OPTIMIZING HIGHWAY RECONSTRUCTION AND REHABILITATION PROJECTS

BY

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DISSERTATION

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ABSTRACT

Optimizing Highway Reconstruction and Rehabilitation Projects

The nation's transportation networks including its roads, highways and bridges are aging and deteriorating at an increasing and rapid rate. The vulnerability of these aging networks of roads and bridges is exacerbated when they are subjected to natural disasters such as earthquakes and hurricanes which often cause severe disruption of the level of service provided by these transportation networks. Significant financial and construction resources are needed to complete the highway reconstruction and rehabilitation projects required to repair these aging and damaged transportation networks and bringing them to acceptable levels. The lack of sufficient resources to complete these highway construction projects concurrently requires effective and efficient utilization of these limited financial and construction resources in order to satisfy multiple and often conflicting objectives. Accordingly, there is a pressing need for new decision support models that are capable of: (1) analyzing the impact of reconstruction/rehabilitation efforts on the performance of transportation networks; (2) optimizing post-disaster reconstruction efforts of damaged transportation networks in order to simultaneously minimize reconstruction costs and network service disruption; and (3) optimizing highway rehabilitation of deficient transportation networks in order identify optimal program(s) that maximize net societal benefits while minimizing the level of service disruption experienced by travelers during the construction efforts.

First, a highway service disruption model is developed to support measuring and evaluating the expected disruption in the level of service provided by aging and

damaged transportation networks during highway reconstruction and rehabilitation projects. The model considers the impact of construction projects and their dynamic nature on the functional performance of aging and damaged transportation networks during reconstruction and rehabilitation efforts. The capabilities of the developed model in assessing the service disruption in aging and damaged transportation networks, include: (1) considering the dynamic nature of construction operations and activities and identifying their expected impact on the functional performance of aging and damaged transportation networks during reconstruction and rehabilitation efforts; (2) accounting for the rationality of travelers in choosing which route/detour to use to reach their destinations; and (3) evaluating the overall loss/savings in network travel time of the aging and damaged transportation networks during highway reconstruction and rehabilitation efforts. These new and unique capabilities of the developed model should prove useful to decision makers and planners in departments of transportation (DOTs) and should contribute to planning and optimizing highway reconstruction and rehabilitation efforts.

Second, resource utilization model and multi-objective optimization models are developed to enable an efficient and effective reconstruction process for damaged transportation networks in the aftermath of natural disasters. The developed models provide a number of new and unique capabilities in generating optimal tradeoffs between network service disruption and reconstruction cost. These capabilities include: (1) considering the impact of the limited availability of resources on scheduling the reconstruction efforts for damaged transportation networks; (2) evaluating the service disruption in the damaged transportation network during the reconstruction efforts; and

(3) optimizing the utilization of reconstruction resources to minimize the network service disruption of damaged transportation networks while keeping the reconstruction costs to a minimum. These new and unique capabilities of the developed models should prove useful to decision makers and planners in emergency management agencies and should contribute to enhancing the planning of reconstruction efforts for damaged transportation networks after natural disasters.

Third, a highway rehabilitation planning and optimization model is developed to enable efficient and effective rehabilitation of aging transportation networks. This model incorporates four new modules that provide new capabilities in generating optimal tradeoffs between maximizing net rehabilitation benefits and minimizing network service disruption. These capabilities are demonstrated in the ability of the developed rehabilitation planning and optimization model to consider a number of practical highway rehabilitation requirements, including: (1) considering the impact of the limited availability of funding on planning rehabilitation efforts for aging transportation networks; (2) evaluating the expected service disruption and road user savings during and after completion of rehabilitation efforts; (3) estimating the expected net benefits of rehabilitation programs; and (4) optimizing the allocation of financial resources to maximize net rehabilitation benefits and minimize network service disruption. These new and unique capabilities of the research developments presents in this chapter should prove useful to decision makers and planners in departments of transportation (DOTs) and should contribute to enhancing the planning of rehabilitation efforts for aging transportation networks.

The main research developments of this study are expected to contribute to the advancement of current practices in highway construction planning and optimization and can lead to: (1) accelerating the completion of highway reconstruction and rehabilitation projects and minimizing the service disruption experienced by travelers during the construction work; (2) optimizing the allocation of limited budgets and financial resources to competing highway projects; and (3) improving the utilization efficiency of construction resources in highway projects and therefore increasing their productivity.

To my parents:

You are the first and greatest teachers of my lifetime

To my daughters:

You are my most important students ever, and the true measure of my accomplishment

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CHAPTER 1
INTRODUCTION

1.1 Overview

The American Society of Civil Engineers (ASCE) estimates that a total investment of $930 billion is required over a period of five years to substantially improve the current conditions of the nation's aging surface transportation infrastructure (ASCE 2009). This includes repairing more than 26% of the nation's bridges that are rated structurally deficient or functionally obsolete and one-third of the major roads that are in poor or mediocre condition (ASCE 2009). The vulnerability of these aging highways and bridges are exacerbated when they are subjected to natural disasters such as earthquakes and hurricanes which often cause severe disruption of the level of service provided by these transportation networks (Housner and Thiel 1995).

This service disruption in aging and/or damaged transportation networks leads to significant social and economic losses to local communities. For example, travelers on the nation's poor roads spend about 4.2 billion hours a year stuck in traffic at a cost of $72.8 billion to the economy, and pay an annual cost of $67 billion in repairs and operating costs (ASCE 2009). Similarly, the 1994 Northridge earthquake forced the closure of Interstate-10 for months causing severe service disruption to an average daily traffic (ADT) of 341,000, which in turn led to an estimated daily loss of $1 million to Californians for lost wages, added fuel cost, and depressed business activity (Chang and Nojima 2001; Zamichow and Ellis 1994). In order to control and minimize these adverse impacts on society, decision makers in departments of transportation (DOTs) need to carefully plan both the post-disaster reconstruction efforts of damaged networks and the rehabilitation efforts of deficient networks. Planning these reconstruction or rehabilitation efforts involves deploying and utilizing limited construction and financial resources to restore damaged transportation networks to their pre-disaster conditions or improve the performance of deficient networks to acceptable levels. This is a challenging task mainly due to the limited availability of these construction and financial resources. For example, only limited reconstruction resources are typically available for competing post-disaster reconstruction projects of damaged civil infrastructure systems (Augusti et al. 1998). Similarly, there is a projected shortfall of $550 billion in federal investments that are required to repair the nation's transportation networks and bring them up to acceptable levels (ASCE 2009). These limited construction and financial resources would allow only a few of the competing reconstruction/rehabilitation projects to proceed concurrently. In addition, inadequate planning of construction efforts could significantly increase the service disruption experienced by travelers. Therefore, decision makers need to create and implement reconstruction/rehabilitation plans that deploy and utilize the limited resources available in such an optimal and cost-effective manner to maximize societal benefits.

In order to enhance and optimize highway reconstruction and rehabilitation plans, decision makers need to decide on: (1) the selection of reconstruction/rehabilitation projects from a pool of competing projects; (2) the priority of each of these selected projects; (3) the procurement method to adopt in each project; (4) the assignment of these projects to interested contractors; and (5) the overtime policy to adopt in each project. These decision variables have a direct and significant impact on the important and conflicting construction planning objectives of: (1) maximizing the overall social benefit; (2) minimizing the service disruption experienced by travelers during the reconstruction and rehabilitation projects; and (3) minimizing public expenditures on highway reconstruction and rehabilitation efforts.

In order to illustrate the complexity of this decision-making process, Table 1-1 shows an example for planning post-disaster reconstruction efforts for a damaged transportation network with two contractors competing for three reconstruction projects. Each contractor has submitted a bid on project duration and cost for each of the three projects, as shown in Table 1-1. Each of these reconstruction projects is planned to restore the disrupted service for a number of travelers represented by the average daily traffic (ADT), as shown in Table 1-1. Each contractor has construction resources that are adequate to work on only one project at the same time.

Table 1-1 Example bids for reconstruction projects after a natural disaster

Reconstruction Projects	CONTRACTOR (1)		CONTRACTOR (2)		ADT
	Duration (weeks)	Construction Costs ($)	Duration (weeks)	Construction Costs ($)	(Vehicle/day)
Project 1	6	3,726,000	4.5	5,510,000	150,000
Project 2	8	4,940,000	6	7,284,000	100,000
Project 3	4	2,512,000	3	3,705,000	300,000

The DOT decision makers in this example need to decide on the optimal project prioritization and contractor assignment that simultaneously minimize construction costs and service disruption to travelers. Figure 1-1 shows three out of 48 possible different alternatives of project prioritization and contractor assignment combinations, each providing a unique tradeoff between construction costs and service disruption. On the

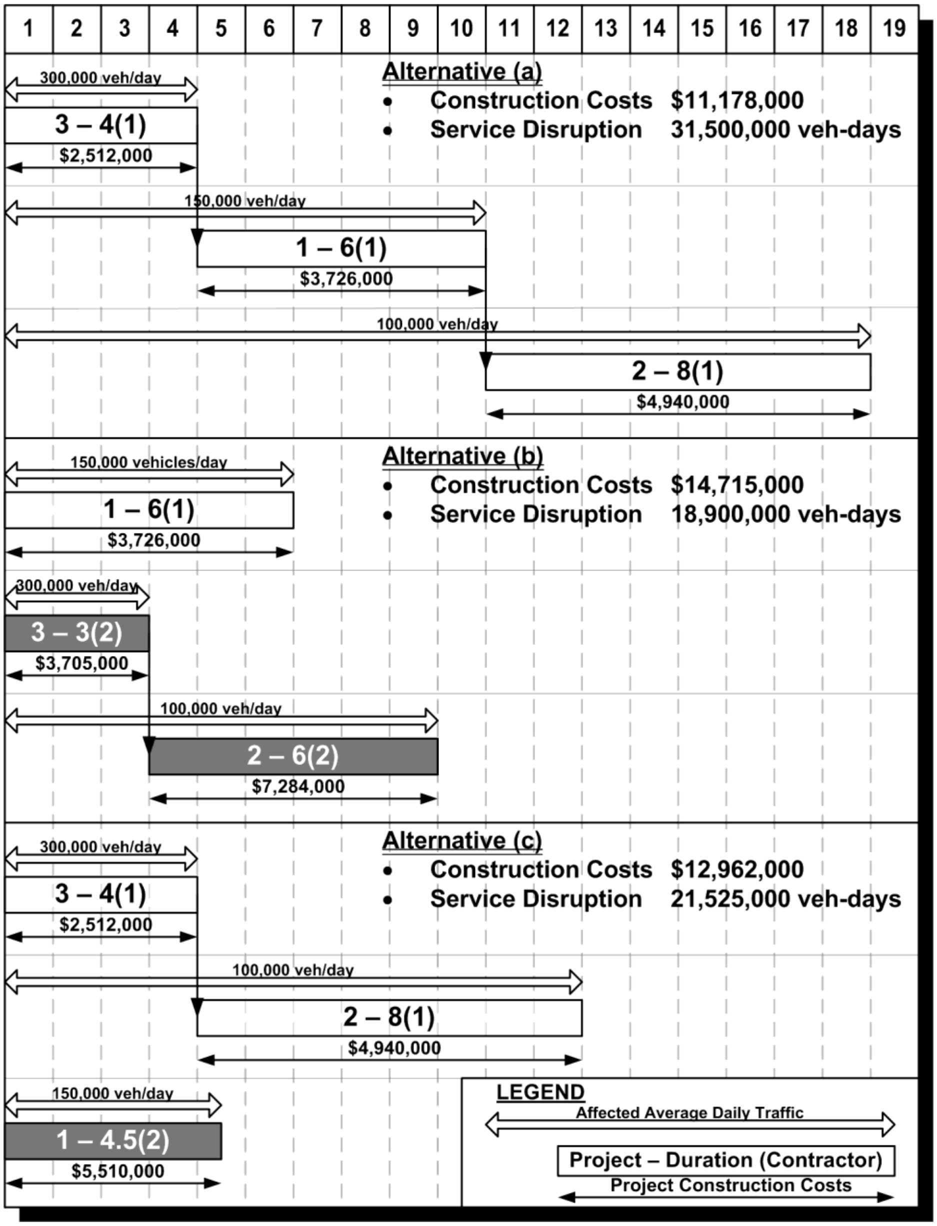


Figure 1-1 Impact of project prioritization and contractor assignment on planning objectives

one hand, alternative (a) in Figure 1-1 minimizes the total construction costs to approximately $11 million by assigning all the projects to contractor (1) who submitted the lowest construction costs on all three projects, as shown in Figure 1-1. This alternative however extends the reconstruction duration to 18 weeks, which in turn leads to a huge disruption to the level of service provided by the damaged transportation network to travelers who cumulatively lose almost 32 million vehicle-days in disrupted service over the reconstruction period, as shown in Figure 1-1. On the other hand, alternative (b) minimizes the service disruption to almost 19 million vehicle days at total construction costs of approximately $15 million (31.6% higher than alternative (a)). This was possible by: (1) assigning two projects to contractor (2) who submitted the shortest project durations; and (2) giving priority to projects 1 and 3 which have higher impact on service disruption, as shown in Figure 1-1. In between these two extremes, alternative (c) provides a balanced tradeoff between minimizing total construction costs and service disruption. This alternative reduces the service disruption by 31.7% at additional construction costs of $1.8 million (16%) compared to alternative (a), as shown in Figure 1-1.

The above simple example emphasizes the complexity and multi-objective nature of identifying the project prioritization and contractor assignment for only a few reconstruction projects. In real life problems however this level of complexity increases multifold as the DOTs in charge of planning and implementing the reconstruction/rehabilitation efforts need to: (1) consider other decision variables in addition to the project prioritization and contractors assignment, such as project selection, procurement methods and overtime policy; (2) examine the impact of limited resource utilization on the recovery/upgrade efforts; (3) analyze the impact of the recovery/upgrade efforts on the level of service disruption experienced by travelers on the damaged/deficient transportation network; and (4) investigate significantly larger problems that involve analysis and evaluation of several reconstruction/rehabilitation projects and various combinations of construction and financial resources. This highlights the significance and substantial challenges in handling the task of effectively and efficiently planning the reconstruction and rehabilitation efforts for damaged and aging transportation networks. This critical and challenging planning task needs to be carefully analyzed by the DOTs in charge of the recovery/upgrade efforts. Accordingly, there is a pressing need for new decision support models that are capable of (Figure

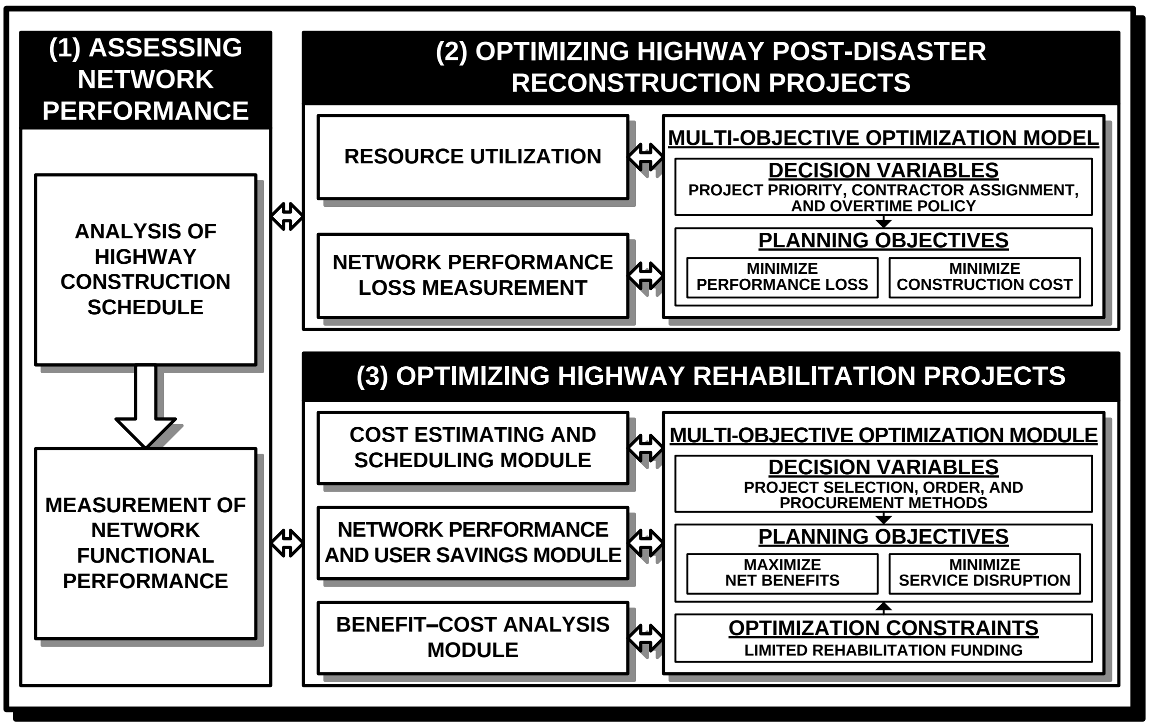


Figure 1-2 Planning reconstruction/rehabilitation works for transportation networks

1-2): (1) analyzing the impact of reconstruction/rehabilitation efforts on the performance of transportation networks; (2) optimizing post-disaster reconstruction efforts of damaged transportation networks in order to simultaneously minimize reconstruction costs and network service disruption; and (3) optimizing highway rehabilitation of deficient transportation networks in order identify optimal program(s) that maximize net rehabilitation benefits while minimizing the level of service disruption experienced by travelers during the construction efforts.

1.2 Problem Statement

In order to enable the development of the aforementioned models for planning transportation reconstruction/rehabilitation efforts, this study will thoroughly investigate thee important domain problems: (1) evaluating the impact of reconstruction and rehabilitation efforts on the functional performance of damaged and aging transportation networks; (2) optimizing the utilization of limited resources in post-disaster reconstruction projects of damaged transportation network; and (3) optimizing the rehabilitation efforts of deficient transportation networks in order to identify optimal rehabilitation programs that simultaneously maximize social benefit while minimizing service disruption.

First, reconstruction/rehabilitation efforts have a significant impact on the functional performance of damaged/deficient transportation networks. For example, the closure of a major transportation artery for an extended period results in significant disruption to the level of service provided by the local transportation network. It is therefore essential for decision makers to be able to evaluate the impact of various reconstruction and rehabilitation plans on the functional performance of the damaged and aging transportation networks during the construction period. Existing research in the area of measuring performance of transportation networks focus on: (1) estimating the actual performance of functioning transportation networks (Bell 2000; Chen et al. 2001); (2) developing flow-independent metrics for measuring post-disaster performance of damaged transportation networks (Chang and Nojima 1998; Chang and Nojima 2001); and (3) forecasting the impact of natural disasters on the functional performance of transportation networks (Nojima and Sugito 2000; Chen and Eguchi 2003). Despite the significant contributions of these research studies to the body of knowledge, there is a research gap in studying the dynamic nature of the reconstruction/rehabilitation efforts and its impact on the performance of damaged/deficient transportation networks over the construction period. Therefore, there is a pressing need for innovative models for measuring the performance of transportation networks that are capable of analyzing and quantifying the impact of reconstruction/rehabilitation efforts on the level of service disruption experienced by travelers.

