	2.09	2.12	2.11
M4, *e*=0.75	31	31	32	32	Y	Y	Y	Y	3.02	3.25	3.41	3.50	2.00	2.05	2.12	2.11
M4, *e*=1	31	32	32	32	Y	Y	Y	Y	3.02	3.25	3.39	3.50	2.00	2.09	2.12	2.11

Note: Y<=0.005

4.5 Sensitivity analysis

4.5.1 Benefits vs budget

In this subsection, we developed 18 new budget scenarios by increasing/decreasing budget B2. We used $\pm 10\%$ increment with a maximum/minimum budget of $\pm 90\%$ of B2. For this analysis, the equity in opportunity and outcome parameters values were set to 0.5 and 0.3 respectively as they provide the best tradeoff between equity and total benefits (see subsection 4.5.2 for a detailed discussion on the selection of these values). Results from this analysis are shown in Figure 5 where we observe that ***M0*** behaves in an unpredictable manner with cases in which the total benefits decrease with the increase of the total budget (e.g., while the total budget moves from 50% to 60% increment, the total benefits decrease by ~20%). As expected the remaining four models exhibit reasonable trends (i.e., an increase/decrease in the total budget results in an increase/decrease in the total benefits) with model ***M1*** exhibiting the largest and model ***M4*** the smallest slopes. Overall, we observe that for most models the relationship between available budget and benefits received is not linear. For policy analysis, it is helpful to assess the increase or decrease in benefits when compared to budget to augment decision making.

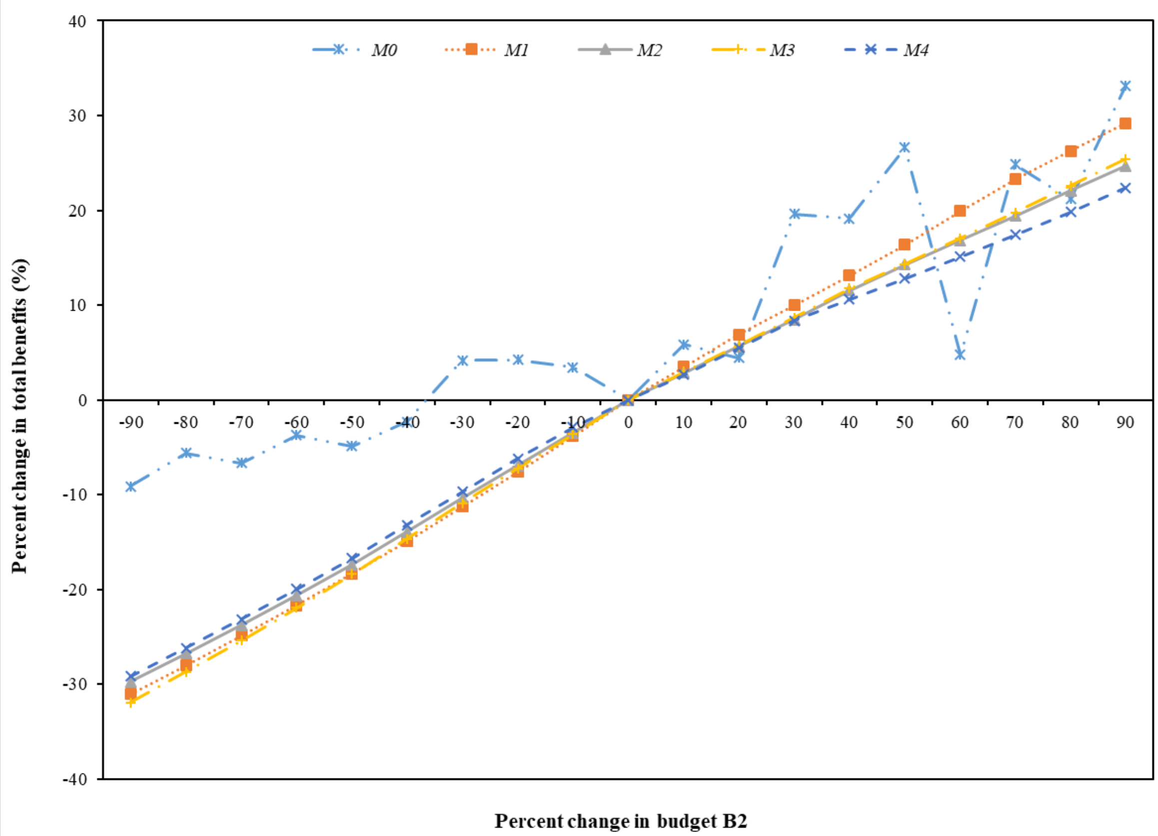


Figure 5: Variation of total benefits by budget and model (Note: B2 is 95.78 million dollars)

