MULTIDIMENSIONAL RESOURCE ALLOCATION IN FREIGHT TRANSPORTATION PLANNING: A CASE STUDY OF TENNESSEE

by

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A Thesis
Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science

Major: Civil Engineering

The University of Memphis
August 2018
Acknowledgments

I would first like to thank my thesis advisor, assistant professor, Dr. Sabya Mishra of the Department of Civil Engineering at the University of Memphis. The door to Dr. Mishra’s office was always open whenever I had a question about my research or writing. He consistently allowed this thesis to be my own work but steered me in the right direction by providing valuable inputs whenever he thought I needed it.

I would also like to thank associate professor, Dr. Mihalis Golias of the Department of Civil Engineering at the University of Memphis and the second reader of this thesis, who constantly strived for the betterment of this thesis and added his expertise in the model formulation. I would like to appreciate the valuable efforts of Dr. Ahmadreza Talebian for his continuous guidance and feedbacks on the data analysis and writing of this research. Without their passionate participation and input, this work could not have been successfully conducted.

I would also like to acknowledge adjunct faculty, Dr. Mohamed Osman of the Department of Civil Engineering at the University of Memphis as the third reader of this thesis, and I am gratefully indebted to him for his very valuable comments on this thesis. I would like to thank Tennessee Department of Transportation (TDOT) for providing fund, data, and support for this research.

Finally, I must express my very profound gratitude to my parents and my brothers for providing me with unfailing support and continuous encouragement throughout my years of study and
through the process of researching and writing this thesis. This accomplishment would not have been possible without them. Thank you.

Author
Santosh Bhattarai
Abstract

This thesis develops the multidimensional resource allocation models to prioritize the freight improvement projects. Multiple dimensions of the model include transportation modes, performance measures, improvement types, geographic regions, policy criteria, and planning horizon. The total benefits is maximized subject to budget, policy, and other constraints. Four models are developed based on four different policies including economic competitiveness with and without mutual exclusiveness in location, equity in opportunity, and equity in outcome. Models are compared with each other as well as a non-optimization model, where resources are allocated based on maximum benefits. The models are applied in the State of Tennessee considering two modes, three improvement types consisting of over 2,000 projects in 51 counties, and a 10-year planning horizon. The results show that the project selection based on equity in outcome provides total benefits that are very close to the maximum and still provides equitable distribution of these benefits.
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1. Introduction

The economy of a region highly depends on freight activities. According to the Federal Highway Administration (FHWA), freight volume is expected to grow over 60% over next 25 years (FHWA, 2017a). The America’s Surface Transportation Act, referred 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, Masliah, & Park, 2015). In the last few years, State DOTs have started the planning process to develop ways to utilize scarce resources in prioritizing freight improvement projects. The freight planning prioritization process consists of three steps: (i) identification of problematic sections (or projects) of multimodal freight network; (ii) development of alternatives for each project; and (iii) allocation of the resources in the multimodal freight network consisting of numerous projects and limited funds. While the first two steps are based on engineering design, the third step is a resource allocation problem.

To the best of the author’s knowledge, resource allocation for freight improvement is missing from literature. The contribution of this thesis is twofold. First, development of a resource allocation model that considers various policies State DOTs encounter in decision making. Second, application of the model in a real-world case study and insights for public agencies to consider unique model features in various policy settings to augment prioritization of multimodal freight projects. Development of such models poses some new challenges as it includes multiple dimensions. The first dimension is multimodality, as freight network consists of truck, rail, air, water, and pipeline working together. The second dimension is performance measures. State DOTs typically deal with multiple performance measures such as congestion, air
quality, safety, and others. The third dimension pertains to the improvement projects proposed for addressing the problematic sections of the freight network, and the benefits and costs associated with each. The fourth dimension is geographic regions. A State consists of multiple counties, and multiple projects belonging to each mode and performance measure are identified within each county. The fifth dimension is policy considerations. Each State has some policies such as economic competitiveness, carryover of surplus to next fiscal year, equitable funds allocation, etc. Finally, the sixth dimension revolves around time. Typically, agencies do not plan on a year-by-year basis, 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. to invest now or to wait, is important.