Second, optimizing the reconstruction efforts of damaged transportation networks in the aftermath of natural disasters is a challenging and complex task due in large part to the limited availability of construction resources in post-disaster conditions; and the conflicting planning objectives that need to be considered during the reconstruction phase. Accordingly, limited reconstruction resources must be deployed and utilized in an optimal way in order to effectively and efficiently satisfy the post-disaster societal needs of: (1) minimizing the overall disruption in the level of service provided by the damaged transportation network during the reconstruction efforts; and (2) minimizing the total public expenditures on reconstruction efforts. Mitigating the adverse impacts of natural disasters on transportation networks has been investigated in a number of research studies that focused on: (1) measuring the performance of damaged transportation networks in post-disaster environments (Chang and Nojima 1998; Chang and Nojima 2001; Chen and Eguchi 2003; Nojima and Sugito 2000); (2) analyzing recovery planning strategies and developing post-event recovery planning models (Farris and Wilkerson 2001; Kozin and Zhou 1990; Lambert et al. 1999; Opricovic and Tzeng 2002); (3) evaluating pre-disaster mitigation policies and developing pre-event mitigation planning models (Gunes and Kovel 2000; Masri and Moore II 1995); and (4) investigating the role of public agencies in post-disaster environments (Kovel and Kangari 1995; Lambert and Patterson 2002). In addition, existing resource utilization studies focus on: (1) allocating limited resources to a single construction project (Leu and Yang 1999; Leu and Hung 2002; Kim and de la Garza 2003; Senouci and Eldin 2004); (2) optimizing resource utilization for repetitive construction projects (El-Rayes and Moselhi 1996; El-Rayes and Moselhi 2001; Zhang et al. 2006); (3) scheduling multiple distributed construction projects (Hegazy et al. 2004); (4) optimizing resource allocation and leveling problems simultaneously (Hegazy 1999); (5) optimizing resource utilization in individual construction operations (Hegazy and Kassab 2003); and (6) planning multiple facility management projects (East and Liu 2006). Despite the significant contributions of these research studies, there is no reported research that focused on planning the utilization of limited resources in order to optimize post-disaster reconstruction efforts of damaged transportation networks. Decision makers need to create and implement resource utilization plans that (Figure 1-2): (1) prioritize the competing reconstruction projects (Fwa and Chan 1991; Hegazy et al. 2004); (2) award these projects to interested and qualified contractors; and (3) identify the overtime policy suitable for each project. Accordingly, there is a need for new resource utilization models that are capable of allocating limited reconstruction resources to competing projects and optimizing the reconstruction efforts in order to identify optimal resource utilization plans that simultaneously minimize both service disruptions during the reconstruction efforts and the reconstruction costs.

Third, the nation's aging and deteriorating civil infrastructure systems, including transportation networks, are in urgent need for immediate rehabilitation efforts in order to preserve them and improve their performance (ASCE 2009). These efforts require an annual federal funding of $186 billion to improve the surface conditions of transportation infrastructure (ASCE 2009); however, the government was unable to increase funding for transportation improvement (ASCE 2009; Weiss 2008). Accordingly, there is a need to optimize rehabilitation programs under budget constraints in order to maximize net rehabilitation benefits and minimize service disruption. These rehabilitation programs should provide the capability of (Figure 1-2): (1) identifying rehabilitation projects that maximize net benefits to the traveling public which can be represented by the difference between the savings in road user costs due to the rehabilitation efforts and the construction and maintenance costs; (2) prioritize the identified rehabilitation projects; and (3) determine the most suitable procurement method for each project (Soloway 2005; Tuttle et al. 2006). Each of these decision variables has a significant impact on the important and conflicting planning objectives of maximizing net social benefits and minimizing service disruption. Accordingly, there is a pressing need for an innovative model for planning highway rehabilitation efforts that are capable of generating rehabilitation plans that provide optimal tradeoffs between maximizing net social benefits and minimizing disruption in the level of service provided by deficient transportation networks.

1.3 Research Objectives

The main goal of this study is to develop novel models for planning the reconstruction/rehabilitation efforts of damaged/deficient transportation networks. In order to accomplish this goal, the objectives of this study are identified along with their pertinent research questions and hypotheses as follows:

Objective 1:

To model the impact of highway construction work on the functional performance of transportation networks and develop a model to measure service disruption during construction efforts.

Research Questions:

(a) What are the factors that affect the functional performance of transportation networks during reconstruction/rehabilitation efforts? (b) What is the impact of reconstruction/rehabilitation work on the level of service disruption experienced by travelers? and (c) How can the overall service disruption during reconstruction/rehabilitation efforts be objectively measured in order to support decision making in highway construction projects?

Hypothesis:

Measuring the service disruption experienced by travelers during highway construction can support decision makers in evaluating and minimizing these service disruptions during highway reconstruction/rehabilitation projects.

Objective 2:

To develop a novel multi-objective optimization model for post-disaster reconstruction of damaged transportation networks that is capable of (a) allocating limited construction resources to competing recovery projects; and (b) simultaneously minimizing network service disruption and reconstruction costs.

Research Questions:

(a) What are the decision variables that need to be considered in post-disaster reconstruction of damaged transportation networks? (b) How can the planning objectives of minimizing service disruption and reconstruction costs be evaluated and measured? (c) How can this multi-objective optimization model be implemented in order to identify optimal tradeoffs between these conflicting planning objectives? (d) What is the impact of reconstruction project prioritization on post-disaster recovery duration and cost? (e) What is the impact of double shifts and nighttime construction on the reconstruction efforts? and (f) How to best share limited reconstruction resources among competing recovery projects?

Hypothesis:

New post-disaster recovery planning models can support the analysis of alternative highway reconstruction plans and identifying optimal solutions that provide tradeoffs between minimizing network service disruption and reconstruction costs. In addition, new post-disaster resource utilization models can help construction planners allocate limited reconstruction resources among competing recovery projects for damaged civil infrastructure systems taking into consideration the prioritization of these projects, assignment of projects to interested qualified contractors and the overtime policy adopted for each project.

Objective 3:

To develop a new multi-objective optimization model for the rehabilitation efforts of aging transportation networks that is capable of maximizing net social benefits and minimizing network service disruption simultaneously.

Research Questions:

(a) What are the decision variables that affect highway rehabilitation projects? (b) What is the impact of these decision variables on the rehabilitation program cost and schedule? (c) What are the costs and benefits of highway rehabilitation programs to society? (d) How can the impact of rehabilitation programs on the net social benefits be measured and quantified? (e) How can the impact of different rehabilitation programs on road user costs be estimated? and (f) How can optimal tradeoffs between maximizing net social benefits and minimizing service disruption during highway rehabilitation programs be generated under budget constraints?

Hypothesis:

New highway rehabilitation planning models can provide the capabilities of searching for and identifying optimal highway rehabilitation programs that maximize the net social benefit while simultaneously minimizing highway service disruption.

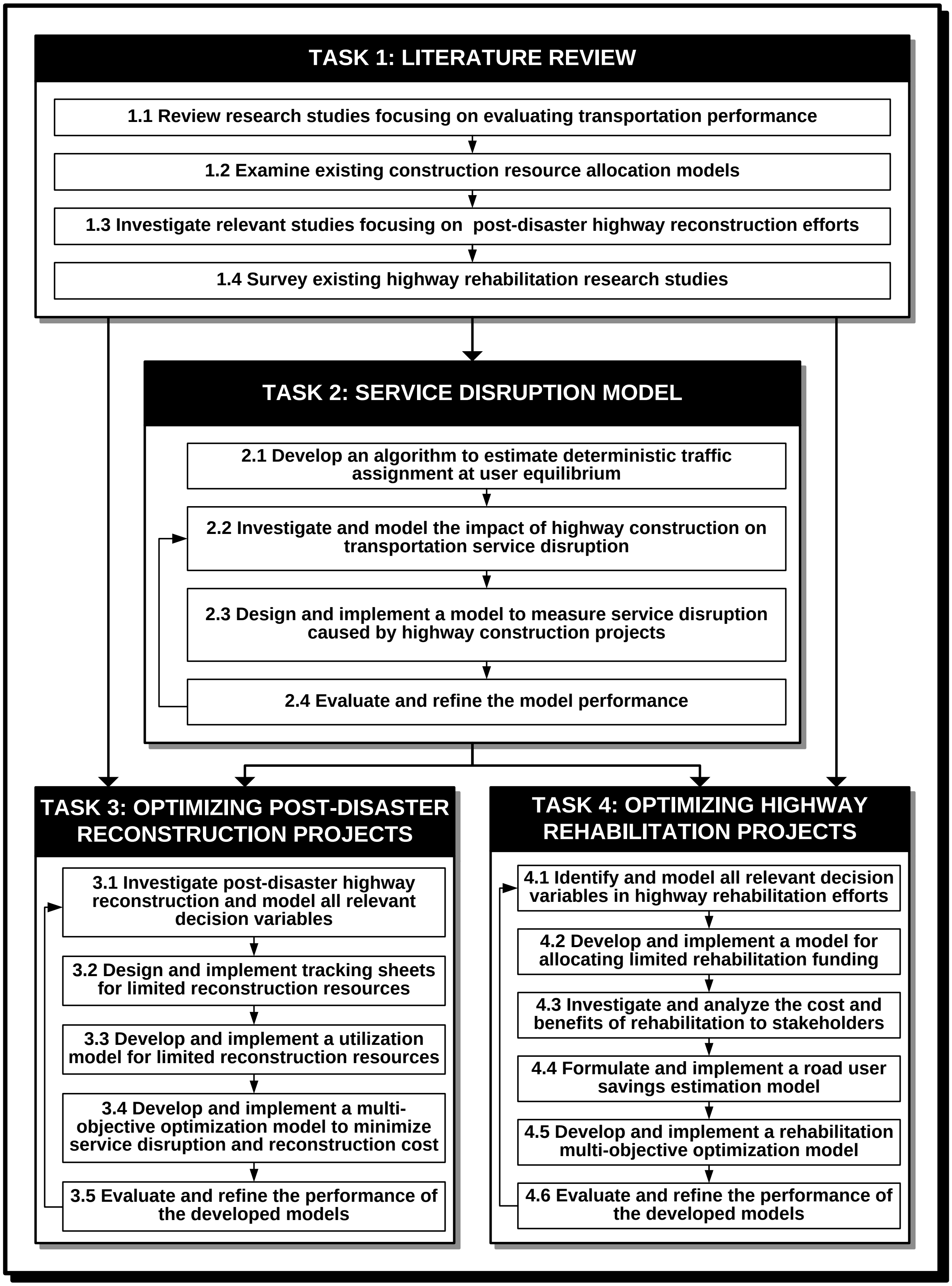


Figure 1-3 Research tasks

1.4 Research Methodology

In order to achieve the aforementioned objectives, the research work in this study is organized into four main research tasks that are designed to: (1) conduct a comprehensive literature review of the latest research developments in planning and optimization of transportation reconstruction/rehabilitation efforts; (2) model the impact of construction progress on the performance of transportation networks and measure the service disruption caused by implementing specific construction plans; (3) develop models to plan and optimize post-disaster reconstruction works for damaged transportation networks; and (4) formulate a model to plan and optimize transportation rehabilitation efforts, as shown in Figure 1-3.

1.4.1 Task 1: Conducting a Comprehensive Literature Review

The objective of this task is to investigate the latest research developments in planning and optimizing highway reconstruction/rehabilitation projects in order to identify the research gaps that need to be addressed by this study. This task is subdivided into the following four sub-tasks:

1- Review research studies focusing on measuring and evaluating the functional performance of transportation networks especially in post-disaster situations.
2- Examine existing construction resource utilization models and their capabilities in terms of sharing limited reconstruction resources among competing post-disaster recovery projects.
3- Investigate relevant research studies focusing on post-disaster reconstruction of damaged transportation networks.

4- Survey existing highway rehabilitation research studies and examine their capabilities in maximizing net social benefit of rehabilitation programs.

1.4.2 Task 2: Measuring Service Disruption of Highway Projects

The main objective of this task is to evaluate and model the transportation networks service disruption during highway reconstruction/rehabilitation projects. In order to achieve this objective, the work in this research task is subdivided into the following four sub-tasks:

1- Develop an algorithm to estimate deterministic traffic assignment at user equilibrium.
2- Investigate and model the impact of highway reconstruction/rehabilitation projects on service disruption in transportation networks.
3- Design and implement a model to measure the level of service disruption experienced by travelers during construction.
4- Evaluate and refine the performance of the developed service disruption model.

1.4.3 Optimizing Highway Post-Disaster Reconstruction Projects

The task is aimed at developing a new post-disaster reconstruction planning model for damaged transportation networks that is capable of: (1) sharing limited reconstruction resources among competing projects; and (2) optimizing the reconstruction efforts in order to simultaneously minimize service disruption and reconstruction costs. This task is subdivided into the following five sub-tasks:

1- Investigate post-disaster highway reconstruction and model all decision variables that have direct and significant impact on planning post-disaster reconstruction works of damaged transportation networks.
2- Design and implement resource tracking sheets to monitor the movement and deployment of resources at activity and project levels.
3- Develop and implement a utilization model to allocate limited resources to competing projects.
4- Develop and implement a multi-objective optimization model for post-disaster highway reconstruction efforts that simultaneously minimizes network service disruption and reconstruction costs.
5- Evaluate and refine the performance of the developed resource utilization and multi-objective optimization models.

1.4.4 Task 4: Optimizing Highway Rehabilitation Projects

The objective of this task is to optimize highway rehabilitation efforts under funding constraints with the objective of identifying the rehabilitation program(s) that provide optimal tradeoffs between maximizing net social benefits and minimizing network service disruption. The work in this research task is subdivided into the following six sub-tasks:

1- Identify and model all decision variables that have a direct impact on highway rehabilitation efforts.
2- Develop and implement a model to allocate limited funding to competing highway rehabilitation projects.

3- Investigate and analyze the costs and benefits of highway rehabilitation programs to different stakeholders.

4- Formulate and implement a model to analyze and estimate expected road user savings for selected rehabilitation programs.

5- Develop and implement a multi-objective optimization model for highway rehabilitation efforts that simultaneously maximizes net social benefit and minimizes network service disruption.

6- Evaluate and refine the performance of the developed models.

1.5 Research Significance

This research study is designed to support and enhance decision making in highway reconstruction and rehabilitation projects. The research developments described in this dissertation are expected to have a significant impact on: (1) accelerating the completion of highway reconstruction and rehabilitation projects and minimizing the service disruption experienced by travelers during the construction work; (2) optimizing the allocation of limited budgets and financial resources to competing highway projects; and (3) improving the utilization efficiency of construction resources in highway projects and therefore increasing their productivity. Accordingly, these developments hold a strong promise to provide significant benefits to society, departments of transportation (DOTs) and contractors.

- **Benefit to society:**

  These research developments hold a strong promise to provide significant benefits to society. Accelerating the completion of highway reconstruction and rehabilitation projects and minimizing their related service disruption provides many benefits, including: (i) generating savings in road user costs by minimizing traffic congestions and decreasing vehicle operating and repair costs; (ii) reducing the hazardous impacts of highway work zones on the traveling public; and (iii) minimizing the adverse impacts of highway construction work and its related disruptions on local businesses. Similarly, optimizing the allocation of construction and financial resources to competing highway projects can lead to maximizing societal benefits and ensure the cost-effectiveness of investing taxpayers' money in these national assets.

- **Benefit to DOTs:**

  The research developments also hold a strong promise to support and enhance decision-making in state departments of transportation (DOTs) in a number of critical and challenging areas, including: (i) designing and implementing long and short-term plans for highway construction projects and operations; (ii) allocating limited financial and construction resources to competing highway construction projects; (iii) ensuring that taxpayers' money are allocated in a cost-effective and transparent manner; and (iv) improving the resiliency of transportation networks.

- **Benefit to contractors:**

  Contractors working on highway projects are also expected to benefit from these research developments mainly due to the strong promise to increase the utilization efficiency of construction resources, which will in turn lead to an increase in construction productivity and profits.

1.6 Dissertation Organization

The organization of this dissertation and its relation to the main research tasks of this study are described as follows:

Chapter 2 presents a comprehensive literature review that studies all relevant research that focused on measuring the performance of transportation networks; examines the capabilities of existing resource utilization models; reviews existing research studies on planning and optimizing post-disaster reconstruction efforts of damaged transportation networks; and investigates existing research studies on optimizing rehabilitation efforts of deficient transportation networks.

Chapter 3 discusses measuring the functional performance of transportation networks during highway reconstruction and rehabilitation projects. First, the chapter presents an analysis of the impact of highway construction operations and activities on the level of service disruption experienced by travelers. Second, the chapter presents the design and development of a new service disruption model for highway reconstruction and rehabilitation efforts. This model uses deterministic traffic assignment to evaluate the impact of a given construction plan on the performance of a transportation network throughout the construction duration and assess the total service disruption experienced by travelers during this period.

Chapter 4 discusses optimizing post-disaster reconstruction efforts of damaged transportation network in order to identify the reconstruction plan(s) that minimize both network service disruption and public expenditures on reconstruction costs simultaneously. To this end, this chapter presents the development of a new model for utilizing and sharing limited reconstruction resources among competing recovery projects. This chapter also presents the design and development of a new multi-objective optimization model that uses genetic algorithms to identify the optimal/near optimal post-disaster recovery plans and their associated impact on network performance and public expenditures on reconstruction efforts.

Chapter 5 discusses planning and optimizing rehabilitation efforts of aging transportation network in order to identify the rehabilitation program(s) that provide optimal tradeoffs between maximizing net rehabilitation benefits and minimizing network service disruption during rehabilitation efforts. To this end, this chapter presents the development and implementation of innovative algorithms capable of: (1) calculating the cost and schedule of rehabilitation programs while considering the allocation of limited financial resources to competing highway rehabilitation projects; (2) identifying the impact of implementing specific rehabilitation programs on the performance of aging transportation networks and the expected saving in road user costs; (3) analyzing the benefits and costs associated with rehabilitation programs; and (4) generating optimal rehabilitation programs that simultaneously maximize net rehabilitation benefits and minimize network service disruption.

Chapter 6 presents a summary and the conclusions of the research developments, states the contributions of this research study, and lists recommendations for future research.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

This chapter introduces a comprehensive literature review of the latest research developments relevant to planning and optimizing highway reconstruction and rehabilitation projects. This review is aimed at identifying the research gaps that need to be addressed by this study. This task is subdivided into the following five sub-tasks: (1) review research studies focusing on measuring and evaluating the functional performance of transportation networks especially in post-disaster situations; (2) examine existing construction resource utilization models and their capabilities in terms of sharing limited reconstruction resources among competing post-disaster recovery projects; (3) investigate relevant research studies focusing on post-disaster reconstruction of damaged transportation networks; and (4) survey existing highway rehabilitation research studies and examine their capabilities in maximizing net benefits of rehabilitation programs.

2.2 Measurement of Transportation Networks Performance

Many research studies focused on measuring different metrics for the performance of transportation networks (e.g. reliability, comfort, travel time …etc.). There is however little or no reported studies focusing on: (1) measuring the performance of damaged transportation networks in post-disaster situations; and (2) studying the impact of dynamic changes in the status of transportation networks (e.g. progress in construction efforts) on the network's expected performance.

2.2.1 Post-Disaster Measurement of Transportation Performance

Transportation systems have been identified as the most important lifeline (Du and Nicholson 1997) in the event of a disaster (e.g., earthquakes, floods, tornadoes, hurricanes, landslides …etc.). This is mainly due to the dependency of restoring normalcy to any damaged lifeline system on the moving of people and equipment. Some research studies focused on measuring the performance of damaged transportation networks in post-disaster environments. These studies provided two main type of metrics to measure post-disaster the level of service disruption experienced by travelers on damaged transportation networks: (1) flow-independent (Chang and Nojima 1998; Chang and Nojima 2001); and (2) flow-dependent (Nojima and Sugito 2000).

Flow-Independent Metrics

Chang and Nojima (1998) proposed four alternative flow-independent measures to estimate the performance of transportation networks in post-disaster environments. These measures are simple ratios, ranging from 0 (system non-functional) to 1 (system fully functional), of the post-disaster to pre-disaster conditions of: (1) total number of highway sections open (N); (2) total length of highway open (L); (3) total connected length of highway open (C); and (4) total weighted connected length of highway open (W). Measure (N) simply estimates the percentage of highway open segments compared to the pre-disaster conditions. Measure (L) is similar but for the length of highway open. Measure (C) identifies the degree of connectivity of highway open.

Finally, measure (W) is similar to measure (C) but takes into consideration the relative importance of different highway segments.

In another research study, Chang and Nojima (2001) revisited the aforementioned flow-independent performance measures and introduced another three performance measures for evaluating network performance in terms of coverage and transport accessibility. These measures are: (1) total length of network open (L); (2) total distance-based accessibility (D); and (3) areal distance-based accessibility (D_S). Similar to their predecessors, each of these measures is estimated as a ratio of post-disaster to pre-disaster conditions and ranges from 0 (system non-functional) to 1 (system fully functional). Measures (L) and (D) are concerned with the overall performance of the system, while measure (D_S) is specific to individual subareas within the study region. These measures are time-specific. Measure (L) reflects the length of the network that is open to traffic at any time and is defined as a ratio to the pre-disaster length open. Measure (D) is based on minimum network travel distances and takes into account both the extent and the location of damage. It measures changes in accessibility at all nodes on the network. Measure (D_S) is similar to (D) but is concerned with accessibility in a specific subarea (S). These measures are designed to be applied simply and use commonly available data.