4.5.2 Benefits vs equity

This subsection shows the trade-off between the total benefits and the equity parameter values i.e., the lower the value of equity parameter ($\mathscr{E}$ and e), lower is the total benefits and vice versa. When the value of equity parameter is lower, the distribution is more equitable and vice versa (Mishra et al. 2015). Next, we present results from an analysis to quantify the effects of the equity parameters to the total benefits for the equity models ***M3*** and ***M4***.

4.5.2.1 Equity in Opportunity (*M3*)

Recall that the equity constraint (3-3) in ***M3***, restricts the difference of the number of selected projects between any two counties below a predefined value ($\mathcal{E} * d_{j\hat{j}}$) and acts as an equity measure (the lower its value the higher the equity). In this subsection, we present results from an analysis aimed at quantifying the change of the total benefits with respect to the value of the equity in opportunity parameter ($\mathcal{E}$). For this analysis, $\mathcal{E}$ value varied from 0 to 1 with an increment of 0.05 and the percent change of the total benefits with respect to the maximum total benefits (i.e., when $\mathcal{E}$=1) are shown in Figure 6. We observe that the curve patterns are very similar irrespective of the budget used (which was one of the reasons why we did not run the analysis for the nineteen different budgets used in subsection 4.5.1). Furthermore, we obsrerve that once ($\mathcal{E} \geq \sim 0.3$), the total benefits increase remains rather small (until a big jump is observed when the value of $\mathcal{E}$ increases from 0.95 to 1 because of a significant increase in number of projects at $\mathcal{E}$=1, for this particular dataset). This indicates a break point (or knee[4]) and suggests that a value of $0.3 < \mathcal{E} \leq 0.5$ would result in the optimal split between total benefits and equitable (in opportunity) distribution of projects. The break point is helpful for decision making as it suggests equitable allocation benefits to a specific budget considering equity in opportunity. Further deviation from the break point would result in inequitable allocation of benefits.