The resource allocation problem has been investigated by researchers in various fields including transportation, safety, production, and energy. In the rest of this chapter, the relevant literature is reviewed to learn different approaches employed by researchers to address the resource allocation problem. Various sectors in the transportation arena employ mathematical techniques to effectively and efficiently allocate scarce resources among agents/units. For example, (Churchill & Lovell, 2012) present a stochastic programming model to coordinate matching flights to the slots at congested airports. The proposed problem differs from previous models such that it explicitly takes into consideration uncertainty in capacity of air transportation resources (i.e., airports and air space regions). (Kim & Hansen, 2013) develop a framework to evaluate different strategies employed to allocate ground delays to flights in order to limit flow through the constrained capacity of airspace regions. Four allocation strategies are evaluated: full information system-optimal, parametric system-optimal, first-submitted first-assigned, and ration-by-schedule. (Zargayouna, Balbo, & Ndiaye, 2016) develop an optimization model for efficient allocation of parking spaces to drivers. The objective of this problem is reduce search
time for drivers with dynamic geographical positions. Difficulty of this problem arises from nondeterministic appearance of the agents, i.e., drivers. (Sheu, 2006) proposes a dynamic customer group-based logistics resource allocation methodology for the use of demand-based responsive distribution. The uniqueness of the model is the introduction of time value of money. By coupling optimization and simulation techniques, (Sánchez-Martínez, Koutsopoulos, & Wilson, 2016) proposes a framework to allocate a fixed number of buses to a group of routes. The model maximizes service frequency but maintains the existing service frequencies and operating strategies. (Wang, 2016) considers a containerized cargo transportation problem in which the freight operator allocates uncertain capacities to products to maximize its profit. The problem is formulated as a constrained stochastic programming model. (Wang, Wang, & Zhang, 2016) propose stochastic programming models to allocate seats to each cabin class for each train service. Stochasticity of the problem arises from random demand and passenger choice behavior. (Vasco & Morabito, 2016) study the problem of movement of a fleet of vehicles transporting goods between terminals. The problem is formulated as an integer programming model and emphasis is given to problem solving in real-world situations using heuristic methods including greedy randomized adaptive search and simulated annealing. (Wey & Wu, 2007) propose an analytic network process approach considering interdependencies among evaluation criteria and candidate projects. (Melkote & Daskin, 2001) investigate a resource allocation model that simultaneously optimizes facility locations and design of the underlying transportation network using budgeting and planning decisions.

The resource allocation model has been widely used in safety projects to find the optimal policy scenarios. (Kar & Datta, 2004) develop a model to implement safety projects in high-priority areas in Michigan. Based on a set of safety performance index values, the authors
develop an optimal resource-allocation model using linear programming to achieve the overall safety benefits. (Lambert, Baker, & Peterson, 2003) address the need for allocation of resources to run-off-road and fixed object hazards on immense secondary road systems. Transportation researchers analyzed various policies that are specific to unique resource allocation models. For example, the concept of equity was introduced to reduce the difference in the distribution of the resources among sub-regions within a larger region. (Mathew, Khasnabis, & Mishra, 2010) describe the procedure of equitable resource allocation among transit agencies for the purpose of transit fleet management. (Mishra, Golias, Sharma, & Boyles, 2015) discuss the equity constraints for a set of safety projects in urban intersections, each of which can have different alternatives. These constraints are based on the policies of equitable allocation in outcome benefits among counties and minimum budget for subset of locations. Another policy used in the literature was the mutual exclusiveness of project allocation to locations meaning thereby a given location can receive at most one project. (Fang & Li, 2015) use a resource allocation model to analyze mutual exclusivity of projects in centralized and decentralized systems of operation.

Apart from transportation, (Luscombe & Kozan, 2016) integrate the theory of parallel machine and flexible job shop environments to assign patients to beds for managing the scarce resources of the emergency department. This problem has a dynamic nature as assignments are performed in a real-time fashion. (Arora, Raghu, & Vinze, 2010) develop a quadratic optimization model for allocating regional aid during public health emergencies. The objective function, which is square of the lost benefits due to a non-availability of resources, is minimized subject to a set of constraints ensuring equitability of allocation across regions. (Fiedrich, Gehbauer, & Rickers, 2000) introduce a dynamic optimization model that uses detailed descriptions of the operation areas and the available resources to calculate the resource
performance and efficiency for different tasks, immediately after a strong earthquake. (Rauch & Casella, 2003) develop a model that is applied to the trade and wages debate to address whether ties can reduce the world welfare through trade diversion, and to compare the effect of ties on trade in differentiated versus homogeneous products. (Vidal & Goetschalckx, 2001) present a model for the optimization of after tax profits for multinational corporation. This model includes the transfer prices and the allocation of transportation costs as explicit decision variables. (Li, Chen, & Tao, 2016) couple queuing and optimization models to study demand allocation and pricing in an energy market consisting of two providers that are renewable and fossil-based energy providers. When the queue length for renewable energy increased, new customers originally interested in renewable energy service might select fossil-fired energy service. By allocating server capacity and pricing each service, service providers maximize their profits.