Although the above measures are simple and can be applied using commonly available data, they are only adequate for a rough estimate of network performance. These measures therefore cannot be reliably used to plan for and optimize post-disaster reconstruction of damaged transportation networks, mainly due to:

- The use of empirical equations that depend on arbitrarily defined multipliers can lead to significant variance in the estimated values for these measures.
- The application of flow-independent metrics does not take into account the preferences of trip makers when choosing which of the available routes to use.
- The disregard of the dynamic changes in the capacity of damaged road segments depending on their state (i.e. open, closed, or partially open) throughout the reconstruction period.
- The inefficiency of these measures in terms of comparing different reconstruction plans to select the plan that maximizes the societal benefits.

Flow-Dependent Metrics

Nojima and Sugito (2000) developed a flow-dependent model for simulating and evaluating post-disaster functional performance of a highway transportation network. This model is based on a combination of Monte Carlo simulation and a modified version of the incremental assignment method (MIAM) and is developed in three major steps: (1) using Monte Carlo simulation to generate a large number of damage patterns; (2) using the MIAM to load the network with O-D trips; and (3) evaluating the performance of the network in terms of traffic volumes, trip length, and travel time at various levels of the network. Despite the significant contributions of this research study, it focuses mainly on preparing for the impact of expected disasters on fully functioning transportation networks and does not consider the impact of reconstruction efforts on the functional performance of damaged networks.

2.2.2 Impact of Changes of Transportation Network Status

Highway construction projects and operations have a significant impact on the functional performance of damaged and aging transportation networks. It is therefore important to capture this impact and measure the expected levels of service disruption associated with construction projects and operations. Only a few research studies addressed this important research point and they focused mainly on: (1) analyzing highway rehabilitation and reconstruction projects scheduling; (2) minimizing duration of highway construction projects; and (3) planning highway construction under innovative contracting methods.

First, a knowledge-based model was designed to analyze highway rehabilitation and reconstruction projects scheduling (Lee et al. 2005; Lee and Ibbs 2005). The main objective of this model is to calculate the schedule and cost of pavement rehabilitation projects; however, the model can be interfaced with traffic simulation tools to evaluate the impact of rehabilitation on highway service disruption and road user cost (Lee et al. 2005; Lee and Ibbs 2005).

Second, several research studies focused on optimizing the utilization of construction resources in highway projects with the objective of minimizing project durations, which in turn can result in controlling and minimizing network service disruption due to highway construction projects and operations (El-Rayes and Moselhi 1998; El-Rayes and Kandil 2005; Hyari and El-Rayes 2006; Kandil and El-Rayes 2006; Ipsilandis 2007).

Finally, some research studies focused on planning and optimizing highway projects delivered under innovative contracting methods which aim to minimize projects duration and network service disruption (El-Rayes 2001; Shr and Chen 2003; Shr and Chen 2004; Shr et al. 2004).

Despite the significant contributions of the aforementioned research studies, they are inadequate to depicting the behavior of transportation networks during highway construction projects or measuring the expected level of service disruption experienced by travelers.

2.3 Utilization of Construction Resources in Highway Projects

Proper utilization of construction resources is critical to the success of highway projects, especially in post-disaster reconstruction situations. The lack of adequate construction resources places a great burden on decision makers to make a prudent use of these scarce resources in an efficient and effective manner. This includes deployment of limited resources to competing highway projects in such a way that minimizes the impact of construction works on network service disruption and construction costs. The literature is rich of research studies that addressed utilization of construction resources and they focused on two types of optimization problems: (1) single-objective optimization, and (2) multi-objective optimization.

2.3.1 Single-Objective Optimization

Many research studies focused on planning and optimizing the utilization of resources in construction projects with the objectives of either: (1) minimizing fluctuations in resource requirements (resource leveling); or (2) resolving conflicts between activities/projects competing for the same resources (resource allocation).

First, a number of research studies tried to minimize the fluctuations in resource requirements and the negative impact these fluctuations have on construction productivity and cost. These studies used different optimization tools including: (1) heuristic methods (Ahuja 1976; Akpan 2000; Burgess and Killebrew 1962; Harris 1978); (2) linear programming (Easa 1989; Mattila and Abraham 1998); (3) integer programming (Son and Mattila 2004); (4) dynamic programming (Bandelloni et al. 1994); (5) simulated annealing (Son and Skibniewski 1999); (6) mathematical method (Senouci and Adeli 2001); and (7) genetic algorithms (Chan et al. 1996; Chua et al. 1996; Hegazy 1999; Leu and Yang 1999; Senouci and Eldin 2004).

Second, different research and optimization methods were utilized in an effort to allocate limited resources among activities/projects competing for the same type of resource, such as: heuristics, genetic algorithms (GA), dynamic programming, and particle swarm. Heuristic methods were used in several research studies to resolve conflicts between competing activities of a single project, especially in highway projects (Ahuja 1976; Bell and Han 1991; Boctor 1990; Sampson and Weiss 1993; El-Rayes and Moselhi 1998). Similarly, GAs are extensively used in the literature to: (1) optimize resource allocation with the single objective of minimizing project durations (Chan et al. 1996; and Chua et al. 1996); (2) solve large-scale resource allocation problems (Kim and Ellis 2008); (3) suggest modifications to genetic operators to better suit resource allocation problems (Sou-Sen Leu 1999); and (3) compare the use of GAs to other optimization methods such as simulated annealing (Lee and Y. Kim 1996). Also, El-Rayes (2001) used a dynamic programming approach to develop a resource utilization optimization model for highway that utilize A+B bidding method with the objective of minimizing the total bid cost. Finally, Zhang et al. (2006) used particle swarm optimization to solve the same problem of minimizing project durations under resource constraints.

Despite the significant contributions of the above research studies, the resource utilization metrics and models developed are inadequate to deal with sharing limited resources among competing highway construction resource, especially in post-disaster situations. This is mainly due to the following characteristics of highway post-disaster reconstruction projects: (1) unusual large scope of work; (2) similarity of reconstruction resources and therefore high demand for specific types of resources; and (2) spatial dispersion of reconstruction projects over a large geographical area.

2.3.2 Multi-Objective Optimization

Genetic algorithms (GAs) have been extensively used in multi-objective optimization of resource utilization in construction, especially in highway projects. The planning objectives of these optimization problems include: (1) minimizing construction time and cost; (2) minimizing construction time and cost while maximizing quality; and (3) minimizing construction time and maximizing crew work continuity.

First, several research studies used GAs to perform construction time-cost trade-off analyses. For example, Feng et al. (1997) developed a GA-based spreadsheet for analyzing time and cost of construction projects. Similarly, Marzouk and Moselhi (2004) used GAs with discrete event simulation and object-oriented programming to optimize earthmoving operations with the objective of simultaneously minimizing project cost and duration. Zheng et al. (2004) developed a GA-based multi-objective model for solving the time-cost trade-off problem, which uses a fitness function that factors in the values of time and cost of each chromosome using weights that adjust at every generation. In a following paper, Zheng and Ng (2005) integrated risk and uncertainty to the previous model to develop a stochastic approach to multi-objective optimization of time and cost in construction projects.

In addition to the use of GAs, ant colony optimization has also been used to solve time-cost tradeoff problems. Xiong and Kuang (2008) combined ant colony optimization with the modified adaptive weight approach proposed by Zheng et al. (2004) in order to generate optimal tradeoffs between project time and cost. Using the exact problems analyzed by Feng et al. (1997) and Zheng et al. (2004), ant colony optimization provided comparable if not better results that those generated by GAs (Xiong and Kuang 2008)

Second, El-Rayes and Kandil (2005) added a new dimension to the traditional time-cost tradeoff analysis in construction projects by trying to maximize construction quality. In this study, a multi-objective GA-based optimization model was developed to identify the optimal combination(s) of construction method, crew formation, and crew overtime policy that minimizes construction duration and cost while maximizing quality in highway construction projects, simultaneously (El-Rayes and Kandil 2005). In an effort to facilitate analyzing large-scale projects, parallel computing was utilized to reduce the computational time requirements for the GA-based time-cost-quality tradeoff analysis (Kandil and El-Rayes 2006a; Kandil and El-Rayes 2006b).

Finally, Hyari and El-Rayes (2006) developed a multi-objective optimization model to plan and schedule construction repetitive projects. This model is aimed at identifying the combination(s) of crew formation and crew interruption vectors that provide the optimal tradeoff between minimizing project duration and maximizing crew work continuity, simultaneously.

2.3.3 Limitation of Existing Research

Despite the significant contributions and practical features of the aforementioned research studies, further research is needed to cover the following needs in relation to allocating limited resources to competing post-disaster reconstruction projects:

- allocating multiple types of resource among competing reconstruction projects;
- taking into account that reconstruction resources are available from different sources (e.g. contractors) and at different times;
- studying the impact of project prioritization on reconstruction duration and cost;
- identifying a practical methodology to assign highway post-disaster reconstruction projects to qualified interested contractors; and
- considering the impact of working for extended hours and/or multiple shift on productivity and therefore on highway construction duration and cost in post-disaster situations.

2.4 Post-Disaster Reconstruction of Transportation Networks

Planning the recovery and reconstruction efforts of infrastructure systems in post-disaster situations has been the focus of many research studies that employed various methodologies and had different objectives. These research studies focused on: (1) developing pre-event recovery planning models; (2) simulating post-disaster restoration of damaged lifelines; (3) using GIS for allocating limited reconstruction resources among competing post-disaster lifeline restoration projects; and (4) developing a multi-criteria model to facilitate comparing a number of reconstruction plans that are developed before the natural disaster occurs.

First, Masri and Moore II (1995) introduced a disaster mitigation planning information system called Disaster Policy Analysis System (DPAS). DPAS integrates the use of relevant knowledge, theory, methods, and technology to evaluate different disaster mitigation policies based on a cost-benefit analysis. DPAS is however a pre-event planning system that lacks important capabilities in critical decision-making such as: dispatching of emergency response services; generating backup mitigation plans in case the disaster obstructed execution of some or all elements original plan; and defining priority of responding under the conditions of inadequacy of resources (Masri and Moore II 1995).

Second, Kozin and Zhou (1990) used simulation to model the restoration of damaged lifelines in post-earthquake episode. They used a discrete-state, discrete-time Markov process to consider the limited availability of reconstruction resources in the simulation of damaged lifelines reconstruction. The deployment of these limited resources was optimized by means of dynamic programming with the single objective of minimizing the total loss caused by damaged lifelines failure. This research study assumes only two predominant factors that can influence the restoration efforts, the initial damage probability state and immediate economic return and therefore suggests restoration priority setting rules (Kozin and Zhou 1990). This assumption is not completely accurate since it overlooks the different nature of different lifelines and the indirect economic losses.

Third, Gunes and Kovel (2000) developed a GIS-based decision support system for emergency management in Douglas County, Kansas (DCEMA). The main objective of this system is to aid Douglas County in preparing for, mitigating, and responding to floods. The system consists of three main databases in a GIS frame. The first database is for disaster data and is supposed to provide a damage overlay. The second database stores critical facilities data and is designed to identify and evaluate key public facilities that are expected to be damaged. The third and last database stores resource data and is designed to include all construction and engineering resources that can support response operations (Gunes and Kovel 2000). Despite the significant contributions of this research study, it is not practical for use in planning post-disaster reconstruction of damaged transportation networks mainly due to the enormous effort required for data collection and maintenance, which might be infeasible especially for the resources database. Additionally, this research study lacks any optimization of resource utilization in such a way that meets the societal needs of minimizing service disruption and reconstruction costs.

Finally, Opricovic and Tzeng (2002) developed a multi-criteria model to analyze the planning of recovery strategies for areas affected by natural disasters. This model is aimed at helping decision makers choose among various mitigation strategies rating highly on reducing social and economic costs. The model assumes the existence of scenarios of sustainable hazard effects mitigation in the form of comprehensive reconstruction plans. These alternatives are designed to consider redevelopment of urban areas and infrastructures; multi-purpose land use; and restrictions on building in hazardous areas. The model comprises criteria that capture relevant hazard impacts in appropriate and representative units. These criteria represent public safety, sustainability, social environment, economy, culture, and politics. The mitigation alternatives are evaluated against each criterion from the set of established criteria and are ranked using a compromise ranking method developed by one of the authors in an earlier research study (Opricovic 1998).

2.5 Rehabilitation of Aging Transportation Networks

Several research studies investigated optimizing and planning highway rehabilitation efforts. These studies focused on: (1) allocating limited highway rehabilitation and maintenance funds to district agencies and highway assets; (2) planning and scheduling highway construction and rehabilitation projects; and (3) identifying the scope of highway rehabilitation work.

2.5.1 Allocating Limited Funding

Chan et al. (2003) properly assume that fund allocation decisions should account for the planning goals of regional highway agencies, which can differ from one district to the other, as well as the planning goals of the central highway agency. They therefore utilized a two-staged genetic-algorithm to optimize fund allocation for highway rehabilitation projects across different regional highway agencies under the jurisdiction of a central highway agency (Chan et al. 2003). In the first stage, the developed model identifies the road repair projects that best satisfies the regional planning objectives of each district at different funding levels. The results of the first stage are used together with the planning goals of the central agency in the second stage to identify the optimal levels of fund allocation to each district under budget constraints (Chan et al. 2003).

Cook (1984) developed models that are capable of identifying highway maintenance strategies that can achieve the decision maker's specified pavement serviceability levels. In order to achieve this objective, a two-phase priority planning methodology was adopted (Cook 1984). In phase 1, a financial planning model is used to determine the minimal level of funding required to achieve specified pavement serviceability standards. Following, these funding levels are used as a constraint in phase 2 that employs a goal programming model to select maintenance strategies that prioritize pavement rehabilitation efforts in such a way that satisfies the target serviceability levels specified by the user. In order to facilitate this process, historical data is utilized to forecast the expected pavement performance resulting from applying specific maintenance treatments (Cook 1984).

Gharaibeh et al. (2006) developed a model that employs multi-attribute utility (MAU) theory to measure the decision maker's risk attitude towards the impact of fund allocation on the performance of transportation infrastructure assets such as pavement, bridges and roadway signs. The MAU function is developed by combining single-attribute utility functions that are developed for each asset class based on the decision maker's risk attitude toward infrastructure poor performance (Gharaibeh et al. 2006). The developed MAU function is then used to evaluate the decision maker's risk attitude in different fund allocation alternatives and the alternative with the maximum MAU, i.e. lowest risk of infrastructure failure, is selected. This study lists four potential funding alternatives each maximizing a factor that is important to decision makers and the public including: utility, infrastructure efficiency, adequacy, and a by choice alternative according to the user's preferences (Gharaibeh et al. 2006).

Despite of the significant contributions of the above studies, they have a number of major drawbacks that limits their usefulness in planning and optimizing highway rehabilitation projects, including:

- the inability to identify the highway projects that maximize the total net benefits of rehabilitation programs;
- not considering the important and practical rehabilitation decision variables of project selection, project prioritization, and procurement methods;
- not considering the impact of the rehabilitation efforts on the level of service provided by transportation networks to travelers;
- considering only specific types of rehabilitation or maintenance works;
- the inaccurate assumption of availability of unlimited funding;
- the inadequacy of some of these research studies for planning and optimizing rehabilitation efforts for large-scale transportation networks; and

- the utilization of subjective approaches that depends solely on the risk attitude of decision makers which can vary from one person to the other and does not provide the optimum rehabilitation alternatives that satisfies the societal needs.

2.5.2 Planning and Scheduling Highway Projects

Hassanein and Moselhi (2004) developed a model to plan and schedule highway construction operations. This model stores project templates for new and rehabilitation highway reconstruction operations in order to enable the automatic generation of the work breakdown structure (WBS) and activity precedence information for highway projects (Hassanein and Moselhi 2004). The main objective this model is to optimize the resource utilization in highway projects in order to minimize the total bid cost including construction cost and duration (Hassanein and Moselhi 2004). In order to achieve this objective, this model employs a dynamic programming-based resource-driven scheduling algorithm that also takes into consideration the impact of inclement weather on the productivity of construction crews. In addition, the model incorporates three databases for storing weather, soil and resource data (Hassanein and Moselhi 2004).

Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS) is a knowledge-based model that is designed to analyze highway rehabilitation and reconstruction projects scheduling (Lee et al. 2005; Lee and Ibbs 2005). CA4PRS is developed to calculate the schedule and cost of highway pavement rehabilitation projects for different pavement strategies (Lee and Ibbs 2005). The pavement strategies considered in CA4PRS include: reconstruction with concrete; overlay with asphalt concrete; and full-depth replacement with asphalt concrete (Lee at al. 2005). The scheduling of pavement rehabilitation work that can be completed using each of these strategies depends on: the pavement materials used; the highway closure schedule adopted; and the availability of the contractor's resources (Lee and Ibbs 2005). In order to analyze each of these pavement rehabilitation strategies, CA4PRS evaluates the constructability and productivity of a number of "what-if" scenarios selected by the user (Lee et al. 2005; Lee and Ibbs 2005). In addition, CA4PRS employs Monte-Carlo simulation to account for the uncertainty in the decision variables and can also be interfaced with traffic simulation tools to evaluate the impact of rehabilitation on highway service disruption and road user cost (Lee et al. 2005; Lee and Ibbs 2005).

Despite the significant contributions of the aforementioned research studies, they are insufficient for planning and optimizing highway rehabilitation programs mainly due to the following limitations:

- not accounting for limited availability of highway rehabilitation funding ;
- not considering the impact of rehabilitation efforts on the level of service provided by transportation networks during and after the implementation of highway rehabilitation programs;
- do not seek to search for and implement rehabilitation program(s) that maximize net rehabilitation benefits to the society
- implementing "what-if" scenarios in the selection of the rehabilitation projects, which does not guarantee finding the optimal solution

2.5.3 Identifying Scope of Highway Rehabilitation

Khan et al. (1994) developed 4RSCOPE which is a knowledge-based computer program for use by California Department of Transportation (Caltrans) to identify the scope of work of highway rehabilitation projects. The main objective of this expert system is to assist engineers in early identification of some project features that may be overlooked during the design phase and can cause cost overruns and schedule delays if introduced later in the process (Khan et al. 1994). In order to achieve this objective, 4RSCOPE integrates a relational database module for storing rehabilitation data and an expert system module that reasons about rehabilitation needs to identify project scope of work. The database module stores data pertaining to features and design of previous projects and design needs of upcoming projects (Khan et al. 1994). The expert system module then analyzes these data and the suggested rehabilitation strategy for new projects in order to identify the design features that need to be added, removed or modified (Khan et al. 1994).

Despite the significant contributions of 4RSCOPE, it is not capable of evaluating the impact of rehabilitation efforts on service disruption in transportation networks or the net rehabilitation benefits mainly due to: (1) its concern only with identifying the scope of work in highway rehabilitation projects rather than prioritizing and implementing these projects; and (2) its methodology that only takes into consideration cost-effective selection of design features that increase highway safety.

2.6 Summary

This chapter presented an extensive review of existing literature on latest developments in the areas of: (1) measuring the functional performance of transportation networks; (2) utilizing limited reconstruction resources in highway construction projects; (3) planning and optimizing post-disaster reconstruction of damages transportation networks; and (4) planning and optimizing rehabilitation efforts of aging transportation networks. This literature review shows that there is a pressing need for further research to cover important gaps in each of the aforementioned areas in order to plan for and optimize highway reconstruction and rehabilitation projects in an effective and efficient manner. The aforementioned research needs include:

(1) developing innovative models for measuring the performance of transportation networks that are capable of analyzing and quantifying the impact of reconstruction and rehabilitation efforts on network service disruption;

(2) formulating new models that are capable of sharing limited reconstruction resources among competing projects, and optimizing post-disaster reconstruction efforts in order to identify optimal resource utilization plans that simultaneously minimize both network service disruption and reconstruction costs; and

(3) developing and implementing innovative models for planning highway rehabilitation efforts that are capable of generating rehabilitation plans that provide optimal tradeoffs between maximizing net social benefits and minimizing disruption in the level of service provided by deficient transportation networks.