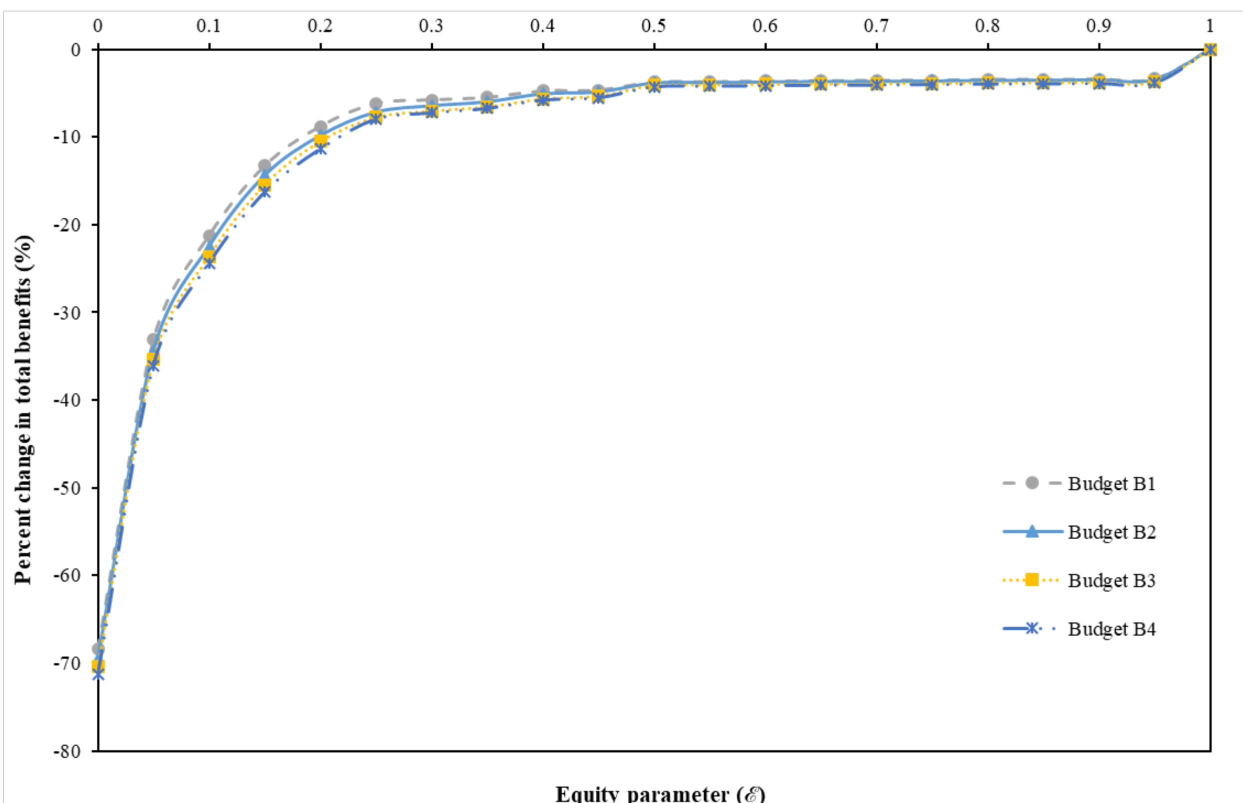


Figure 6: Total benefits vs. equity in opportunity parameter ($\mathcal{E}$) for different budgets (***M3***)

[4] The data points in Figure 6 form a Pareto Front. The "knee" is formed by those solutions of the Pareto front, where a small improvement in one objective would lead to a large deterioration in at least one other objective (Das 1999).

4.5.2.2 Equity in Outcome (*M4*)

Recall that the equity constraint (4-3) in ***M4***, restricts the difference between the maximum and minimum benefits received by the counties below a predefined value ($e \sum_{i,t} B_{Ti=0} X_{it}$) and, similar to $\mathscr{E}$, acts as an euqity measure (the lower its value the higher the equity. In this subsection, we present results from an analysis aimed at quantifying the change of the total benefits with respect to the value of the equity in outcome parameter (e) for four different budgets (B1, B2, B3, and B4). For this analysis, e values varied from 0 to 1 with an increment of 0.05 and the percent change of the total benefits with respect to the maximum total benefits (i.e., when $e = 1$) are shown in Figure 7. Similar to model ***M3***, we observe that the curve patterns are very similar irrespective of the budget used. Furthermore, we observe that once ($e \geq \sim 0.3$), the change of the total benefits becomes insignificant. This is a slightly different pattern from the one observed with model ***M3***, and indicates that a value of $0.2 \leq e \leq \sim 0.3$ would result in the optimal split between the total benefits and equitable (in outcome) distribution of benefits. We note that the equity parameters values where the knee is observed (for both ***M3*** and ***M4***) are significantly affected by the data. In such instances, these values should be re-estimated for any new dataset. Note, that the form of the graphs will remain the same (i.e., a concave form with reducing marginal total benefits as the values of $\mathscr{E}$ and e increase). Similar to equity in opportunity, equity in outcome sensitivity analysis shows the break point illustrating equitable allocation benefits to a specific budget. Equity in outcome sensitivity analysis outcome can be used in policy analysis when agencies are interested to gain benefits in an equitable mannger across all jurisductions included in consideration.