Despite the rich literature on resource allocation, no systematic approach is developed to prioritize freight improvement projects based on specific dimensions of freight transportation systems. This thesis fills this gap by developing a set of resource allocation models that explicitly capture various dimensions of freight operations. The rest of the thesis is organized as follows. The methodology is put forward in chapter 2, followed by description of data in chapter 3. Model results are discussed in chapter 4. The thesis concludes with major findings and directions for the future research in chapter 5.
2. Methodology

In this chapter, integer programming models are developed to prioritize freight improvement projects based on specific features of freight transportation systems discussed in the previous chapter. Notations used in the models are presented in Table 1. It is assumed that there exists a pre-specified set of projects $I$, in which each project relates to a specific mode, location, and improvement type. The benefits and costs of implementation of each project are assumed to be given. The total benefits are calculated as the present worth (PW) of all the annual benefits over the service life $n$ of the selected projects adjusted with annual interest rate $\alpha$ and expected annual growth of benefits with increasing infrastructure users $\beta$ in cash flow. The budget remaining at the end of each year (surplus budget), that cannot afford any project, is carried to the successive year to maximize the total benefits. Four resource allocation models based on four different policies are put forward to select the optimal set of projects. These policies are formalized in this chapter.

Before presenting and discussing the four optimization models, it is worth establishing a base model to facilitate model comparison. The base project selection model (in this thesis) is obtained using a simple benefit sorting algorithm in which projects in $I$ are sorted in descending order of total benefits assuming they will be implemented at the first year. The projects with the highest benefits are then selected conditional the available budget of that year. The selected projects are removed from set $I$, any remaining budget is added to the budget of the following year and the process is repeated for all the years (from second to tenth) in the planning horizon. This intuitive sorting model is termed as the base model which is referred to as $M0$ in this thesis.
<table>
<thead>
<tr>
<th>Type</th>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sets</strong></td>
<td>$I, i$</td>
<td>Set and index of projects</td>
</tr>
<tr>
<td></td>
<td>$J, j$</td>
<td>Set and index of counties</td>
</tr>
<tr>
<td></td>
<td>$T, t$</td>
<td>Set and index of time periods of planning horizon</td>
</tr>
<tr>
<td></td>
<td>$L, l$</td>
<td>Set and index of locations</td>
</tr>
<tr>
<td><strong>Parameters</strong></td>
<td>$B_{it=0}$</td>
<td>Annual benefits from project $i$ calculated at time $t=0$</td>
</tr>
<tr>
<td></td>
<td>$B_{Tt=0}$</td>
<td>$B_{it=0} - \frac{B_{it=0}(1+\beta)^{t}}{(\alpha-\beta)} \left[ 1 - \left( \frac{1+\beta}{1+\alpha} \right)^{n} \right] \frac{1}{(1+\alpha)^{t-1}}$, Total benefits from project $i$ at time $t=0$</td>
</tr>
<tr>
<td></td>
<td>$K_{it=0}$</td>
<td>Construction costs of project $i$ calculated at time $t=0$</td>
</tr>
<tr>
<td></td>
<td>$\gamma$</td>
<td>Expected annual growth rate of costs</td>
</tr>
<tr>
<td></td>
<td>$K_{it}$</td>
<td>$= K_{it=0} \ast (1 + \gamma)^{t-1}$, Construction costs of project $i$ at time $t$</td>
</tr>
<tr>
<td></td>
<td>$g_{ij}$</td>
<td>Binary parameter indicating if project $i$ lies in county $j$</td>
</tr>
<tr>
<td></td>
<td>$h_{ll}$</td>
<td>Binary parameter indicating if project $i$ lies on location $l$</td>
</tr>
<tr>
<td></td>
<td>$d_{jj}, j \neq j \in J$</td>
<td>$= \max(\sum_{l} g_{ij} - \sum_{l} g_{ij}, \sum_{l} g_{ij} - \sum_{l} g_{ij})$, maximum difference in number of the candidate projects between county $j$ and $j$</td>
</tr>
<tr>
<td></td>
<td>$\varepsilon$</td>
<td>Equity parameter multiplied to $d_{jj}$, constraining the maximum allowable difference in number of projects between county $j$ and $j$ over planning horizon</td>
</tr>
<tr>
<td></td>
<td>$P^t$</td>
<td>Budget for all improvement projects at time $t$</td>
</tr>
<tr>
<td></td>
<td>$e$</td>
<td>Factor of the total benefits, restricting the maximum difference in benefits between any two counties</td>
</tr>
<tr>
<td><strong>Variables</strong></td>
<td>$X_{it}$</td>
<td>Binary decision variable denoting if project $i$ is chosen at time $t$</td>
</tr>
<tr>
<td></td>
<td>$SP_{t-1}$</td>
<td>Carry over budget from year $t-1$ to year $t$</td>
</tr>
<tr>
<td></td>
<td>$R$</td>
<td>Maximum benefits that can be allocated to any county</td>
</tr>
<tr>
<td></td>
<td>$S$</td>
<td>Minimum benefits that can be allocated to any county</td>
</tr>
</tbody>
</table>
**M1: Economic Competitiveness**