CHAPTER 3
MEASURING SERVICE DISRUPTION OF HIGHWAY CONSTRUCTION PROJECTS

3.1 Introduction

The main objective of this chapter is to develop a new service disruption model for highway reconstruction and rehabilitation efforts that is capable of: (1) analyzing the impact of highway construction projects on service disruption in damaged and aging transportation networks during reconstruction and rehabilitation efforts; and (2) identifying the level of service disruption experienced by road users as a result of implementing specific reconstruction or rehabilitation plans. These capabilities enable decision makers to compare different highway construction plans in terms of their impact on the functional performance of transportation networks. Accordingly, the following sections in this chapter focus on: (1) measuring network service disruption during highway construction projects; (2) developing a new service disruption model due to highway construction; and (3) evaluating the performance of the model and demonstrating its capabilities by analyzing two application examples.

3.2 Impact of Highway Construction on Service Disruption

In order to evaluate the service disruption in transportation networks during reconstruction or rehabilitation efforts, there is a need to analyze the impact of highway construction work on the functional performance of these networks, as shown in Figure 3-1. There are a number of metrics used to measure the functional performance of transportation networks including: travel time, distance, direct cost, reliability and

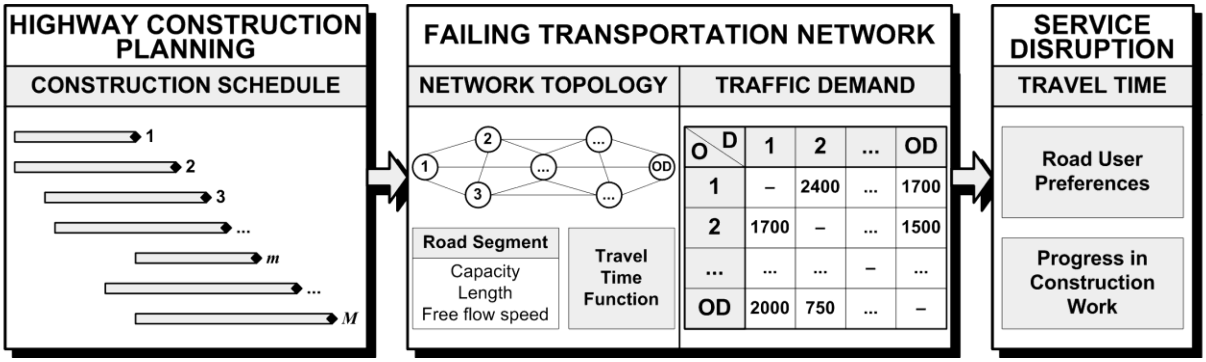


Figure 3-1 Impact of highway construction planning on network service disruption

comfort (Bell and Iida 1997). In the present model, travel time is used to measure transportation networks performance because it is often considered to be the most important factor affecting travelers on damaged or aging networks. This is especially true when road users need to travel longer detours or their original routes but with significantly reduced speeds. Accordingly, service disruption is represented in this model by the net change in total travel time, measured in $vehicle.hours$, experienced by travelers on the transportation network throughout the duration of the construction work, as shown in Figure 3-1. Since travel time is a flow-dependent metric, it requires the estimation of the traffic flow on each of the network links. This is a challenging task due to two main reasons: (1) the challenge in identifying the route preferences of individual travelers; and (2) the dynamic nature of the progress in construction work, as shown in Figure 3-1.

First, travelers are often reported to choose routes that they perceive to have the least travel time (Bell and Iida 1997). Accordingly, travel routes that are perceived to be faster attract larger traffic volumes. These routes can then experience traffic volumes that exceed their capacities, creating traffic congestions and increased travel times that in turn cause travelers to consider other faster alternatives. These dynamic changes in traveler preferences make it difficult to estimate the volume of traffic on each link in the network accurately. This problem gets even more challenging in larger networks which may include thousands of links. Second, the dynamic nature of the progress in construction work also adds to the complexity of estimating the traffic flow using each of the network links. This is true because as the reconstruction and rehabilitation efforts progress, the functional status of different road segments can dynamically alternate between open, partially closed and closed based on the construction schedule, as shown in Figure 3-1.

Therefore, these two factors can have a significant and dynamic impact on the change in network total travel during reconstruction and rehabilitation efforts. In case of post-disaster reconstruction of damaged transportation networks, the total change in network travel time is usually negative representing a loss in the total travel time compared to pre-disaster levels. The maximum loss in travel time is experienced immediately after

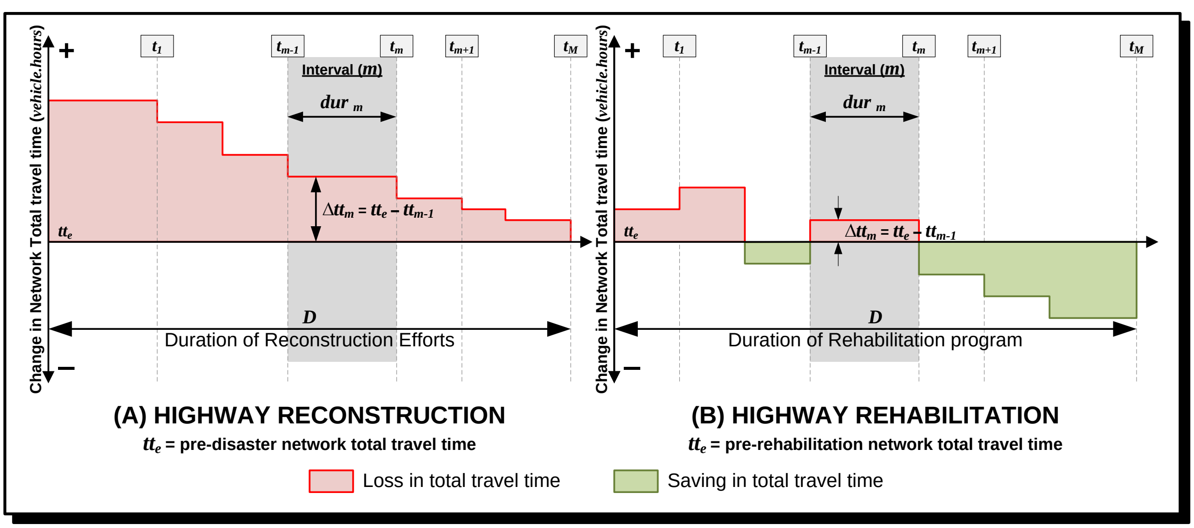


Figure 3-2 Change in network total travel time during highway reconstruction and rehabilitation efforts

the disaster and diminishes at the end of the recovery duration when all reconstruction works are completed and the damaged network is restored to its pre-disaster conditions, as shown in Figure 3-2. However, in the case of highway rehabilitation efforts, the change in the network total travel time can alternate between losses and savings depending on the varying road closure conditions throughout the duration of rehabilitation efforts, as shown in Figure 3-2. Nevertheless, it is expected that rehabilitation work would bring about savings in network total travel time compared to the pre-rehabilitation levels towards the end of any rehabilitation program, as shown in Figure 3-2.

3.3 Service Disruption Model Development

In order to overcome the two aforementioned main challenges in estimating the traffic flow on the network links, the service disruption model is designed to assess the functional performance of aging transportation networks during construction works in three main phases: (1) initialization; (2) deterministic traffic assignment; and (3) service disruption assessment, as shown in Figure 3-3.

3.3.1 Initialization

This phase is designed to initialize the required data for the service disruption model. This initialization process is performed in three main steps: (1) input the transportation network data; (2) integrate the construction plan data which will be described in more detail in the following chapters; and (3) identify the frequency of performance analysis, as shown in Figure 3-3.

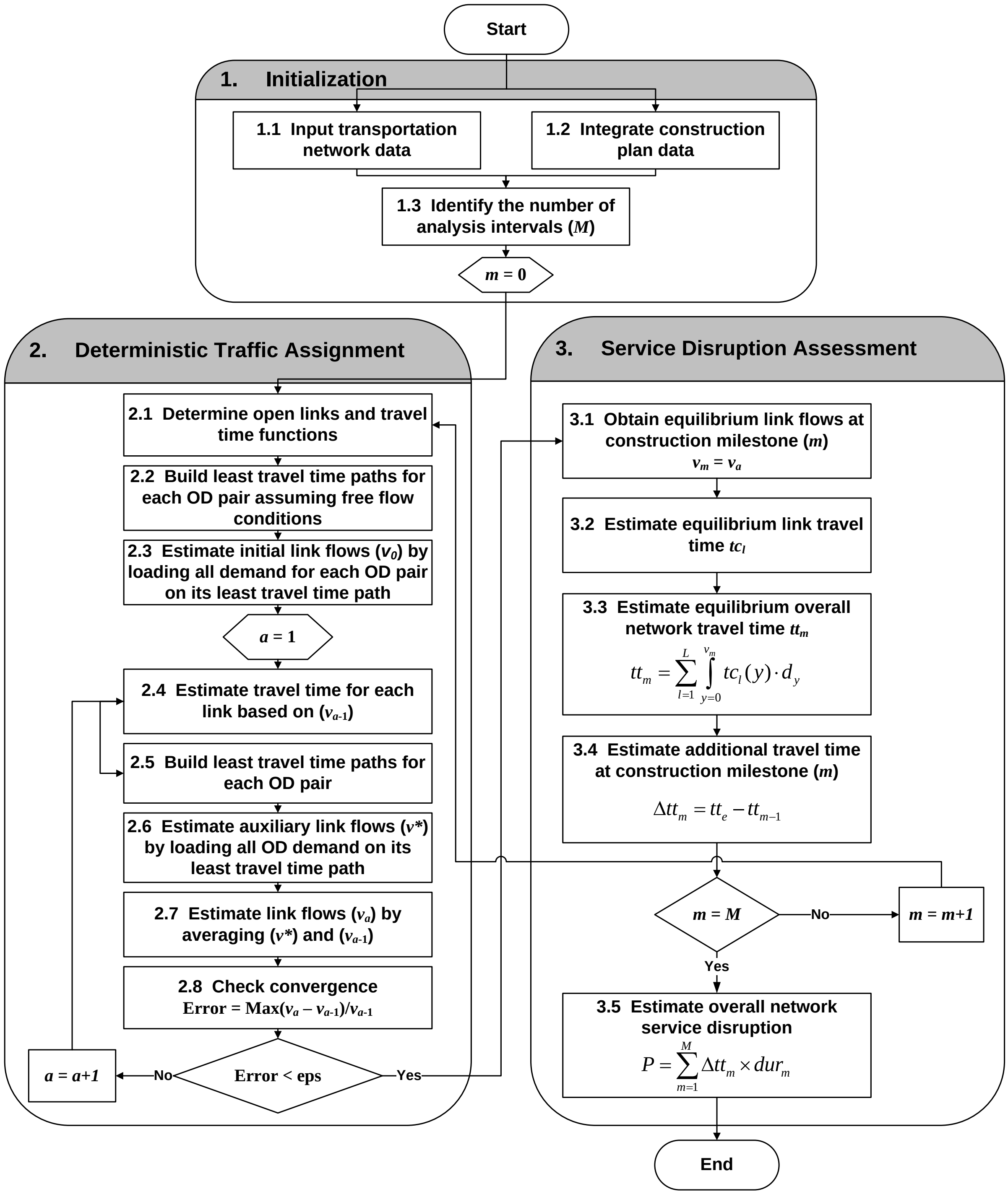


Figure 3-3 Flowchart for service disruption model

Input transportation network data

This data is needed in the service disruption model to represent the traffic data and topology of the transportation network. The traffic data include: (1) the traffic demand on the network which can be described by the origin-destination (OD) pair flows; (2) the capacity of the road segments; (3) the free flow speed for each road on the network; and (4) the functions used to estimate the travel time on the different routes of the network based on the capacities of these routes and their traffic flow. For simplicity, the present model assumes that the OD pair flows are static which indicates that there are no changes in the traffic demand on the network during different hours of the day, days of the week, or seasons of the year. Similarly, the network topology include data on: (1) the nodes which represent the traffic loading/unloading points to/from the network such as cities, intersections, and exits; (2) the links which represent the road segments connecting different nodes; and (3) the incidence information which identifies the relationship between nodes and links and the direction of traffic flow on each link.

Integrate construction plan data

Construction plan data are generated by the multi-objective optimization models for reconstruction and rehabilitation efforts as will be described in the following chapters. This data is integrated in this service disruption model in order to account for the expected impact of progress in the construction works on the functional performance of different road segments. This set of data includes: (1) the estimated construction duration (D); (2) the schedule of the reconstruction or rehabilitation projects and the planned road closures during construction efforts; and (3) the prioritization of these highway construction projects. The purpose of analyzing this data is to identify the status (i.e., open, partially open, or closed) of the road segments in the network at different stages of the construction efforts.

Identify frequency of performance analysis

This step in the initialization phase is designed to identify the frequency of performing the computational steps in the deterministic traffic assignment and the service disruption assessment phases. These computational steps need to be repeated in an iterative process to account for the dynamic nature of the construction efforts and its impact on the losses or savings in the travel time on the transportation network being analyzed. This iterative process is repeated at important milestones ($m = 1$ to M) during the construction duration (D), as shown in Figure 3-3. The number of these milestones (M) and their distribution over the construction duration is identified based on the construction schedule that is calculated in the other models. Each of these milestones represents the start or completion of a significant portion of highway construction work and therefore bringing about changes to the state of the network. These changes can for example include the reopening of highway segment(s) of the network that were previously closed to travelers and/or close other segment(s). As shown in Figure 3-2, the network performance is assumed to be fixed between each two successive milestones such as ($m-1$) and (m).

3.3.2 Deterministic Traffic Assignment

In order to overcome the earlier described challenges in identifying the route preferences of travelers, the traffic demand need to be loaded on the network in a way that reflects the perception of individual travelers of the routes with least travel time.

This is based on an individualistic rationality which requires travelers to pursue their own interests individually (Bell and Iida 1997). This individualistic rationality assumption in traffic assignment is known as Wardrop's first principle (Wardrop 1952) in which a user equilibrium state is achieved when all alternative travel routes have equal travel times and no single traveler can reduce his/her travel time by unilaterally changing their travel route. Accordingly, the main objective of this step of the performance loss model is to identify the volume of traffic on each link of the network at equilibrium at each construction milestone (m). Although the network might not fully reach the equilibrium state due to the frequency of change in the network status (Yang and Liu 2007), a deterministic traffic assignment algorithm is utilized in this model due to its adequate accuracy to estimate the flow on the network links and to avoid the heavy computational overhead of stochastic traffic assignment algorithms.

As mentioned earlier, the traffic demand is assumed to be static throughout the construction duration. Accordingly, the present problem is a deterministic traffic assignment problem which can be solved using the Frank-Wolfe algorithm for deterministic user equilibrium assignment. Frank-Wolfe is a very effective and widely used algorithm for estimating the link flows at equilibrium (Bell and Iida 1997). The Frank-Wolfe algorithm employed in the present model is executed using the following eight steps (Figure 3-3):

1. Determine the status of the network links at construction milestone (m) based on the network and construction plan data identified in the initialization phase.

2. Identify the paths with least travel time (i.e. fastest) for each OD pair using the Dijkstra's algorithm (Dijkstra 1959) and considering an empty network condition which assumes free flow speeds on all the open links in the network.
3. Estimate an initial set of link flows (v_0) by loading the traffic demand for each OD pair on its associated shortest path.
4. Calculate the travel time on each link using the travel time function adopted in this model ($tc = \mathrm{f}(v_{a-1})$) and based on the current set of link flows (v_{a-1}) and capacities.
5. Identify the new set of shortest paths for each OD pair based on the new travel times (tc) using Dijkstra's algorithm.
6. Estimate a set of auxiliary link flows (v^*) by load the traffic demand for each OD pair on the new set of shortest paths identified in step 5.
7. Estimate a new current set of link flows (v_a) by averaging (v_{a-1}) and (v^*) as shown in Equation (3-1). This is a single objective optimization problem that can be solved using linear optimization for the value of the multiplier (λ).

$$v_a = \mathrm{Min}\,\mathrm{f}(v_{a-1} \cdot \lambda + v^*(1-\lambda)) \tag{3-1}$$

Where

v_a = set of link flows at iteration step (a);

v_{a-1} = set of link flows at iteration step ($a-1$);

v^* = set of auxiliary link flows for shortest paths estimated at step (a); and

λ = averaging multiplier

8. Check convergence of the set of link flows (v_a) to the true solution at equilibrium as shown in Equation (3-2). If convergence occurs, (v_a) is the set of link flows at equilibrium at construction milestone (m) and the algorithm stops; otherwise, counter (a) is incremented by 1 and steps 4 through 7 are repeated until convergence.

$$\mathrm{Max}((v_a - v_{a-1}) / v_{a-1}) > eps \qquad (3\text{-}2)$$

Where

eps = the maximum permissible error.

3.3.3 Service Disruption Assessment

The main objective of this phase is to evaluate the overall service disruption of the transportation network undergoing reconstruction or rehabilitation works as a result of implementing the recommended highway construction plan. This objective is achieved in this model by: (1) calculating the change (i.e. losses or savings) in total network travel time at each construction milestone (m) based on the links flows (v_m) calculated in the deterministic traffic assignment phase; and (2) integrating the change in travel time at different milestones during the construction duration (D) to estimate the overall network service disruption (P). In order to complete this service disruption evaluation, the following five steps are used (Figure 3-3):

1. Obtain the link flows at equilibrium (v_m) for construction milestone (m) from the deterministic traffic assignment phase, as described above.

2. Estimate the travel time on each link (tc_l) by dividing its length by the speed of traveling on this link, as shown in Equation (3-3). This travel speed is flow-dependent and is function of both the link flow and capacity. The present model uses Equation (3-4) to calculate these travel speeds (Highway Capacity Manual, 2000).

$$tc_l = len_l / s_l \tag{3-3}$$

$$s_l = \frac{FS_l}{1 + \alpha (v_l / c_l)^{\beta}} \tag{3-4}$$

Where

tc_l = travel time on link (l);

len_l = length of link (l);

s_l = travel speed on link (l);

FS_l = free flow speed on link (l);

v_l = traffic flow on link (l);

c_l = capacity of link (l); and

α and β = scalar parameters that depend on the type of the link.

3. Estimate the overall travel time for all travelers (tt_m) at equilibrium for construction milestone (m) using the travel time on each individual link (tc_l), as shown in Equation (3-5).

$$tt_m = \sum_{l=1}^{L} \int_{y=0}^{v_m} tc_l(y).dy \tag{3-5}$$

Where

tt_m = overall travel time on the network at construction milestone (m);

L = number of the transportation network links; and

v_m = set of link flows at construction milestone (m)

4. Estimate the change in travel time (Δtt_m) for all travelers on the network at milestone (m), as shown in Equation (3-6). It should be noted that as described previously, the value and tendency of change in (Δtt_m) depends on the progress of construction efforts. On one hand, the incremental post-disaster restoration of repaired links in the network over the reconstruction duration (D) leads to a gradual reduction in the additional travel time (Δtt_m) until full restoration of pre-disaster conditions (tt_e) at the end of the construction duration (D), as shown in Figure 3-2. On the other hand, the dynamic nature of rehabilitation efforts causes the change in travel time (Δtt_m) to fluctuate over the duration of the rehabilitation program as the status of network links alternates between open, partially open and closed, as shown in Figure 3-2. Steps 1 through 4 are repeated to estimate (Δtt_m) for all construction milestones ($m = 1 \text{ to } M$).

$$\Delta tt_m = tt_e - tt_{m-1} \qquad (3\text{-}6)$$

Where

Δtt_m = additional travel time at construction milestone (m); and

T_0 = overall travel time before the start of construction efforts.

5. Calculate the overall service disruption (i.e., total change in total network travel time in $vehicle.hours$) during the construction efforts by integrating the change in network travel time (Δtt_m) at different construction milestones ($m = 1 \text{ to } M$) which is represented by the area under the curve of (Δtt_m), as shown in Figure 3-2. This area under the curve is estimated as shown in Equation (3-7).

$$P = \sum_{m=1}^{M} \Delta tt_m \times dur_m \tag{3-7}$$

Where

P = the overall network service disruption;

Δtt_m = change in network travel time at construction milestone ($m - 1$);

M = number of construction milestones; and

dur_m = the length of time between construction milestones ($m - 1$) and (m).