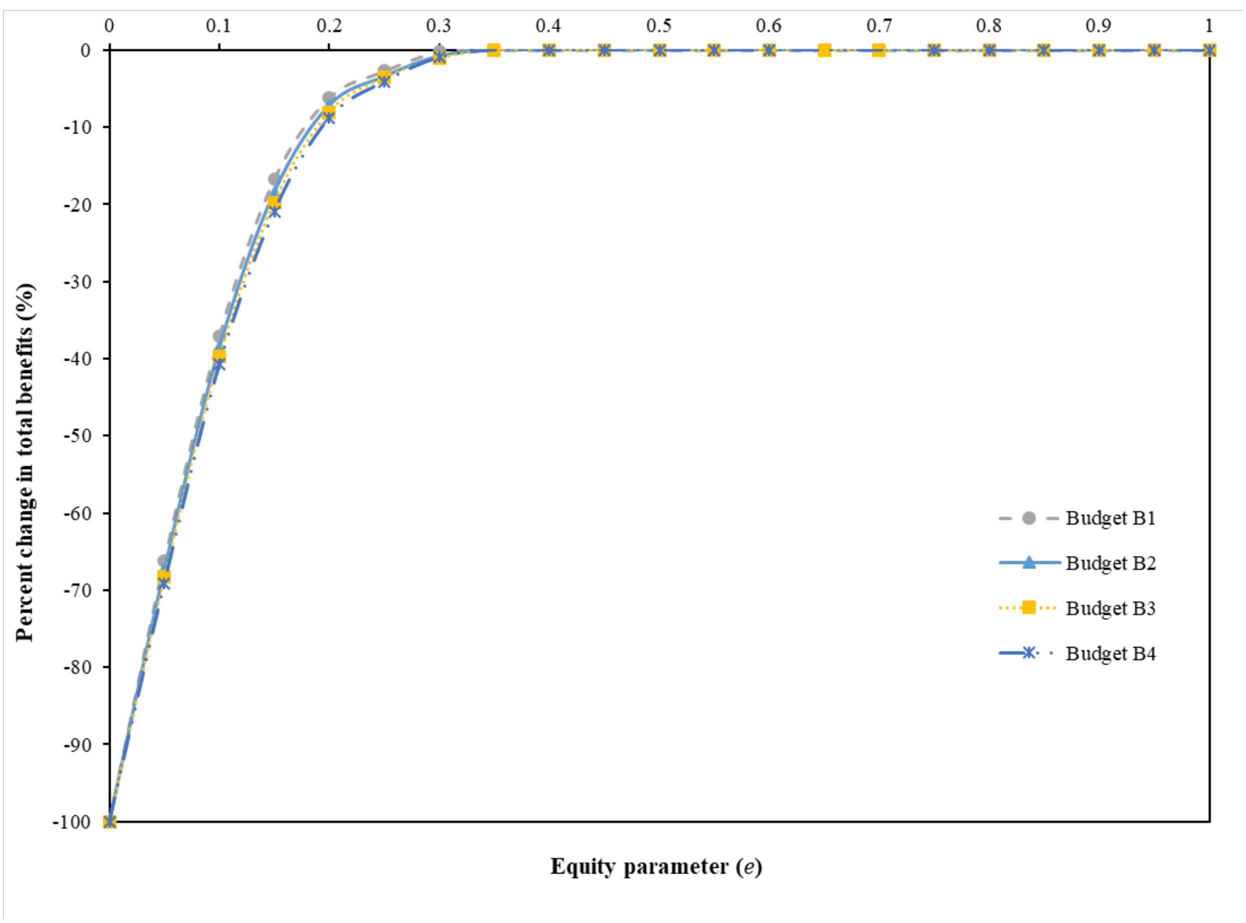


Figure 7: Total benefits vs. equity in outcome parameter (e) for different budgets (***M4***)

5. CONCLUSION

This paper developed a six-dimensional (modes, performance measures, improvement types, time periods, regions, and policies) freight resource allocation methodology that can be used for the allocation of funds to alleviate congestion and enhance safety. To the authors' best knowledge, this is the first paper that addresses freight resource allocation considering this combination of dimensions. The contribution of this paper in viewpoint of research and practice is twofold. First, the development of a set of multidimensional freight resource allocation models that public agencies can utilize considering policy, budget, and other constraints. Second, the application of the model to a real-world case and offering insights to public agencies to consider unique model features in various policy settings to augment prioritization of multimodal freight projects.

We developed four resource allocation models, each consisting of a unique policy, and compared results from these four models and from a model with a heuristic based project selection. Our results showed that introduction of equity in outcome does not reduce benefits significantly when compared to models without equity while introduction of equity in opportunity results in significant benefits reduction. We found that the addition of mutual exclusiveness constraint increases the total number of projects for all budgets but at the cost of lower total benefits. We observed that the benefit distribution over time follows a bell-shaped curve with a long right-side tail indicating a trade-off between the value of interest rate and the number of projects selected every year. Sensitivity analysis of the models revealed that for most models the relationship between budget and benefits received is nonlinear. Also, there exists an equity value breakpoint beyond which reduction of equity does not result in a significant increase of benefits. Future research could focus on the following: i) inclusion of additional modes, ii) inclusion of maintenance and operations costs, iii) generation of benefits after a pre-specified time period of project completion, and iv) consideration of a diverse and conflicting set of objectives in a multi-objective resource allocation modeling framework. The former three future research items can be easily included in the models and solved using the same solution algorithms presented in this research. The last research item would require significant effort (e.g., introduction of new decision variables and constraints) and, most likely, a metaheuristic solution algorithm to be developed.

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