As economic competitiveness is one of the major goals of USDOT’s strategic plan (USDOT, 2012), this policy has been incorporated in the first model *M1* of this thesis shown in 1.1 through 1.5. *M1* is a resource allocation model, in which total benefits are maximized (1.1) subject to budgetary constraints. Constraints set (1.2) ensures that the project selection does not exceed the available budget of each year. Constraints set (1.3) ensures that each project *i* is selected only once over the planning horizon. Constraints set (1.4) carries over any unspent portion of the budget from time period *t* to *t+1*. In this thesis, *SP* 0 is assumed zero. Constraints set (1.5) defines the binary restrictions of the decision variables.

\[
M1: \max \sum_{i,t} B_{it} X_{it} \tag{1.1}
\]

Subject to

\[
\sum_i K_{it} X_{it} \leq P_t + SP_{t-1} \quad \forall t \in T \tag{1.2}
\]

\[
\sum_i X_{it} \leq 1 \quad \forall i \in I \tag{1.3}
\]

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

\[
X_{it} \in \{0,1\} \tag{1.5}
\]

**M2: Economic Competitiveness with Mutual Exclusiveness**

Model *M2* ((2.1)-(2.2)) extends *M1* by adding a mutual exclusiveness constraint (constraints set 2.2) to ensure that a location cannot be assigned more than one project over the planning horizon. The rational for introducing this constraint is to increase (or 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 in same location. In that scenario, the model might end up selecting very few projects with huge leftover budget.
M2: \( \max \sum_{t,l} B_{\tau_l} X_{lt} \)  

Subject to 
(1.2)-(1.5) 
\( \sum_{t,l} X_{lt} h_{lt} \leq 1 \quad \forall \ l \in L \)  

M3: Economic Competitiveness with Equity in Opportunity

Model M3 is introduced to distribute the available funds in a fair manner among the counties. Fairness is introduced via constraints sets (3.2) and (3.3) that bound the difference in the number of projects selected between any two counties. Constraints set (3.2) ensures that at least one project is selected in each county while constraints 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, \( \mathcal{E}_{j} \)) of the difference in the number of candidate projects for each county pair \( (d_{jj}) \). 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 \((10-3) \mathcal{E}_{j} \) or \(7 \mathcal{E}_{j} \). Note that the equity in opportunity parameter for any county pair is assumed to be same in this thesis (i.e., \( \mathcal{E}_{j} = \mathcal{E}_{kk} \forall j, j, k, \bar{k} \in J | j \neq \bar{j}, k \neq \bar{k} \)).

M3: \( \max \sum_{t,l} B_{\tau_l} X_{lt} \)

Subject to 
(1.2)-(1.5), (2.2) 
\( \sum_{t,l} X_{lt} g_{lj} \geq 1 \quad \forall \ j \in J \)  
\( |\sum_{t,l} X_{lt} g_{lj} - \sum_{t,l} X_{lt} g_{lj}| \leq \mathcal{E}_{jj} d_{jj} \quad \forall \ j, j \in J | j \neq \bar{j} \)
**M4: Economic Competitiveness with Equity in Outcome**

*M3* distributes the available resources across the 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 address equity in outcome, constraints (4.2)-(4.4) are added to *M2* and the resulting model is termed, model *M4*. Constraints set (4.2) bounds the benefits of each county between the upper ($R$) and lower bounds ($S$). Constraints set (4.3) ensures that the difference between $R$ and $S$ is less than a pre-specified percentage (i.e., equity in opportunity parameter $e$) of the total benefits. Constraints set (4.4) states that the lower and upper bounds cannot be negative. 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.

**M4:** $\max \sum_{t\tau} B_{\tau t=0} X_{\tau t}$

Subject to

(1.2)-(1.5), (2.2)

\[ R \geq \sum_{t\tau} B_{\tau t=0} X_{\tau t} g_{tj} \geq S \quad \forall \ j \in J \]  
(4.2)

\[ R - S \leq e \sum_{t\tau} B_{\tau t=0} X_{\tau t} \]  
(4.3)

\[ R, S \geq 0 \]  
(4.4)
3. Model Application

Study Area

The models formulated in Chapter 2 is applied in the freight corridor for the State of Tennessee. The multimodal freight network of Tennessee consists of over 28,413 miles of functionally classified roadway, over 1,200 miles of railway, 949 miles of navigable waterway, and 3,360 miles of pipeline (TDOT, 2016; USDOE, 2016). Because of unavailability of data, only truck and rail modes are considered for the model application. There is a total of 2,238 candidate projects in 51 counties, over a 10-year planning horizon.

Data Preparation

In this section, 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, because of unavailability of data, only safety performance measure is used for identification of potential locations.