3.4 Evaluation of Model Performance

Two application examples are analyzed to illustrate the use of the service disruption model and demonstrate its capabilities in analyzing the impact of highway construction efforts on the functional performance of transportation networks and measuring the overall network service disruption experienced by travelers during highway reconstruction and rehabilitation projects. One of these application examples seeks to analyze the impact of post-disaster reconstruction efforts on the functional performance of the damaged transportation network, while the other example seeks to analyze the impact of implementing a highway rehabilitation program on the level of service provided by the transportation network.

3.4.1 Example 1: Post-Disaster Highway Reconstruction Efforts

In this application example, the developed service disruption model is used to evaluate the impact of post-disaster reconstruction efforts on the performance of a damaged transportation networks and measure the expected service disruption during recovery. The application example seeks to analyze the performance of the transportation

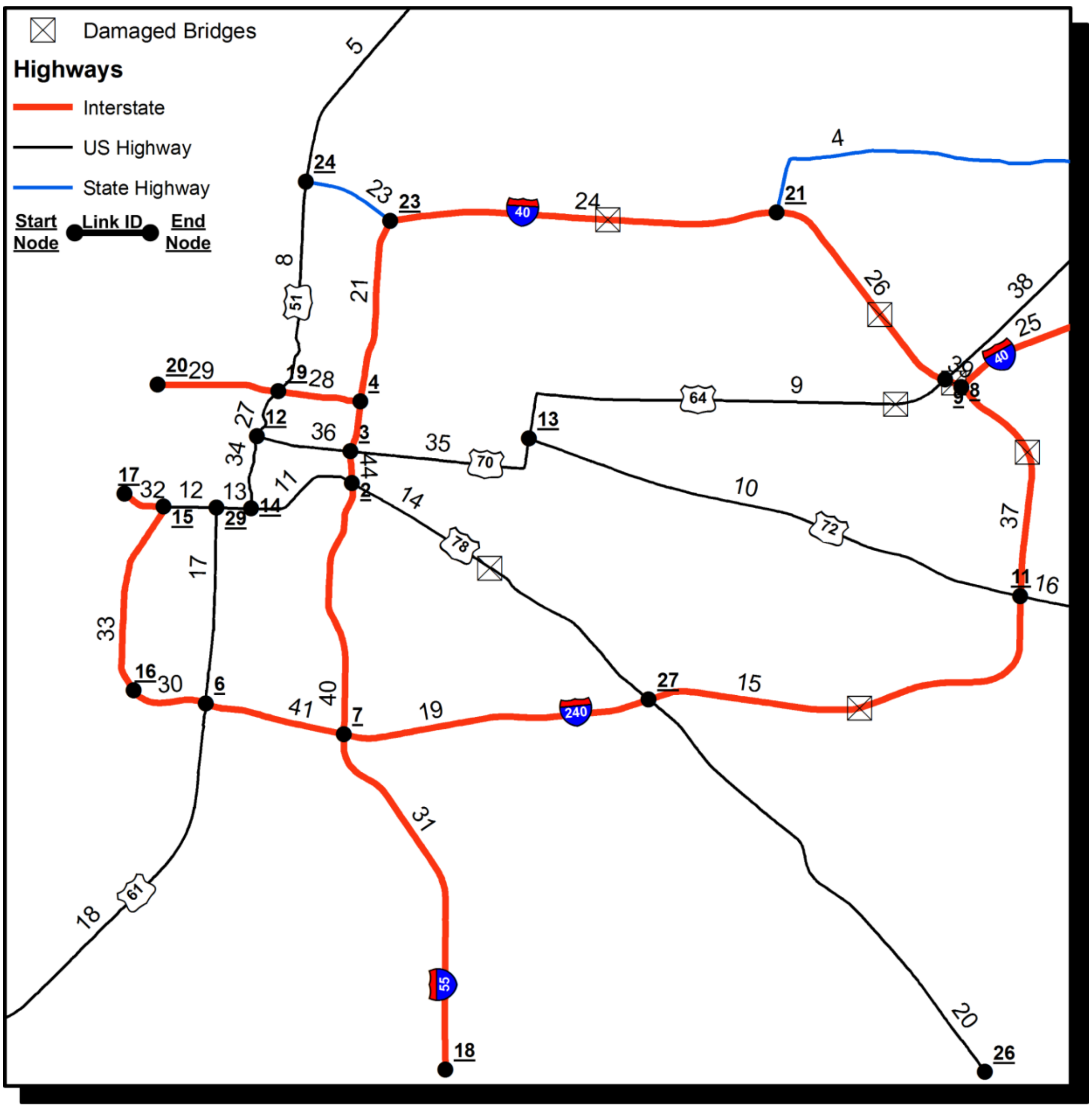


Figure 3-4 Map of the damaged transportation network (Memphis, TN)

network in Memphis, Tennessee that is assumed to have suffered varying levels of structural damages to seven bridges at different locations in the aftermath of an earthquake, as shown on the map in Figure 3-4. The topology of this transportation network and the traffic demand are shown in Table 3-1 and Table 3-2, respectively. The reconstruction efforts for this damaged transportation network is estimated to complete in 180 days and includes eight important milestones at which there is a significant change to the status of the damaged transportation network, as shown in Table 3-3. The first milestone (t_0) is immediately after the occurrence of the earthquake, which caused closure of 14 links on the transportation network during to the structural damages in the bridges (Table 3-3). At each subsequent reconstruction milestone, one of the bridges is repaired and the two associated links (in both directions) is reintroduced to the network until all links are fully functional at the end of the reconstruction duration (t_{180}), as shown in Table 3-3. The aforementioned data were analyzed using the developed model, which was able to evaluate the expected impact of reconstruction work (Table 3-3) on the disruption in the level of service provided by the damaged transportation network during the post-disaster recovery efforts, as shown in Figure 3-5. The highest level of service disruption is experienced immediately after the occurrence of the earthquake and gradually decreases as bridge repair efforts progress and closed links are reintroduced to the transportation network (Figure 3-5). For example, the repair of the bridge on links 9 and 55 (east and west bounds of US-64) is scheduled to complete on (t_{20}) and the reopening of these roads to

Table 3-1 Topology of the transportation network in Memphis, TN

Link	Start Node	Finish Node	Speed (*mph*)	α	β	Length (*mile*)	Capacity (*veh/day*)
0	25	33	45	0.15	4	5.256	33,600
1	1	32	45	0.15	4	2.808	33,600
2	22	0	55	0.15	4	6.487	64,800
3	10	1	45	0.15	4	10.450	33,600
4	21	10	45	0.15	4	5.904	33,600
5	24	25	45	0.15	4	11.299	33,600
6	22	31	45	0.15	4	7.692	33,600
7	10	22	45	0.15	4	3.499	33,600
8	19	24	45	0.15	4	3.431	33,600
9	13	9	45	0.15	4	6.168	33,600
10	13	11	45	0.15	4	6.894	33,600
11	14	2	45	0.15	4	1.578	33,600
12	15	29	45	0.15	4	0.694	33,600
13	29	14	45	0.15	4	0.447	33,600
14	2	27	45	0.15	4	5.223	33,600
15	27	11	55	0.15	4	6.066	64,800
16	11	30	45	0.15	4	14.795	33,600
17	6	29	45	0.15	4	3.125	33,600
18	28	6	45	0.15	4	7.304	33,600
19	7	27	55	0.15	4	4.048	64,800
20	26	27	45	0.15	4	7.458	33,600
21	4	23	55	0.15	4	2.920	64,800
22	25	1	55	0.15	4	14.396	38,400
23	24	23	55	0.15	4	1.298	38,400
24	23	21	55	0.15	4	5.049	64,800
25	8	22	55	0.15	4	7.242	64,800
26	21	9	55	0.15	4	3.565	64,800
27	12	19	45	0.15	4	0.814	33,600
28	19	4	55	0.15	4	1.083	64,800
29	20	19	55	0.15	4	1.579	64,800
30	16	6	55	0.15	4	1.029	64,800
31	18	7	55	0.15	4	5.750	64,800
32	17	15	55	0.15	4	0.573	64,800
33	16	15	55	0.15	4	3.077	64,800
34	14	12	45	0.15	4	1.170	33,600
35	3	13	45	0.15	4	2.740	33,600
36	12	3	45	0.15	4	1.244	33,600
37	8	11	55	0.15	4	3.672	64,800
38	9	10	45	0.15	4	4.620	33,600
39	8	9	55	0.15	4	0.242	64,800
40	7	2	55	0.15	4	4.092	64,800
41	7	6	55	0.15	4	1.866	64,800
42	0	5	55	0.15	4	2.620	64,800
43	3	4	55	0.15	4	0.813	64,800
44	2	3	55	0.15	4	0.503	64,800
45	0	1	55	0.15	4	2.390	38,400

Table 3-1 Topology of the transportation network in Memphis, TN (continued)

Link	Start Node	Finish Node	Speed (*mph*)	α	β	Length (*mile*)	Capacity (*veh/day*)
46	33	25	45	0.15	4	5.256	33,600
47	32	1	45	0.15	4	2.808	33,600
48	0	22	55	0.15	4	6.487	64,800
49	1	10	45	0.15	4	10.450	33,600
50	10	21	45	0.15	4	5.904	33,600
51	25	24	45	0.15	4	11.299	33,600
52	31	22	45	0.15	4	7.692	33,600
53	22	10	45	0.15	4	3.499	33,600
54	24	19	45	0.15	4	3.431	33,600
55	9	13	45	0.15	4	6.168	33,600
56	11	13	45	0.15	4	6.894	33,600
57	2	14	45	0.15	4	1.578	33,600
58	29	15	45	0.15	4	0.694	33,600
59	14	29	45	0.15	4	0.447	33,600
60	27	2	45	0.15	4	5.223	33,600
61	11	27	55	0.15	4	6.066	64,800
62	30	11	45	0.15	4	14.795	33,600
63	29	6	45	0.15	4	3.125	33,600
64	6	28	45	0.15	4	7.304	33,600
65	27	7	55	0.15	4	4.048	64,800
66	27	26	45	0.15	4	7.458	33,600
67	23	4	55	0.15	4	2.920	64,800
68	1	25	55	0.15	4	14.396	38,400
69	23	24	55	0.15	4	1.298	38,400
70	21	23	55	0.15	4	5.049	64,800
71	22	8	55	0.15	4	7.242	64,800
72	9	21	55	0.15	4	3.565	64,800
73	19	12	45	0.15	4	0.814	33,600
74	4	19	55	0.15	4	1.083	64,800
75	19	20	55	0.15	4	1.579	64,800
76	6	16	55	0.15	4	1.029	64,800
77	7	18	55	0.15	4	5.750	64,800
78	15	17	55	0.15	4	0.573	64,800
79	15	16	55	0.15	4	3.077	64,800
80	12	14	45	0.15	4	1.170	33,600
81	13	3	45	0.15	4	2.740	33,600
82	3	12	45	0.15	4	1.244	33,600
83	11	8	55	0.15	4	3.672	64,800
84	10	9	45	0.15	4	4.620	33,600
85	9	8	55	0.15	4	0.242	64,800
86	2	7	55	0.15	4	4.092	64,800
87	6	7	55	0.15	4	1.866	64,800
88	5	0	55	0.15	4	2.620	64,800
89	4	3	55	0.15	4	0.813	64,800
90	3	2	55	0.15	4	0.503	64,800
91	1	0	55	0.15	4	2.390	38,400

Table 3-2 Traffic demand (OD pairs) for the transportation network in Memphis, TN (in hundreds, ***vehicles/day***)

T/F	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**
0	0	1	5	5	5	1	4	4	3	3	2	3	5	4	5	5	4	5	2	5	5	3	2	4	4	2	2	3	2	5	1	1	1	1
1	1	0	5	5	5	1	4	4	3	3	2	3	5	4	5	5	4	5	2	5	5	3	2	4	4	2	2	3	2	5	1	1	1	1
2	5	5	0	25	25	5	20	20	15	15	10	15	25	20	25	25	20	25	10	25	25	15	10	20	20	10	10	15	10	25	5	5	5	5
3	5	5	25	0	25	5	20	20	15	15	10	15	25	20	25	25	20	25	10	25	25	15	10	20	20	10	10	15	10	25	5	5	5	5
4	5	5	25	25	0	5	20	20	15	15	10	15	25	20	25	25	20	25	10	25	25	15	10	20	20	10	10	15	10	25	5	5	5	5
5	1	1	5	5	5	0	4	4	3	3	2	3	5	4	5	5	4	5	2	5	5	3	2	4	4	2	2	3	2	5	1	1	1	1
6	4	4	20	20	20	4	0	16	12	12	8	12	20	16	20	20	16	20	8	20	20	12	8	16	16	8	8	12	8	20	4	4	4	4
7	4	4	20	20	20	4	16	0	12	12	8	12	20	16	20	20	16	20	8	20	20	12	8	16	16	8	8	12	8	20	4	4	4	4
8	3	3	15	15	15	3	12	12	0	9	6	9	15	12	15	15	12	15	6	15	15	9	6	12	12	6	6	9	6	15	3	3	3	3
9	3	3	15	15	15	3	12	12	9	0	6	9	15	12	15	15	12	15	6	15	15	9	6	12	12	6	6	9	6	15	3	3	3	3
10	2	2	10	10	10	2	8	8	6	6	0	6	10	8	10	10	8	10	4	10	10	6	4	8	8	4	4	6	4	10	2	2	2	2
11	3	3	15	15	15	3	12	12	9	9	6	0	15	12	15	15	12	15	6	15	15	9	6	12	12	6	6	9	6	15	3	3	3	3
12	5	5	25	25	25	5	20	20	15	15	10	15	0	20	25	25	20	25	10	25	25	15	10	20	20	10	10	15	10	25	5	5	5	5
13	4	4	20	20	20	4	16	16	12	12	8	12	20	0	20	20	16	20	8	20	20	12	8	16	16	8	8	12	8	20	4	4	4	4
14	5	5	25	25	25	5	20	20	15	15	10	15	25	20	0	25	20	25	10	25	25	15	10	20	20	10	10	15	10	25	5	5	5	5
15	5	5	25	25	25	5	20	20	15	15	10	15	25	20	25	0	20	25	10	25	25	15	10	20	20	10	10	15	10	25	5	5	5	5
16	4	4	20	20	20	4	16	16	12	12	8	12	20	16	20	20	0	20	8	20	20	12	8	16	16	8	8	12	8	20	4	4	4	4
17	5	5	25	25	25	5	20	20	15	15	10	15	25	20	25	25	20	0	10	25	25	15	10	20	20	10	10	15	10	25	5	5	5	5
18	2	2	10	10	10	2	8	8	6	6	4	6	10	8	10	10	8	10	0	10	10	6	4	8	8	4	4	6	4	10	2	2	2	2
19	5	5	25	25	25	5	20	20	15	15	10	15	25	20	25	25	20	25	10	0	25	15	10	20	20	10	10	15	10	25	5	5	5	5
20	5	5	25	25	25	5	20	20	15	15	10	15	25	20	25	25	20	25	10	25	0	15	10	20	20	10	10	15	10	25	5	5	5	5
21	3	3	15	15	15	3	12	12	9	9	6	9	15	12	15	15	12	15	6	15	15	0	6	12	12	6	6	9	6	15	3	3	3	3
22	2	2	10	10	10	2	8	8	6	6	4	6	10	8	10	10	8	10	4	10	10	6	0	8	8	4	4	6	4	10	2	2	2	2
23	4	4	20	20	20	4	16	16	12	12	8	12	20	16	20	20	16	20	8	20	20	12	8	0	16	8	8	12	8	20	4	4	4	4
24	4	4	20	20	20	4	16	16	12	12	8	12	20	16	20	20	16	20	8	20	20	12	8	16	0	8	8	12	8	20	4	4	4	4
25	2	2	10	10	10	2	8	8	6	6	4	6	10	8	10	10	8	10	4	10	10	6	4	8	8	0	4	6	4	10	2	2	2	2
26	2	2	10	10	10	2	8	8	6	6	4	6	10	8	10	10	8	10	4	10	10	6	4	8	8	4	0	6	4	10	2	2	2	2
27	3	3	15	15	15	3	12	12	9	9	6	9	15	12	15	15	12	15	6	15	15	9	6	12	12	6	6	0	6	15	3	3	3	3
28	2	2	10	10	10	2	8	8	6	6	4	6	10	8	10	10	8	10	4	10	10	6	4	8	8	4	4	6	0	10	2	2	2	2
29	5	5	25	25	25	5	20	20	15	15	10	15	25	20	25	25	20	25	10	25	25	15	10	20	20	10	10	15	10	0	5	5	5	5
30	1	1	5	5	5	1	4	4	3	3	2	3	5	4	5	5	4	5	2	5	5	3	2	4	4	2	2	3	2	5	0	1	1	1
31	1	1	5	5	5	1	4	4	3	3	2	3	5	4	5	5	4	5	2	5	5	3	2	4	4	2	2	3	2	5	1	0	1	1
32	1	1	5	5	5	1	4	4	3	3	2	3	5	4	5	5	4	5	2	5	5	3	2	4	4	2	2	3	2	5	1	1	0	1
33	1	1	5	5	5	1	4	4	3	3	2	3	5	4	5	5	4	5	2	5	5	3	2	4	4	2	2	3	2	5	1	1	1	0

Table 3-3 Impact of post-disaster reconstruction on transportation network status

Reconstruction Milestone		Link	Route	Capacity (*vehicle/day*)	Speed (*mph*)
1	t_0	9	US-64	0	0
		14	US-78	0	0
		15	I-240	0	0
		24	I-40	0	0
		26	I-240	0	0
		37	I-240	0	0
		39	I-240	0	0
		55	US-64	0	0
		60	US-78	0	0
		61	I-240	0	0
		70	I-40	0	0
		72	I-240	0	0
		83	I-240	0	0
		85	I-240	0	0
2	t_{20}	9	US-64	33,600	45
		55	US-64	33,600	45
3	t_{50}	37	I-240	64,800	55
		83	I-240	64,800	55
4	t_{75}	39	I-240	64,800	55
		85	I-240	64,800	55
5	t_{90}	24	I-40	64,800	55
		70	I-40	64,800	55
6	t_{120}	15	I-240	64,800	55
		61	I-240	64,800	55
7	t_{145}	26	I-240	64,800	55
		72	I-240	64,800	55
8	t_{180}	14	US-78	33,600	45
		60	US-78	33,600	45

traffic is expected to ease the service disruption by almost 90% (from 14.94 to 1.46 $vehicle.hour/vehicle$), as shown in Figure 3-5. The analysis of this example also shows that the expected service disruption towards the end of the reconstruction efforts is very small compared to the pre-disaster conditions. For example, travelers are expected to suffer an additional travel time of only 0.04 $vehicle.hour/vehicle$ (slightly more than two minutes per day on average for each traveler) after 120 days (t_{120}), which further decreases to only one minute per day on average for each traveler from

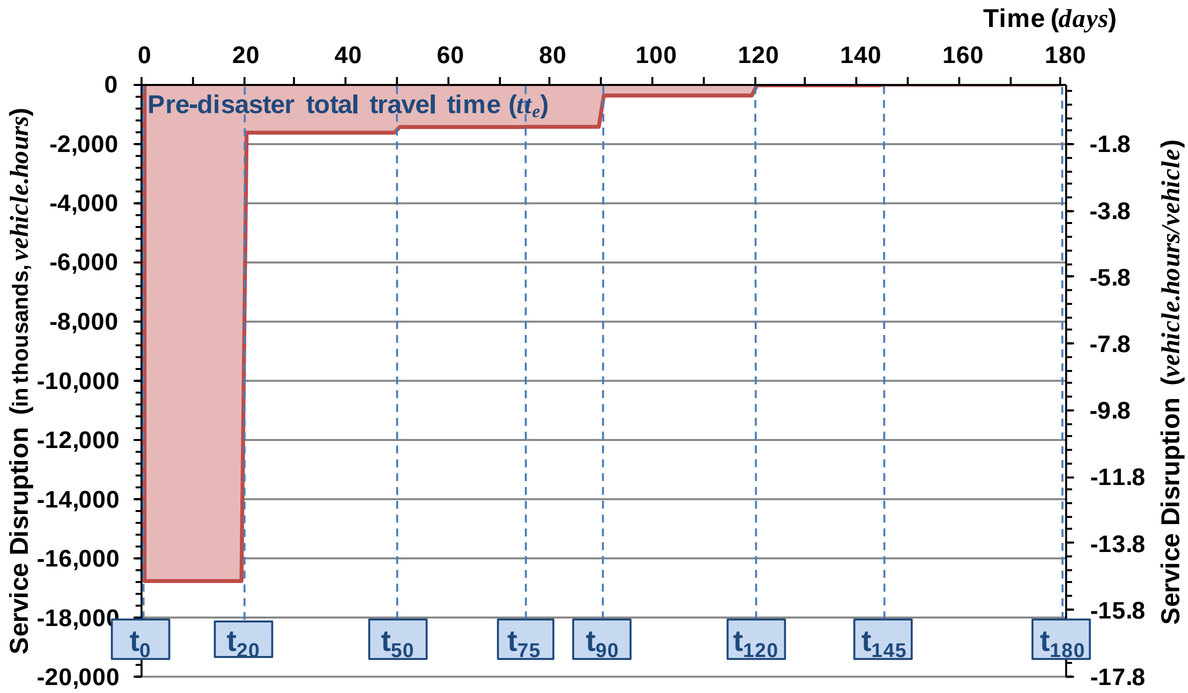


Figure 3-5 Performance of the transportation network during post-disaster reconstruction efforts

(t_{145}) onward, as shown in Figure 3-5. Finally, the model was able to estimate that a total of about 457 million *vehicle.hours* in overall service disruption is expected to be experienced by travelers on this transportation network during the recovery efforts.