Data collection. Three major sources of data have been used for identification of freight improvement projects related to truck. These are Statewide Travel Demand Model (S-TDM), National Performance Management Research Data Set (NPMRDS), and 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 crossing crash, etc. Roadway inventory and crash data for all the public roads, including the roads crossing 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 last 15 years are identified along the interstates and expressways as well as railroad-highway crossing.

**Projects identification.** In this thesis, candidate project locations and the corresponding improvements are selected based on the following three criteria.

*Congestion performance.* This is the first criteria to select the candidate project locations. Any roadway segment with volume to capacity ratio (VCR) greater than or equal to 0.8 and truck volume to total volume percentage (TP) greater than or equal to 20%. VCR and TP are computed from S-TDM. Capacity expansion projects (one and two-lane addition) are proposed as the improvements for these segments.

*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). Increase in the speed limit is proposed with projects such as patching and rehabilitation, and asphalt overlays.

*Safety performance.* Any roadway segment having a fatal crash rate greater than 1 per mile. Fatal, injury, property damage only, and total crash on roadway and railroad-highway crossing are obtained from ETRIMS. Similarly, vulnerable railroad crossing segments are identified from the accident probability given in the dataset. For these segments, countermeasures recommended in the Highway Safety Manual (HSM) are proposed. Similarly,
three types of countermeasures (flashing lights, median, and gates) are used as safety countermeasures for railroad-highway crossing (Konur, Golias, & Darks, 2013; Volmer et al., 2006).

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

Table 2: Parameter values used in case study

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatal</td>
<td>4,008,900</td>
<td>$/crash</td>
<td>(Herbel, Laing, &amp; McGovern, 2010)</td>
</tr>
<tr>
<td>Injury</td>
<td>113,300</td>
<td>$/crash</td>
<td></td>
</tr>
<tr>
<td>PDO</td>
<td>7,400</td>
<td>$/crash</td>
<td></td>
</tr>
<tr>
<td>Crash reduction factor (Signs)</td>
<td>0.35</td>
<td>Per crash</td>
<td>(Bahar, Masliah, Wolff, &amp; Park, 2008; Scopatz et al., 2014)</td>
</tr>
<tr>
<td>Crash reduction factor (Pavement Friction)</td>
<td>0.75</td>
<td>Per crash</td>
<td></td>
</tr>
<tr>
<td>Crash reduction factor (Flashing Lights)</td>
<td>Single track-0.9, multiple track-0.65</td>
<td>Per crash</td>
<td></td>
</tr>
<tr>
<td>Crash reduction factor (Gates)</td>
<td>Single track-0.7, multiple track-0.65</td>
<td>Per crash</td>
<td></td>
</tr>
<tr>
<td>Crash reduction factor (Median)</td>
<td>0.8</td>
<td>Per crash</td>
<td></td>
</tr>
</tbody>
</table>

1 Data in Belenky (2011) was adjusted to 2017 values assuming an annual interest rate of 4%
Projects Summary. Expected annual benefits, construction costs, and service life of each project are estimated based on engineering design and not presented in this thesis for brevity. The sample input data with first five and the last candidate projects is shown in Table 3. Projects costs 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 operational type of improvements. Safety projects have the highest benefits to costs ratio (23.25) and are the most beneficial project type.

Project construction time is not taken into consideration in this thesis (the model starts generating profit from the same year of project selection) as this thesis focuses mainly on the model formulation. Construction time can be added to all the models presented in this thesis in a straightforward manner (i.e., setting $B_{T_i=0} = \frac{B_{it=0}*(1+\beta)^{t+ct_i}}{(\alpha-\beta)} \left[ 1 - \left( \frac{1+\beta}{1+\alpha} \right)^n \right] * \frac{1}{(1+\alpha)^{t-1+ct_i}}$, where $ct_i$ is the construction time of project $i$) but this addition is to be facilitated through future research.
### Table 3: Sample data of candidate project details

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

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

<table>
<thead>
<tr>
<th>Improvement Type</th>
<th>Benefits ($ billion)</th>
<th>Costs ($ million)</th>
<th>Number of Projects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Truck</td>
<td>Rail</td>
<td>Truck</td>
</tr>
<tr>
<td>Capacity</td>
<td>2.944 (11.3%)</td>
<td>-</td>
<td>420.413 (15.4%)</td>
</tr>
<tr>
<td>Operation</td>
<td>18.076 (69.7%)</td>
<td>-</td>
<td>2,254.299 (82.7%)</td>
</tr>
<tr>
<td>Safety</td>
<td>4.821 (18.6%)</td>
<td>0.075 (0.3%)</td>
<td>22.479 (0.8%)</td>
</tr>
<tr>
<td>Total</td>
<td>25.841</td>
<td>0.075</td>
<td>2,697.191</td>
</tr>
<tr>
<td>Grand Total</td>
<td>25.916</td>
<td></td>
<td>2,726.263</td>
</tr>
</tbody>
</table>
4. Results