3.4.2 Example 2: Highway Rehabilitation Efforts

In this application example, the developed service disruption model is used to evaluate the impact of a highway rehabilitation program on the functional performance of an aging transportation network and measure the expected service disruption during rehabilitation efforts. The application example seeks to analyze the performance of the transportation network in Sioux Falls, South Dakota that is assumed to require a rehabilitation program of ten projects to upgrade the surface conditions of aging roads. Figure 3-6 shows a schematic of this aging network and the location of the links which

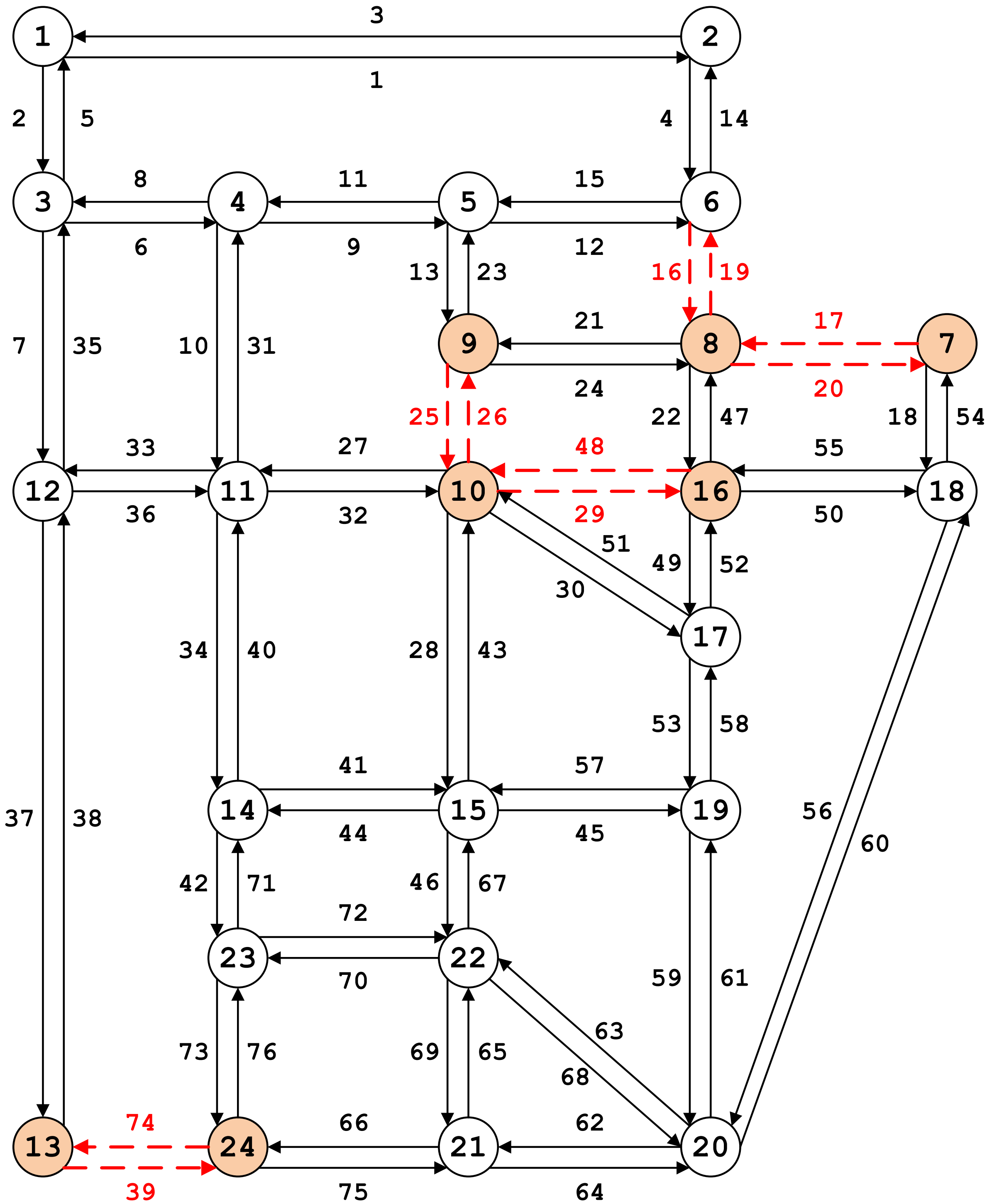


Figure 3-6 Schematic map of the aging transportation network (Sioux Falls, SD)

Table 3-4 Topology of the transportation network in Sioux Falls, SD

Link	Start Node	Finish Node	Speed (*mph*)	α	β	Length (*mile*)	Capacity (*veh/day*)
1	1	2	60	0.15	4	6.000	25,900
2	1	3	60	0.15	4	4.000	23,403
3	2	1	60	0.15	4	6.000	25,900
4	2	6	60	0.15	4	5.000	4,958
5	3	1	60	0.15	4	4.000	23,403
6	3	4	60	0.15	4	4.000	17,111
7	3	12	60	0.15	4	4.000	23,403
8	4	3	60	0.15	4	4.000	17,111
9	4	5	60	0.15	4	2.000	17,783
10	4	11	60	0.15	4	6.000	4,909
11	5	4	60	0.15	4	2.000	17,783
12	5	6	60	0.15	4	4.000	4,948
13	5	9	60	0.15	4	5.000	10,000
14	6	2	60	0.15	4	5.000	4,958
15	6	5	60	0.15	4	4.000	4,948
16	6	8	60	0.15	4	2.000	4,899
17	7	8	60	0.15	4	3.000	7,842
18	7	18	60	0.15	4	2.000	23,403
19	8	6	60	0.15	4	2.000	4,899
20	8	7	60	0.15	4	3.000	7,842
21	8	9	60	0.15	4	10.000	5,050
22	8	16	60	0.15	4	5.000	5,046
23	9	5	60	0.15	4	5.000	10,000
24	9	8	60	0.15	4	10.000	5,050
25	9	10	60	0.15	4	3.000	13,916
26	10	9	60	0.15	4	3.000	13,916
27	10	11	60	0.15	4	5.000	10,000
28	10	15	60	0.15	4	6.000	13,512
29	10	16	60	0.15	4	4.000	4,855
30	10	17	60	0.15	4	8.000	4,994
31	11	4	60	0.15	4	6.000	4,909
32	11	10	60	0.15	4	5.000	10,000
33	11	12	60	0.15	4	6.000	4,909
34	11	14	60	0.15	4	4.000	4,877
35	12	3	60	0.15	4	4.000	23,403
36	12	11	60	0.15	4	6.000	4,909
37	12	13	60	0.15	4	3.000	25,900
38	13	12	60	0.15	4	3.000	25,900
39	13	24	60	0.15	4	4.000	5,091
40	14	11	60	0.15	4	4.000	4,877
41	14	15	60	0.15	4	5.000	5,128
42	14	23	60	0.15	4	4.000	4,925
43	15	10	60	0.15	4	6.000	13,512
44	15	14	60	0.15	4	5.000	5,128
45	15	19	60	0.15	4	3.000	14,565
46	15	22	60	0.15	4	3.000	9,599
47	16	8	60	0.15	4	5.000	5,046

Table 3-4 Topology of the transportation network in Sioux Falls, SD (continued)

Link	Start Node	Finish Node	Speed (*mph*)	α	β	Length (*mile*)	Capacity (*veh/day*)
48	16	10	60	0.15	4	4.000	4,855
49	16	17	60	0.15	4	2.000	5,230
50	16	18	60	0.15	4	3.000	19,680
51	17	10	60	0.15	4	8.000	4,994
52	17	16	60	0.15	4	2.000	5,230
53	17	19	60	0.15	4	2.000	4,824
54	18	7	60	0.15	4	2.000	23,403
55	18	16	60	0.15	4	3.000	19,680
56	18	20	60	0.15	4	4.000	23,403
57	19	15	60	0.15	4	3.000	14,565
58	19	17	60	0.15	4	2.000	4,824
59	19	20	60	0.15	4	4.000	5,003
60	20	18	60	0.15	4	4.000	23,403
61	20	19	60	0.15	4	4.000	5,003
62	20	21	60	0.15	4	6.000	5,060
63	20	22	60	0.15	4	5.000	5,076
64	21	20	60	0.15	4	6.000	5,060
65	21	22	60	0.15	4	2.000	5,230
66	21	24	60	0.15	4	3.000	4,885
67	22	15	60	0.15	4	3.000	9,599
68	22	20	60	0.15	4	5.000	5,076
69	22	21	60	0.15	4	2.000	5,230
70	22	23	60	0.15	4	4.000	5,000
71	23	14	60	0.15	4	4.000	4,925
72	23	22	60	0.15	4	4.000	5,000
73	23	24	60	0.15	4	2.000	5,079
74	24	13	60	0.15	4	4.000	5,091
75	24	21	60	0.15	4	3.000	4,885
76	24	23	60	0.15	4	2.000	5,079

need to be upgraded (highlighted in red dashed lines), while the topology and traffic demand of the network are shown in Table 3-4 and Table 3-5, respectively. The roads are assumed to be partially open for traffic during rehabilitation efforts, as one lane will be closed at a time and speed limits will be decreased to maximize the safety of work zones. This rehabilitation program is expected to take 24 months to complete and includes 12 important milestones at which significant changes to the status of the network occur, as shown in Table 3-6. The first milestone (t_0) is at the onset of the

Table 3-5 Traffic demand (OD pairs) for the transportation network in Sioux Falls, SD (***vehicles/day***)

T/F	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	0	100	100	500	200	300	500	800	500	1300	500	200	500	300	500	500	400	100	300	300	100	400	300	100
2	100	0	100	200	100	400	200	400	200	600	200	100	300	100	100	400	200	0	100	100	0	100	0	0
3	100	100	0	200	100	300	100	200	100	300	300	200	100	100	100	200	100	0	0	0	0	100	100	0
4	500	200	200	0	500	400	400	700	700	1200	1400	600	600	500	500	800	500	100	200	300	200	400	500	200
5	200	100	100	500	0	200	200	500	800	1000	500	200	200	100	200	500	200	0	100	100	100	200	100	0
6	300	400	300	400	200	0	400	800	400	800	400	200	200	100	200	900	500	100	200	300	100	200	100	100
7	500	200	100	400	200	400	0	1000	600	1900	500	700	400	200	500	1400	1000	200	400	500	200	500	200	100
8	800	400	200	700	500	800	1000	0	800	1600	800	600	600	400	600	2200	1400	300	700	900	400	500	300	200
9	500	200	100	700	800	400	600	800	0	2800	1400	600	600	600	900	1400	900	200	400	600	300	700	500	200
10	1300	600	300	1200	1000	800	1900	1600	2800	0	4000	2000	1900	2100	4000	4400	3900	700	1800	2500	1200	2600	1800	800
11	500	200	300	1500	500	400	500	800	1400	3900	0	1400	1000	1600	1400	1400	1000	100	400	600	400	1100	1300	600
12	200	100	200	600	200	200	700	600	600	2000	1400	0	1300	700	700	700	600	200	300	400	300	700	700	500
13	500	300	100	600	200	200	400	600	600	1900	1000	1300	0	600	700	600	500	100	300	600	600	1300	800	800
14	300	100	100	500	100	100	200	400	600	2100	1600	700	600	0	1300	700	700	100	300	500	400	1200	1100	400
15	500	100	100	500	200	200	500	600	1000	4000	1400	700	700	1300	0	1200	1500	200	800	1100	800	2600	1000	400
16	500	400	200	800	500	900	1400	2200	1400	4400	1400	700	600	700	1200	0	2800	500	1300	1600	600	1200	500	300
17	400	200	100	500	200	500	1000	1400	900	3900	1000	600	500	700	1500	2800	0	600	1700	1700	600	1700	600	300
18	100	0	0	100	0	100	200	300	200	700	200	200	100	100	200	500	600	0	300	400	100	300	100	0
19	300	100	0	200	100	200	400	700	400	1800	400	300	300	300	800	1300	1700	300	0	1200	400	1200	300	100
20	300	100	0	300	100	300	500	900	600	2500	600	500	600	500	1100	1600	1700	400	1200	0	1200	2400	700	400
21	100	0	0	200	100	100	200	400	300	1200	400	300	600	400	800	600	600	100	400	1200	0	1800	700	500
22	400	100	100	400	200	200	500	500	700	2600	1100	700	1300	1200	2600	1200	1700	300	1200	2400	1800	0	2100	1100
23	300	0	100	500	100	100	200	300	500	1800	1300	700	800	1100	1000	500	600	100	300	700	700	2100	0	700
24	100	0	0	200	0	100	100	200	200	800	600	500	700	400	400	300	300	0	100	400	500	1100	700	0

Table 3-6 Impact of rehabilitation program on transportation network status

Rehabilitation Milestone			Link	Capacity (*vehicle/day*)	Speed (*mph*)
1	t_0	Month 0	20	6,958	45
			26	3,921	45
			29	2,428	45
2	t_6	Month 6	19	7,842	60
			20	2,450	45
3	t_7	Month 7	25	13,916	60
			26	6,958	45
4	t_8	Month 8	29	4,855	60
			48	2,428	45
5	t_{10}	Month 10	19	4,899	60
6	t_{11}	Month 11	74	2,546	45
7	t_{12}	Month 12	25	13,916	60
8	t_{13}	Month 13	17	3,921	45
9	t_{15}	Month 15	39	4,855	60
			48	2,546	45
10	t_{20}	Month 20	16	5,092	60
			17	7,842	60
			74	2,450	45
11	t_{22}	Month 22	39	5,092	60
12	t_{24}	Month 24	16	4,899	60

rehabilitation program when upgrade efforts start for links 20, 26 and 29 bringing about significant changes to the capacity and speed limit of these roads (Table 3-6). The subsequent milestones bring about similar changes to the status of the transportation network until upgrade works are completed for all links at (t_{24}), which represents the end of the 24th month of the rehabilitation program, as shown in Table 3-6.

These network and rehabilitation data were analyzed using the newly developed service disruption model that was able to evaluate the expected impact of the rehabilitation schedule (Table 3-6) on the disruption in the level of service provided by this aging transportation network during the rehabilitation efforts, as shown in Figure 3-7. The

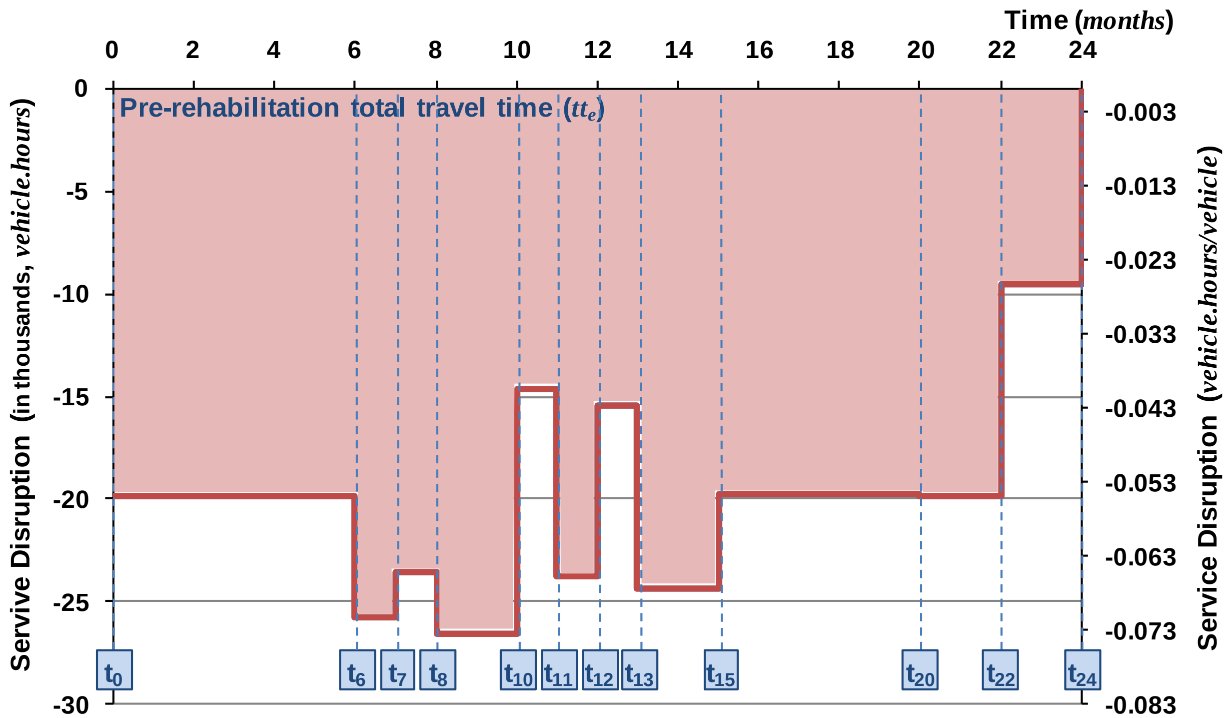


Figure 3-7 Performance of the transportation network during post-disaster reconstruction efforts

analysis of this example shows that the level of service disruption experienced by travelers is expected to fluctuate over the duration of the rehabilitation program with the changes in the status of the transportation network at each milestone (Figure 3-7). For example, the highest level of service disruption is expected to occur during months 9 and 10 of the rehabilitation program when surface upgrade works are planned for links 19, 25 and 48. Similarly, working on only one road (link 16) during the last two months (23 and 24) of the rehabilitation program is expected to yield the lowest travel delay, as shown in Figure 3-7. Finally, the model was able to estimate that a total of about 14.5 million $vehicle.hours$ in travel delay is expected to be experienced by travelers on this aging transportation network over two years of rehabilitation efforts.

3.5 Summary

A highway service disruption model was developed to support measuring and evaluating the expected disruption in the level of service provided by aging transportation networks during highway reconstruction and rehabilitation projects. The model is capable of analyzing the impact of construction projects and their dynamic nature on the functional performance of aging transportation networks during reconstruction and rehabilitation efforts. This model also incorporates a deterministic travel assignment algorithm in order to facilitate considering the impact of individualistic rationality of travelers in selecting which route/detour to use at different phases of the construction efforts. The developed model is therefore capable of portraying the functional performance of aging transportation and identifying level of service disruption experienced by road users as a result of implementing specific reconstruction plans or rehabilitation programs. In order to evaluate the performance of the developed model, two application examples are analyzed to illustrate the use of the model and demonstrate its capabilities in analyzing the impact of highway construction on the functional performance of transportation networks. The analysis of these application examples illustrate the capabilities of the developed model in assessing the service disruption in aging transportation networks, including: (1) considering the dynamic nature of construction operations and activities and identifying their expected impact on the functional performance of aging transportation networks during reconstruction and rehabilitation efforts; (2) accounting for the individualistic rationality of travelers in choosing which route/detour to use to reach their destinations; and (3) evaluating the overall loss/savings in network travel time of the aging transportation network during highway reconstruction and rehabilitation efforts. These new and unique capabilities of the developed model should prove useful to decision makers and planners in departments of transportation (DOTs) and should contribute to planning and optimizing highway reconstruction and rehabilitation efforts, as will be described in the following chapters of this study.

CHAPTER 4
OPTIMIZING POST-DISASTER RECONSTRUCTION OF DAMAGED HIGHWAYS

4.1 Introduction

This chapter discusses planning and optimizing post-disaster reconstruction efforts of damaged transportation network in order to identify the reconstruction plan(s) that minimize both network service disruption and public expenditures on reconstruction costs simultaneously. To this end, this chapter presents the development of two new models for planning reconstruction efforts that are capable of: (1) allocating limited reconstruction resources to competing recovery projects; and (2) generating optimal recovery plans that simultaneously minimize network service disruption and reconstruction cost. The following sections describe the development of these two models and the analysis of an application example to evaluate their performance.

4.2 Resource Utilization Model

The main purpose of this model is to allocate limited reconstruction resources to competing projects and generate a schedule for the reconstruction efforts of the damaged transportation network. The model is designed to take into consideration the potential change in resource availability levels over time. The allocation process therefore utilizes two sets of data: (1) reconstruction data, including the scope of reconstruction work needed and the available reconstruction resources; and (2) a specified set of decision variables, including the prioritization of reconstruction projects, assignment of projects to interested contractors, and overtime policy adopted in each

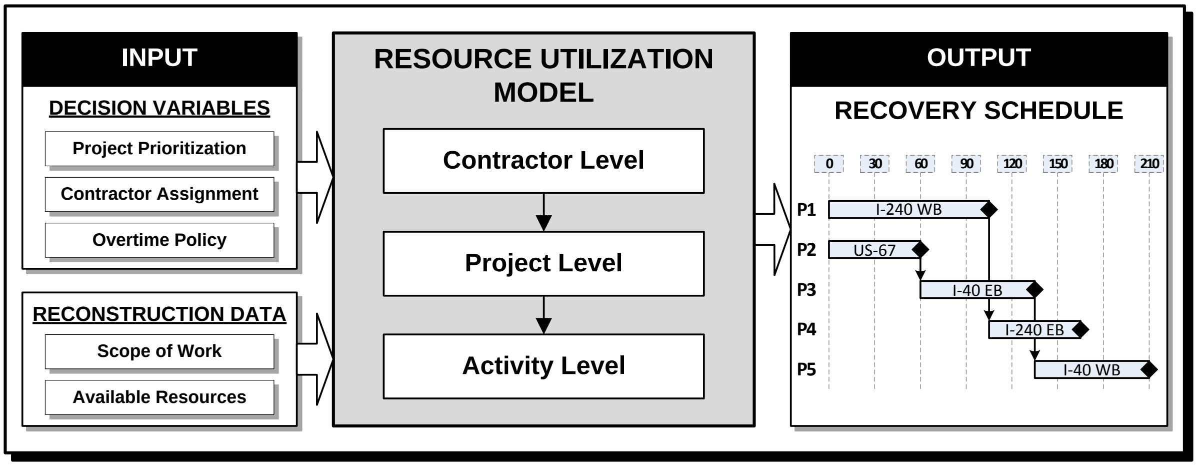


Figure 4-1 Resource utilization model

project, as shown in Figure 4-1. In order to achieve this objective, the model allocates the limited reconstruction resources among the competing projects using a three-level allocation process: (1) contractor level; (2) project level; and (3) activity level, as shown in Figure 4-1.

4.2.1 Contractor Level

The main purpose of this level in the resource utilization model is to organize the scope of reconstruction work data and resource availability data into a set of smaller and more manageable work packages, as shown in Figure 4-2. The number of these work packages is lesser than or equal to the number of interested qualified contractors (X), to which these packages are assigned according to the specified contractor assignment. The data integrated in each work package (x) from the reconstruction data includes the projects assigned to contractor (x) and the reconstruction resources data which are available in the contractor's resource pool, as shown in Figure 4-2. These reconstruction data include: (1) scope of work which represents the planned reconstruction activities in each project, their job logic, and resource requirements; and (2) available resources data which specifies the resources availability dates, productivity rates, and unit costs (see Figure 4-2).

4.2.2 Project Level

The main purpose of the project-level resource utilization is to assign the reconstruction resources available in work package (x) to the competing projects assigned to contractor (x). This resource assignment process is performed according to the following set of rules and assumptions:

- reconstruction resources are deployed to projects according to the priorities of these projects;
- reconstruction projects can start with fewer resources than required and obtain their full requirements at a later stage as additional resources become available;
- reconstruction projects cannot be interrupted once started to avoid the high

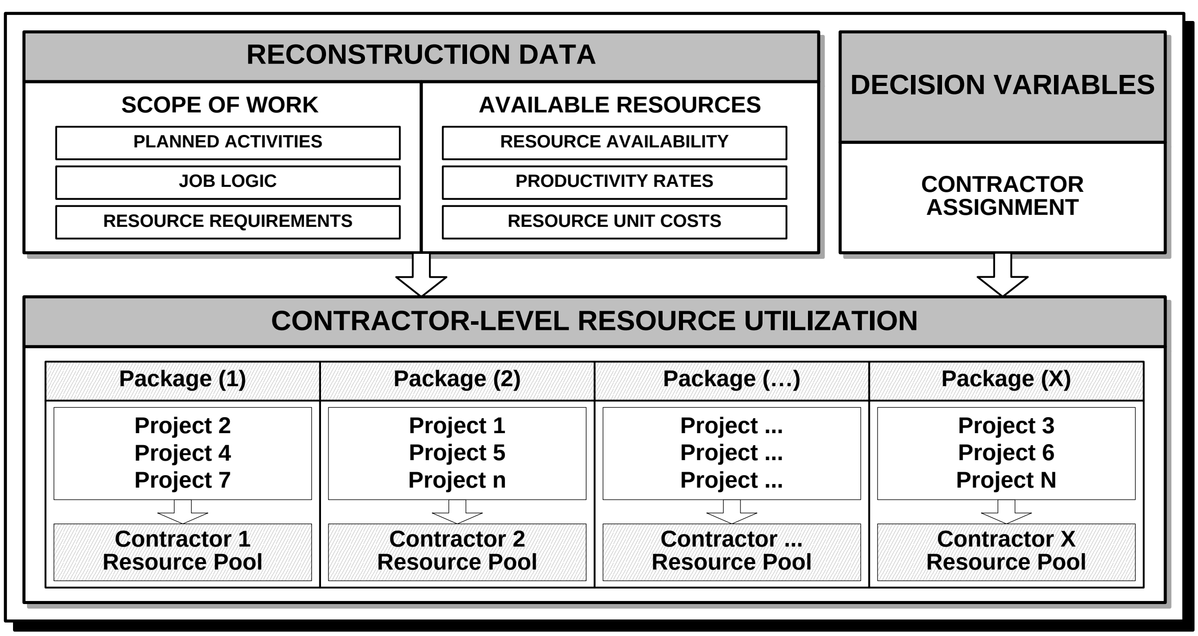


Figure 4-2 Contractor-level resource utilization

mobilization and demobilization costs of moving construction resources between post-disaster reconstruction projects that are typically spread over a large geographical area;

- activity durations, and hence project durations, can extend or shrink based on the number and availability of the resources assigned to each activity; and
- resources are released from a project once they are no longer needed.

The resource utilization model uses the four-step procedure outlined in Figure 4-3 to perform the resource utilization process at the project-level. These steps are as follows:

1. Select the unscheduled project with highest priority (n) from the reconstruction projects of work package (x).
2. Deploy to project (n) its resource requirements from the resource pool of work

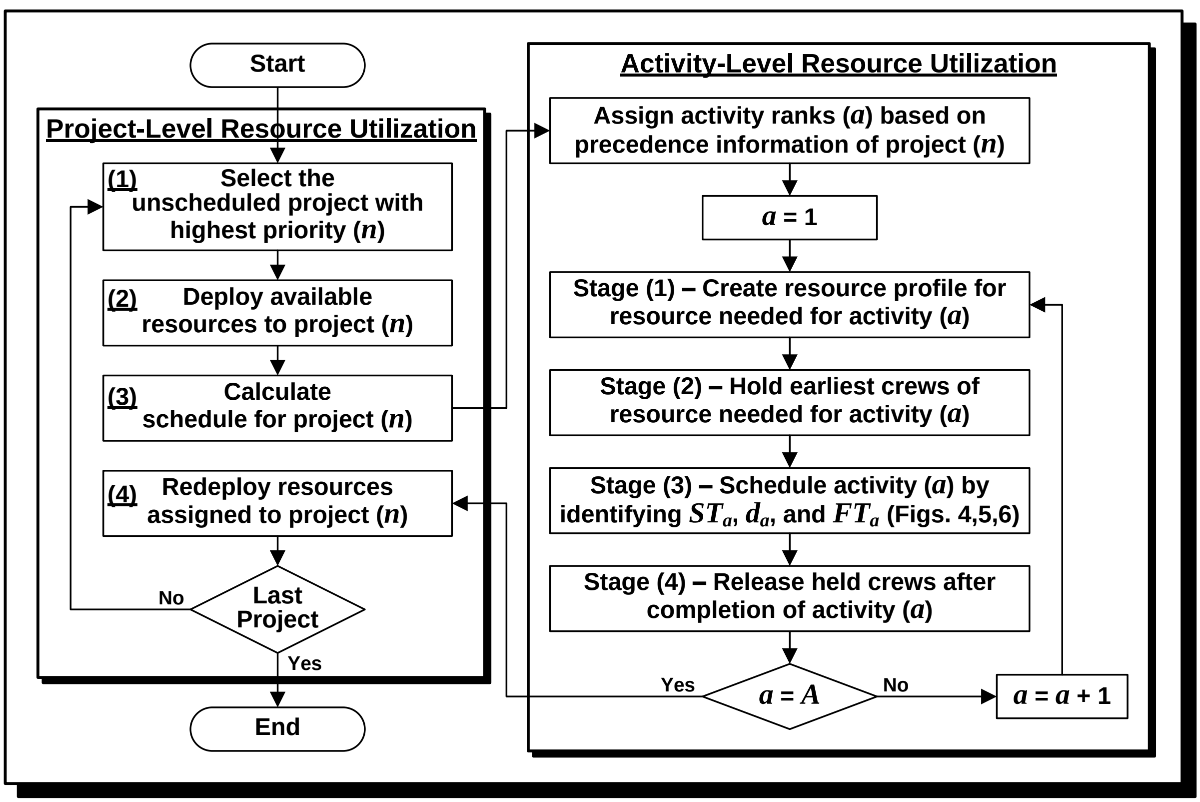


Figure 4-3 Project- and activity-level resource utilization

package (x) based on the availability of these resources. If the required resources are not immediately available, the related reconstruction work is suspended until resources are released from other ongoing projects.

3. Calculate the schedule of project (n), which involves the utilization of the resources deployed to project (n) at the activity level, as shown in Figure 4-3 and described later in the activity level section.
4. Redeploy the resources assigned to project (n) after they complete their work on the project to the resource pool of work package (x). These released resources are then made available to other projects in the same package.

This procedure is repeated until all the reconstruction projects of work package (x) are scheduled. However, in order to facilitate the application of this procedure and to satisfy the above rules and assumptions, the deployment and utilization of the available resources among the reconstruction projects of work package (x) need to be accurately planned and monitored. This includes the ability to identify the location and availability of each of these resources at any time. Accordingly, the present utilization model monitors the movement of each resource using a separate tracking sheet for each resource, as shown in Figure 4-4. These tracking sheets enable the model to identify the location and availability times of each crew for different resources.

4.2.3 Activity Level

The main purpose of the activity-level resource utilization is to calculate the schedule of each reconstruction project (n). This is achieved by assigning the available resources to the individual activities of this project and calculating their schedule accordingly. To clarify this process, Figure 4-4 illustrates how the activity-level resource utilization is used to schedule an example activity (a) that has a total quantity of 8740 CY of bulk excavation and needs to be completed using a maximum number of four crews of B-12F. The activity scheduling procedure is shown in Figure 4-3 and described as

Activity (a)		Resource (B-12F)	
Bulk Excavation Qty: 8740 CY Need: 4 crews of B-12F	→	Hydraulic Excavator (0.75 CY) and 2 Equipment Operators Productivity: 360 CY / day	Seven crews are available from this resource

Stage (1) – Creating resource profile:

Crew Number	1	2	3	4	5	6	7
Day Available	37	21	25	41	29	33	21

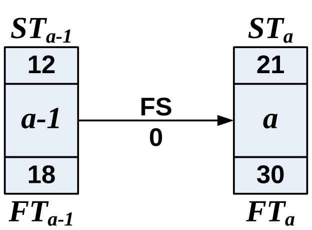
Interval		1	2	3	4	5
Day	21	25	29	33	37	41
Crew Count	2	1	1	1	1	1
Crew Number	2	3	5	6	1	4
	7					

Stage (2) – Holding needed crews:

Crew Number	1	**2**	**3**	4	**5**	6	**7**
Day Available	37	--	--	41	--	33	--

Interval		1	2	3	4	5
Day	21	25	29	33	37	41
Crew Count	2	1	1	1	1	1
Crew Number	**2**	**3**	**5**	6	1	4
	7					

Stage (3) – Calculating activity duration (d_a):



	Day	21	22	23	24	25	26	27	28	29	30
Shift 1	Alloc. Crews	2	2	2	2	2	2	2	2	2	2
		7	7	7	7	7	7	7	7	7	7
	α_1=1.0										
	Output	720	720	720	720	720	720	720	720	720	720
Shift 2	Alloc. Crews					3	3	3	3	3	
										5	
	α_2=0.71										
	Output					257	257	257	257	514	

Stage (4) – Releasing held crews:

Crew Number	1	2	3	4	5	6	7
Day Available	37	31	30	41	30	33	31

Interval		1	2	3	4	
Day	30	31	33	37	41	
Crew Count	2	2	1	1	1	
Crew Number	3	2	6	1	4	
	5	7				

Figure 4-4 Resource tracking sheet and example of activity scheduling

follows:

- Assign a rank ($a = 1$ to A) to each activity in project (n) to represent its order of execution based on the precedence relationships and job logic in the project. If two or more activities can be executed concurrently; their ranks are assigned by giving lower ranks (i.e., earlier execution order) to activities with the earliest late start. If a tie still exists, activity ordering will be based on subsequent priority rules such as least total float and the alphanumeric order of their IDs.
- Deploy the available resources to the project activities according to their ranks and calculate the schedule of these activities. The resource tracking sheets described above are used to monitor the deployment and redeployment of resources among the activities. In order to complete this task, the four-stage process shown in Figure 4-3 is used for each activity (a), as follows:

Stage (1) – Create resource profile

The resource tracking sheet is used to create a resource profile for the available crews needed for activity (a). The purpose of this resource profile is to facilitate the processes of holding and releasing the required crews by grouping these crews based on their availability dates. For example, Figure 4-4 shows the tracking sheet for the seven available crews of resource B-12F which can be used for the execution of the bulk excavation of activity (a). The earliest availability date for this resource is day 21 when crews number 2 and 7 become available; whereas the remaining crews become available between days 25 and 41, as shown in Figure 4-4.

Stage (2) – Hold needed crews

In this stage, a hold is placed on the earliest available crews of the resource needed for the completion of activity (a) based on the resource requirements of this activity. For example, if activity (a) needs two crews per shift and is planned to work for two 10-hour shifts per day, this adds up to a total of four crews required for this activity per day. Accordingly, the present model places a hold on crew numbers 2, 7, 3 and 5, which are planned to become available on days 21, 25, and 29 of the reconstruction efforts, as shown in Figure 4-4.

Stage (3) – Schedule the current activity

The calculation of activity (a) schedule should consider a number of factors that have a direct impact on identifying when to start the activity and how long it takes to finish this activity. These factors include: (1) the quantity of reconstruction work needed to complete this activity (q_a); (2) the availability of the reconstruction crews held for activity (a); and (3) the overtime policy adopted. As described earlier, the availability of reconstruction crews can vary over time and therefore the number of crews available at

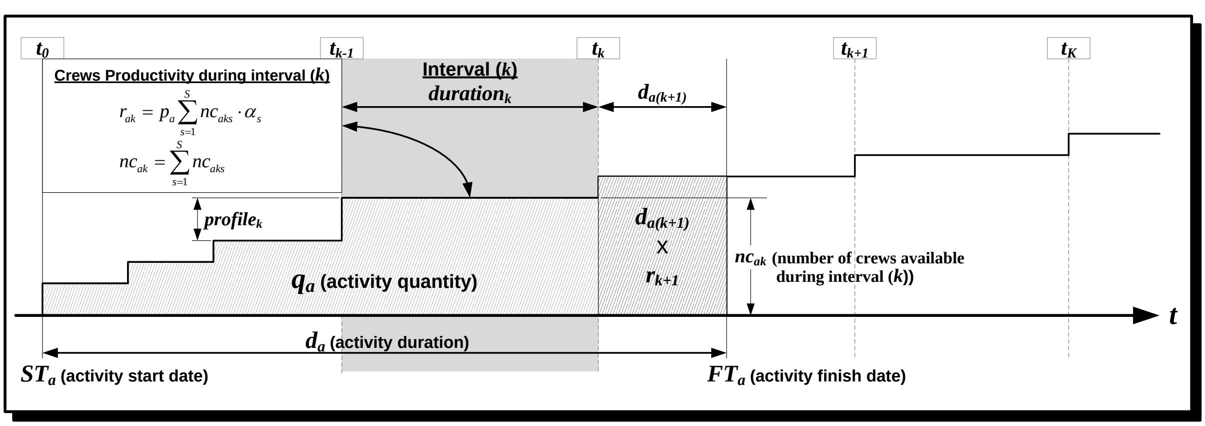


Figure 4-5 Activity scheduling process

the start date (ST_a) of an activity can be fewer than its requirements and increase over time until full resource requirements become available, as shown in Figure 4-5. Similarly, the overtime policy adopted for each reconstruction project imposes different productivity rates for the crews working in different shifts. In order to account for these varying productivity levels due to resource availability and adopted overtime policy, the resource utilization model employs a newly developed process to identify the three scheduling variables for each activity (a): start date (ST_a), duration (d_a), and finish date (FT_a), as shown in Figure 4-5. In this process, the activity duration (d_a) is estimated to cover a number of resource availability intervals ($k = 1 \text{ to } K$) that represent varying levels of resource availability over the activity duration, where the number of available crews at each interval (k) can be represented by (nc_{ak}), as shown in Figure 4-5. This process then estimates and accumulates the amount of reconstruction work that can be completed during each interval until the total activity quantity (q_a) has been completed. Figure 4-6 shows a flowchart for this process, which can be described as follows:

1. Identify the activity start date (ST_a) which is calculated as the latest of: (i) the earliest start date imposed by the job logic and the precedence relationships in the project; and (ii) the earliest availability date of the crews held for activity (a) as described in the previous stage. According to the job logic of the example shown in Figure 4-4, activity (a) can start immediately after activity ($a-1$) finishes on day 18; however, the start date (ST_a) of this activity is set to day 21 when crews 2 and 7 become available.

2. Initialize the estimating of activity duration (d_a) by setting all variables to their initial values, including current interval ($k = 1$) and initial duration ($d_a = 0$).