In this thesis, four different budget scenarios of $86.20, $95.78, $105.36, and $115.896 million are assumed 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 in B2 for B1 and B3 respectively and again 10% increase in B3 for B4. Five values (0, 0.25, 0.5, 0.75, and 1) for the equity in opportunity and outcome parameters (ℰ and 𝑒 respectively) are also considered. These values are estimated from a sensitivity analysis that is presented in later in this chapter. 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. All four models are solved using the IBM ILOG CPLEX Optimizer V12.7 on an Intel Core i7-3770 3.4 GHz CPU personal computer with 16 GB of RAM. The optimality gap is set equal to 1.0 x 10⁻¹⁰. The maximum solution time is approximately 17 minutes which is reasonable, considering the planning nature of this thesis.

In the remainder of this chapter, the total benefits and the number of selected projects by each model during the planning horizon are presented first followed by the distribution of total benefits over the year of project implementation. Then the total benefits received by each mode and improvement type are discussed followed by the distribution of total benefits across the counties in Tennessee. The chapter concludes with a sensitivity analysis of the total benefits with respect to the budget and the equity parameters.
Benefits by Time Period

Figure 1 shows the total benefits and the total number of projects selected by the first three models (M0, M1, and M2) for the four different budgets. Since B1, B3, and B4 are developed with respect to B2, the numbers presented in this chapter without reference to any budget correspond to B2. As expected, the total benefits and number of projects from M1 are higher than in M0 for all the four budgets. 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, which is the trade-off the decision maker decides to accept. As expected, the higher the total budget, higher is 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 to be expected due to the heuristic nature of project selection (discussed more in the sensitivity analysis section).

Figure 1: Total benefits and number of selected projects by budget and by model
Figure 2 shows the same information as Figure 1 for models \( M3 \) and \( M4 \) with the addition of one more dimension i.e., the equity parameters \( \varepsilon \) and \( e \). When the equity parameter value is set to zero, the most equitable distribution among various modes, improvement types, and counties with the lowest total benefits for both \( M3 \) and \( M4 \) are obtained. Increasing the equity parameters values, equity constraints sets 3.3 and 4.3 are relaxed, the benefits distribution becomes less equitable, and the total benefits increase. This pattern is observed across all four budgets for both \( M3 \) and \( M4 \). One interesting observation is that for values of \( e \) greater than 0.5, \( M4 \) produces the same total benefits as \( M2 \) which means that constraints 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 later in sensitivity analysis. The author would like to note that:

1. When \( e = 0 \) 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 model \( M4 \) (when \( e=0 \)) will exist (for any real-world data) such that the minimum and maximum benefits received by all counties are equal to the same constant;

2. Model \( M3 \) results in the least total benefits, compared to other resource allocation models, suggesting that equity in opportunity policy should be very carefully analyzed before implementation.

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Figure 2: Total benefits and number of selected projects by budget, by equity parameter, and by model

2(a): Total benefits and number of selected projects for M3

2(b): Total benefits and number of selected projects for M4

Total benefits by year and budget are shown in Figure 3 (for models M0 through M2) and Figure 4 (for models M3 and M4) where a concave form is observed. This phenomenon 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. As seen in Figure 3, yearly total benefits from M1 and M2 are almost identical (for the same budget) with M1 producing slightly higher benefits for all years. It is also observed that around year 20, all three models for all budgets result in similar (low) yearly total benefits ending in year 25, 29, and...
28 for models $M0$, $M1$, and $M2$ respectively. The slightly different pattern of $M0$ for the different budgets again highlights the randomness of the model (see Figure 3).

In Figure 4, in addition to the four different budgets, the dimension of the equity parameters is added. From the results shown in Figure 4, it is observed that the yearly total benefits increase with the values of the equity parameters $\mathcal{E}$ and $e$ although the pattern over the years remains the same. However, in the case of $M3$, there is a significant jump in benefits when $\mathcal{E}$ increase from 0 to 0.25 with very small change thereafter (i.e., for $\mathcal{E} \geq 0.5$). The same results are observed for model $M4$ when $e \geq 0.25$. 
Figure 3: Total benefits distribution by year, by model, and by budget
4(a): Total benefits distribution for M3 (Economic Competitiveness with Equity in Opportunity)
4(b): Total benefits distribution for \textit{M4} (Economic Competitiveness with Equity in Outcome)

Figure 4: Total benefits distribution by year, by equity parameters ($\ell$ and $e$), and by budget
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 crossing 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, with the exception of $M3$, never select any railroad safety projects. Railroad safety projects are selected by $M3$ in those counties where there is no other type of candidate improvement projects. The other interesting result to note 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

<table>
<thead>
<tr>
<th>Model &amp; equity parameter</th>
<th>Truck</th>
<th>Rail</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Capacity expansion</td>
<td>Operational</td>
</tr>
<tr>
<td><strong>M0</strong></td>
<td>0.937</td>
<td>0.918</td>
</tr>
<tr>
<td><strong>M1</strong></td>
<td>1.197</td>
<td>1.277</td>
</tr>
<tr>
<td><strong>M2</strong></td>
<td>0.715</td>
<td>0.737</td>
</tr>
<tr>
<td><strong>M3, ε=0</strong></td>
<td>0.548</td>
<td>0.558</td>
</tr>
<tr>
<td><strong>M3, ε=0.25</strong></td>
<td>0.768</td>
<td>0.770</td>
</tr>
<tr>
<td><strong>M3, ε=0.5</strong></td>
<td>0.718</td>
<td>0.752</td>
</tr>
<tr>
<td><strong>M3, ε=0.75</strong></td>
<td>0.717</td>
<td>0.748</td>
</tr>
<tr>
<td><strong>M3, ε=1</strong></td>
<td>0.718</td>
<td>0.741</td>
</tr>
<tr>
<td><strong>M4, e=0.25</strong></td>
<td>0.922</td>
<td>0.926</td>
</tr>
<tr>
<td><strong>M4, e=0.5</strong></td>
<td>0.715</td>
<td>0.737</td>
</tr>
<tr>
<td><strong>M4, e=0.75</strong></td>
<td>0.715</td>
<td>0.737</td>
</tr>
<tr>
<td><strong>M4, e=1</strong></td>
<td>0.715</td>
<td>0.737</td>
</tr>
</tbody>
</table>
Benefits by County

In this section, results on the benefits distribution by county are presented. 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. $M_0$ 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 sections indicating that this model should not be used. $M_1$ distributes projects in 31 counties and $M_2$ 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.

$M_3$ allocates benefits across all 51 counties with much less benefits distributed over all the possible counties (see minimum county benefits in Table 6). This is because of the equity constraints in place assuring each county receives at least one project in the 10-year planning horizon. The pattern of benefits distribution across the counties in $M_3$ is similar for all values of equity with significantly lower benefits in case of 0. Then, only 32 counties are benefitted in $M_4$ 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 parameter 0.25, 0.5, 0.75, and 1 respectively. When the equity parameter is set 0, the model ends up selecting no projects at all 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 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

<table>
<thead>
<tr>
<th>Model &amp; equity parameter</th>
<th>Number of benefitted county</th>
<th>Min benefits in a county ($ billion)</th>
<th>Max benefits in a county ($ billion)</th>
<th>Coefficient of variation (CV) of benefits in a county ($ billion)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>M0</strong></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>27</td>
<td>27</td>
<td>27</td>
<td>27</td>
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<tr>
<td><strong>M1</strong></td>
<td></td>
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<tr>
<td></td>
<td>31</td>
<td>31</td>
<td>31</td>
<td>32</td>
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<tr>
<td><strong>M2</strong></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>31</td>
<td>32</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td><strong>M3, ( \varepsilon=0 )</strong></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>51</td>
<td>51</td>
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<tr>
<td><strong>M3, ( \varepsilon=0.25 )</strong></td>
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<td></td>
<td>51</td>
<td>51</td>
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<tr>
<td><strong>M3, ( \varepsilon=0.5 )</strong></td>
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<td>51</td>
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<tr>
<td><strong>M3, ( \varepsilon=0.75 )</strong></td>
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<td></td>
<td>51</td>
<td>51</td>
<td>51</td>
<td>51</td>
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<tr>
<td><strong>M3, ( \varepsilon=1 )</strong></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>51</td>
<td>51</td>
<td>51</td>
<td>51</td>
</tr>
<tr>
<td><strong>M4, ( \varepsilon=0.25 )</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>32</td>
<td>32</td>
<td>33</td>
</tr>
<tr>
<td><strong>M4, ( \varepsilon=0.5 )</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>31</td>
<td>32</td>
<td>32</td>
<td>32</td>
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<tr>
<td><strong>M4, ( \varepsilon=0.75 )</strong></td>
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<td></td>
<td>31</td>
<td>31</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td><strong>M4, ( \varepsilon=1 )</strong></td>
<td></td>
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<td></td>
<td>31</td>
<td>32</td>
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</table>

*Note:* \( Y\leq 0.001 \)
Sensitivity Analysis

**Benefits vs budget.** In this section, results from analysis performed to evaluate the sensitivity of each model to the available budget are presented. Also, 18 new budget scenarios are developed by increasing/decreasing budget B2. An ±10% increment with a maximum/minimum budget of ±90% of B2 are used. 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 trade-off between equity and total benefits (see “Benefits vs equity” for a detailed discussion on the selection of these values). Results from this analysis are shown in Figure 5 where it is observed that $M0$ behaves in an unpredictable manner with cases of total benefits decrement 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 a normal trend (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.
Figure 5: Variation of total benefits by budget and model (Note: B2 is 95.78 million dollars)

**Benefits vs equity.** This section shows the trade-off between the total benefits and the equity parameter values i.e., the lower the value of equity parameter ($\mathcal{E}$ 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, results from an analysis are presented to quantify the effects of the equity parameters to the total benefits for the equity models $M3$ and $M4$. 
**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 ($\mathcal{E} \cdot d_{ij}$). In this section, results from an analysis aimed at quantifying the change of the total benefits with respect to the value of the equity in opportunity parameter ($\mathcal{E}$) are presented. 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. It is observed that the curve patterns are very similar irrespective of the budget used (which was one of the reasons why the analysis for the nineteen different budgets used in benefit-budget sensitivity analysis, is not done).

![Figure 6: Total benefits vs. equity in opportunity parameter ($\mathcal{E}$) for different budgets (M3)](image-url)

Figure 6: Total benefits vs. equity in opportunity parameter ($\mathcal{E}$) for different budgets (M3)
Furthermore, it is observed 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 significant increase in number of projects at $\mathcal{E}=1$, for this particular dataset). This would indicate a break point (or knee) and suggest 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 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).

*Equity in outcome (M4).* Recall that the equity constraint (4.3) in $M_4$, restricts the difference between the maximum and minimum benefits received by the counties below a predefined value ($e \sum_{i,t} B_{R_{i=0}} X_{it}$) in an effort to minimize the difference of benefits between the counties. In this section, 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) are presented. 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 $M_3$, it is observed that the curve patterns are very similar irrespective of the budget used. Furthermore, it is noticed 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 $M_3$, 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.
The author would like to note that the equity parameters values where the knee is observed are significantly affected by the data. In such, 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 $\mathcal{E}$ and $e$ increase).

Figure 7: Total benefits vs. equity in outcome parameter ($e$) for different budgets ($M_d$)
5. Conclusion

This thesis developed a six-dimensional freight resource allocation methodology that can be utilized by State DOTs for the efficient allocation of available funds to alleviate congestion, improve operational efficiency, and enhance safety. The six dimensions consist of modes, performance measures, improvement types, regions, policies, and time periods. To the author’s best knowledge, this is the first thesis that addresses freight resource allocation considering comprehensive set of dimensions. State DOTs are responsible to maintain multimodal freight transportation, however policies between States vary. Hence, this thesis develops four resource allocation models each consisting of a unique policy and compares the results with a base model (\(M_0\)) where selection of projects is conducted using an intuitive sorting methodology. In all four models, maximization of the total benefits is considered as the objective. Each model differs from other by specific nature of constraints.

\(M_1\) is referred as economic competitiveness where projects are not mutual exclusive to the locations. In \(M_2\), mutual exclusiveness constraint is added. \(M_3\) adds equity in opportunity constraint where sub-regions (counties) receive equitable resources (projects). \(M_4\) introduces equity in outcome constraint where the counties receive equitable benefits. The State of Tennessee is used as the case study for the proposed resource allocation model. For each model, a planning horizon of ten years is considered with total available budget where there is a pre-specified annual budget, growth in costs, and benefits of projects over time. The multi-year feature allows the user to effectively utilize the year-end savings in subsequent years, thereby, deriving the most benefits from the available resources. Incorporation of policy constraints allows the analyst, flexibility of selectively adding required constraints to the resource allocation problem. For resource allocation models, the results show that \(M_1\) provides highest total benefits.
followed by $M_2$, but allocation is highly unequitable. $M_3$ provides the least total benefits; however, resources are provided equitably to the sub-regions benefitting all possible counties. $M_4$ provides third best total benefits with most equitable allocation of benefits. At the end, sensitivity analysis is carried out to see the performances of the models developed. The variation of the total benefits is observed with respect to variation in total available budgets and equity parameters. This can be a valuable asset to freight agencies in setting the model parameters in different scenarios (input data, budget, and desired equity) to maximize the total benefits. From the spectrum of models presented, depending on the goal of the public agency, appropriate models can be used for freight resource allocation.

The contribution of this thesis 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, application of the model in a real-world case study and insights for public agencies to consider unique model features in various policy settings to augment prioritization of multimodal freight projects. Due to data constraints, only two freight modes are considered, and projects are identified based on three performance measures. Additional research is required to include diverse set of projects from multiple modes and corresponding changes in the resource allocation results. In practice, the projects only start generating benefits after some period of its selection (construction time) and this period can be a single or multi-year. In addition, there are certain maintenance and operation costs, all of which can be considered in the future work. As the goal of public agencies is not always the maximization of benefits, future research is needed to consider diverse set of objectives in a multi-objective resource allocation modeling framework.
References