3. Identify the total number of crews available for activity (a) during the current interval (nc_{ak}) by adding the number of crews that became available at the beginning of interval (k) according to the resource profile (see Figure 4-5):

$$nc_{ak} = nc_{a(k-1)} + profile_k \tag{4-1}$$

where,

nc_{ak} = number of crews allocated to activity (a) during interval (k)

$nc_{a(k-1)}$ = number of crews allocated to activity (a) during interval ($k-1$)

$profile_k$ = number of crews that become available during interval (k)

4. Estimate the duration of current interval (k), i.e. how long these crews (nc_{ak}) would be available before the availability changes:

$$duration_k = \begin{cases} t_{k+1} - t_k & \text{if}\,(k < K) \\ \infty & \text{if}\,(k = K) \end{cases} \tag{4-2}$$

where,

$duration_k$ = duration of interval (k)

t_{k+1} = start date of interval ($k+1$)

t_k = start date of interval (k)

K = total number of intervals in the crew availability profile

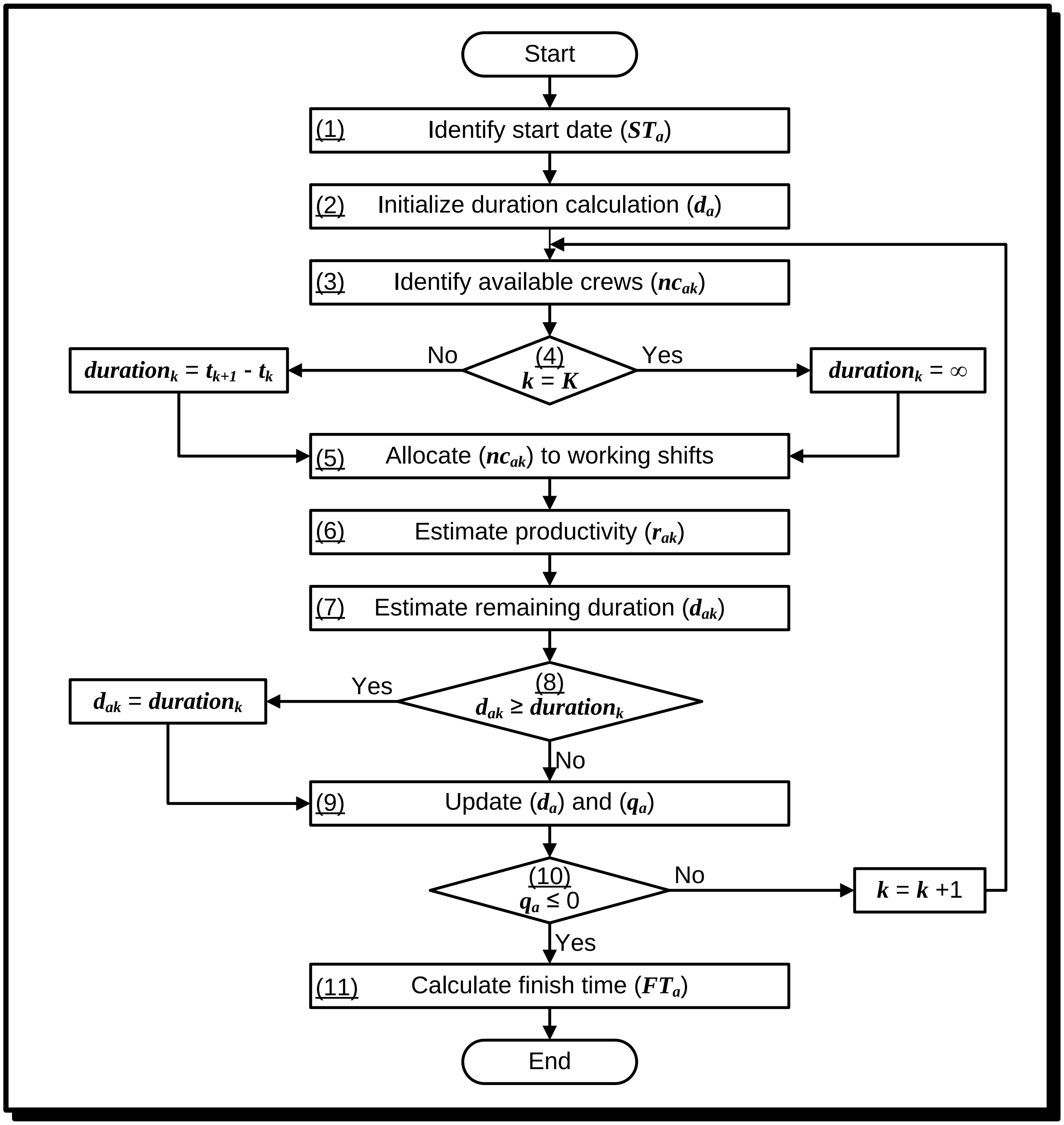


Figure 4-6 Flowchart for calculating activity schedule

5. Allocate the total number of available crews (nc_{ak}) to the shifts working on activity (a) during interval (k) while giving priority to regular shifts in order to maximize productivity and minimize overtime costs.

6. Estimate the total productivity (r_{ak}) of the crews allocated in step (5):

$$r_{ak} = p_a \sum_{s=1}^{S} nc_{aks} \cdot \alpha_s \qquad (4\text{-}3)$$

$$nc_{ak} = \sum_{s=1}^{S} nc_{aks} \qquad (4\text{-}4)$$

where,

r_{ak} = total productivity of crews allocated to activity (a) during interval (k)

p_a = productivity of resources assigned to activity (a) during regular shifts

nc_{aks} = number of crews allocated to shift (s) of activity (a) during interval (k)

α_s = productivity adjustment factor for crews working on shift (s)

S = total number of shifts working on activity (a)

7. Estimate the remaining duration required to complete activity (a) based on the productivity of allocated crews during interval (k):

$$d_{ak} = q_a / r_{ak} \qquad (4\text{-}5)$$

where,

d_{ak} = remaining duration required to complete activity (a) based on the productivity of crews allocated during interval (k)

q_a = remaining quantity of work needed to complete activity (a)

8. Compare (d_{ak}) and ($duratrion_k$) to identify the length of interval (k) duration that should be included in activity duration (d_a):

$$d_{ak} < duration_k \begin{cases} \text{False} \Rightarrow & d_{ak} = duration_k \\ \text{True} \Rightarrow & \text{go to step (9)} \end{cases} \qquad (4\text{-}6)$$

9. Update the activity duration and remaining quantity:

$$q_a = q_a - d_{ak} \cdot r_{ak} \quad (4\text{-}7)$$

$$d_a = d_a + d_{ak} \quad (4\text{-}8)$$

where,

d_a = duration of activity (a)

10. Check the remaining quantity to complete activity (a):

$$q_a \le 0 \begin{cases} \text{False} \Rightarrow & k = k + 1 \quad \text{repeat steps (3) through (10)} \\ \text{True} \Rightarrow & \text{go to step (11)} \end{cases} \quad (4\text{-}9)$$

11. Calculate the finish date of activity (a):

$$FT_a = ST_a + d_a \quad (4\text{-}10)$$

Stage (4) – Release held crews

The reconstruction crews held in stage (2) for the completion of activity (a) are released in this stage for further deployment in the successor activities. In order to release these crews, the present model updates the tracking sheet of these crews according to the finish date (FT_a) of activity (a) estimated in previous stage. In the example shown in Figure 4-4, activity (a) is planned to finish on day 30 of the reconstruction efforts and accordingly the availability dates of the held crews are updated to day 31 for crews 2 and 7, and day 30 for crews 3 and 5 on both the resource tracking sheet and resource profile.

In order to complete the scheduling process, the present resource utilization model calculates the schedule of each reconstruction project and integrates all project schedules into an overall recovery schedule. This includes: (1) performing CPM calculations for each recovery project according to its job logic; (2) calculating activity total and free floats; (3) identifying the critical paths on both the project and global levels; and (4) estimating recovery project durations (d_n). It should be noted that these project schedules are calculated in working days and accordingly they need to be converted to calendar days to facilitate their utilization by planners. In this model, the working days duration of a recovery project (n) are converted to calendar days using Equation (4-11). Similarly, Equation (4-11) can be used to convert start and finish dates of recovery projects from working to calendar dates. It should be noted that estimating these schedule information facilitates identifying all significant completion milestones that may have an impact on the functional performance of damaged transportation networks during the reconstruction process. This reconstruction schedule and its important milestones are input to the service disruption model to analyze the behavior of the transportation network during the reconstruction phase and estimate the expected loss in total network travel time over the same period, as described in the previous chapter.

$$d_n^c = \text{int}\left(d_n / W_n\right) \times 7 + \text{mod}\left(d_n / W_n\right) \qquad (4\text{-}11)$$

where,

d_n^c = duration of project (n) in calendar days

d_n = duration of project (n) in working days

W_n = number of working days per week for project (n)

4.3 Multi-Objective Optimization Model

The main objective of this model is to optimize post-disaster reconstruction efforts in order to satisfy the societal needs of minimizing network service disruption and reconstruction costs. In order to achieve this objective, the model is designed to identify the three main decision variables of: (1) prioritizing the recovery projects; (2) awarding these projects to interested qualified contractors; and (3) identifying an overtime policy for each of these recovery projects. As described earlier in the resource utilization model, each of these important decision variables has a significant impact on the recovery schedule and therefore on the network service disruption and reconstruction costs. Accordingly, this model is designed to generate the optimal project prioritization, contractor assignment, and overtime policy combination(s) that simultaneously minimizes: (1) the overall disruption to the level of service provided by the damaged transportation network during post-disaster reconstruction efforts; and (2) the public expenditures on reconstruction efforts.

The reconstruction costs considered in the present study are the direct (DC) and indirect (IC) costs, as shown in Equation (4-12). The direct costs include the costs of construction resources used to complete the reconstruction works, as shown in Equation (4-13). The overtime policy adopted in each recovery project has a significant impact on the direct costs since working for extended hours and/or multiple shifts requires payment of premiums and can affect the productivity of crews which in turn has a significant impact on effective labor cost, as shown in Equation (4-14). Similarly, the indirect costs include the time-dependent cost such as site overhead, which depends on the duration of each recovery project and the contractor's indirect cost rates, and can be calculated using Equation (4-15).

$$C = \sum_{n=1}^{N} DC_n + IC_n \tag{4-12}$$

$$DC_n = \sum_{a=1}^{A} m_a \times mc_a + \sum_{a=1}^{A} d_a \times lc_a + \sum_{a=1}^{A} d_a \times ec_a \tag{4-13}$$

$$lc_a = nc_a \times c_a \times \sum_{s=1}^{S} \beta_s \tag{4-14}$$

$$IC_n = D_n \times ic_n \tag{4-15}$$

where,

C = reconstruction cost

DC_n = direct reconstruction costs of project (n)

IC_n = indirect reconstruction costs of project (n)

m_a = quantity of material required for activity (a)

mc_a = unit cost of material required for activity (a)

d_a = duration of activity (a)

lc_a = daily labor cost rate for the crew(s) assigned to activity (a)

ec_a = daily equipment cost rate for the crew(s) assigned to activity (a)

nc_a = number of crews assigned to activity (a)

c_a = cost of labor for a single crew assigned to activity (a) during regular shift

β_s = cost adjustment factor for shift (s) which accounts for additional overtime costs, if any

ic_n = daily indirect costs rate for project (n)

This optimization model is equipped with a multi-objective genetic algorithm (Deb et al 2001) that operates as an engine for the optimization of the post-disaster reconstruction planning process. The main purpose of this multi-objective genetic algorithm (GA) is to identify the set(s) of relevant reconstruction planning variables that provide the optimal/near optimal pairs of reconstruction duration and cost. Each of these variable sets represents a solution to the current problem and identifies: (1) the project prioritization, (2) contractor assignment, and (3) overtime policy. The GA starts by generating a population of (Y) random solutions and pass them to the resource utilization model in order to calculate the recovery schedule and estimate the reconstruction duration for each solution (y), as shown in Figure 4-7. These recovery schedules are used to estimate: (1) the expected disruption to the service provided by the damaged transportation network for each schedule, as described in the previous chapter and using Equation (3-7); and (2) the total reconstruction costs for each solution (y) using Equation (4-12). The GA uses the fitness of each solution in the population, in terms of satisfying the planning objectives of minimizing both the network service disruption and reconstruction costs, to rank and sort these solutions, as shown in Figure 4-7. The genetic operations of selection, crossover and mutation are then applied on the best solutions to generate a new population of solutions that are closer to the optimal solution (see Figure 4-7). This series of operations are iteratively repeated for a

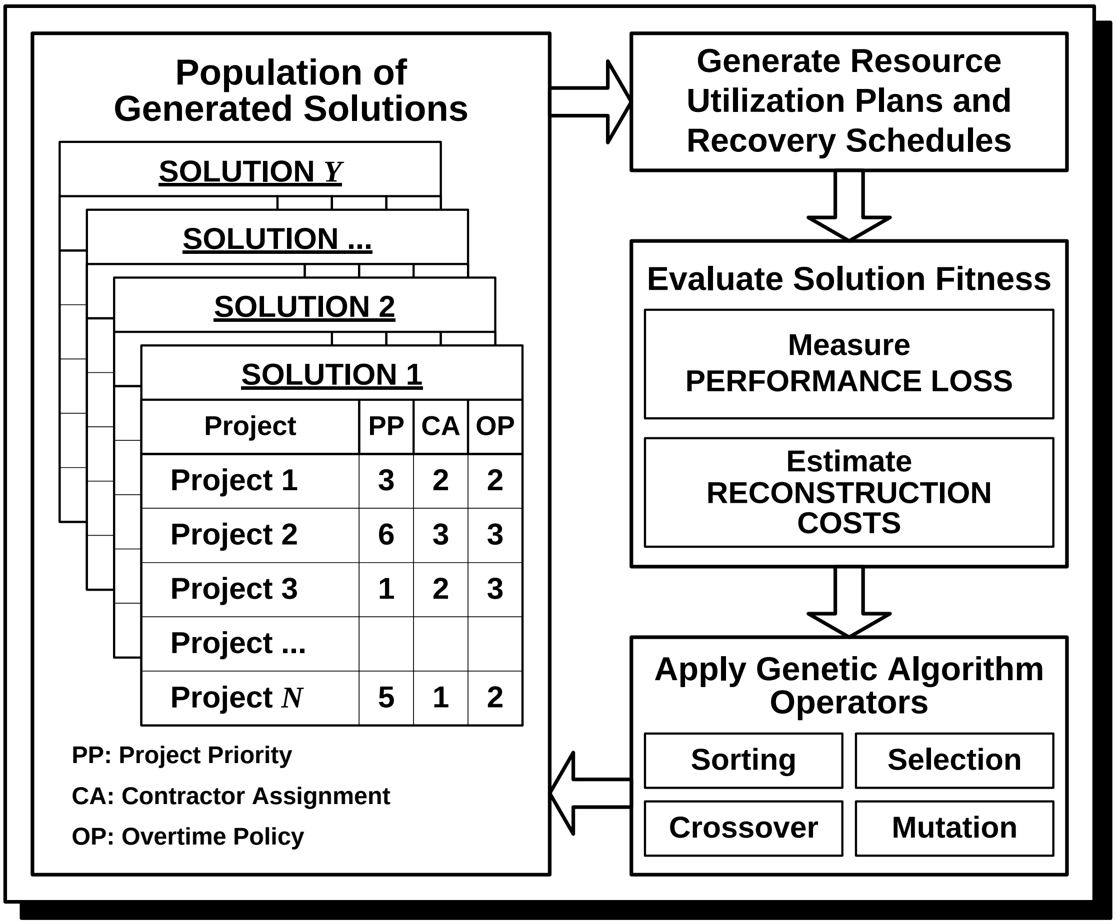


Figure 4-7 Multi-objective optimization model for post-disaster reconstruction efforts

predefined number of generations until convergence to the optimal solution and the optimal/near optimal set of planning variables is extracted from the final population.

4.4 Performance Evaluation

An application example is analyzed to evaluate the performance of the developed models, illustrate their use, and demonstrate their capabilities in allocating the reconstruction resources to competing recovery projects and optimizing the reconstruction efforts of damaged transportation networks after natural disasters. The example seeks to optimize the reconstruction work for a damaged transportation network after an earthquake. In order to evaluate the performance of the developed models in a real-life setting, the transportation data analyzed by the application example are based on the real transportation network data of Shelby County, Tennessee, as shown in Figure 3-4. The damage data is assumed to model the potential damage that may occur in this transportation network following an earthquake. Figure 3-4 shows the topology of the transportation network including the main traffic loading/unloading points and the road segments connecting them; and the locations of seven bridges which are assumed to suffer varying levels of damages ranging from moderate to severe/collapse. In this example, the developed resource utilization and multi-objective optimization models are used to support decision makers and planners in identifying three key reconstruction decisions: (1) project prioritization; (2) contractor assignment; and (3) overtime policy. The two main planning objectives in this problem are: (1) minimizing the network service disruption of the damaged transportation network during the reconstruction period and (2) minimizing the total reconstruction costs. The model requires the user to specify and input the following data: (1) the reconstruction projects data including planned activities, quantities, number and type of crews required, and the closed links and their average daily traffic (ADT), as shown in Table 4-1; (2) the available resource data submitted by interested contractors including the number of crews available for each resource, normal productivity rates, normal labor and equipment cost rates, indirect cost rates for each project, and material costs for each project, as shown in Table 4-2; (3) the overtime policy options including the number of working hours for each option, the number of daily shifts, and the impact of each option on construction productivity and cost, as shown in Table 4-3; (4) the topology data of the damaged transportation network, as shown in Figure 3-4 and Table 3-1; and (5) the

Table 4-1 Project resource requirements

			Project 1		Project 2		Project 3		Project 4		Project 5		Project 6		Project 7	
IDS of closed links			18, 19		28, 29		30, 31		48, 49		52, 53		74, 75		78, 79	
Affected ADT (*veh/day*)			40,605		55,844		91,196		102,630		49,524		57,138		80,931	
Number of activities			12		6		12		6		4		12		5	
Activity	**Resource**	**Unit**	**Qty**	**# Crews**	**Qty**	**# Crews**	**Qty**	**# Crews**	**Qty**	**# Crews**	**Qty**	**# Crews**	**Qty**	**# Crews**	**Qty**	**# Crews**
A	B-8	CY	4,060	1			1,280	1					6,600	1		
B	B-10M	CY	11,150	1			3,520	1					18,150	1		
C	B-19A	LF	700	1			220	1					1,140	1		
D	B-12F	CY	9,640	5			3,050	2					15,700	5		
E	B-43	Each	20	1			6	1					33	1		
F	C-14C	CY	5,770	2			1,820	1					9,400	3		
G	C-14A	CY	1,000	2	1,720	1	320	1	1,300	1			1,620	2		
H	C-14A	CY	440	2	760	1	140	1	580	1			720	2	620	1
I	C-14B	CY	1,180	2	2,040	1	370	1	1,540	1	1,810	1	1,920	2	1,650	1
J	B-26	SY	2,580	1	4,450	1	820	1	3,360	1	3,960	1	4,200	1	3,610	1
K	B-78	LF	200	1	350	1	60	1	260	1	310	1	330	1	280	1
L	C-2A	LF	200	1	350	1	60	1	260	1	310	1	330	1	280	1

Table 4-2 Resources availability and cost rates

	Contractor 1		Contractor 2		Contractor 3	
	Material Costs ($)	**Indirect Costs ($/day)**	**Material Costs ($)**	**Indirect Costs ($/day)**	**Material Costs ($)**	**Indirect Costs ($/day)**
Project 1	1,708,256.00	1,800.00	1,708,256.00	1,800.00	1,708,256.00	1,800.00
Project 2	1,679,200.00	600.00	1,679,200.00	600.00	1,679,200.00	600.00
Project 3	539,809.00	500.00	539,809.00	500.00	539,809.00	500.00
Project 4	1,268,642.00	600.00	1,268,642.00	600.00	1,268,642.00	600.00
Project 5	532,244.00	600.00	532,244.00	600.00	532,244.00	600.00
Project 6	2,781,041.00	2,300.00	2,781,041.00	2,300.00	2,781,041.00	2,300.00
Project 7	659,217.00	600.00	659,217.00	600.00	659,217.00	600.00

Resource	Unit	Contractor 1				Contractor 2				Contractor 3			
		Avail.	**Productivity (/day)**	**Equipment Cost ($/day)**	**Labor Cost ($/day)**	**Avail.**	**Productivity (/day)**	**Equipment Cost ($/day)**	**Labor Cost ($/day)**	**Avail.**	**Productivity (/day)**	**Equipment Cost ($/day)**	**Labor Cost ($/day)**
B-8	CY	1	11,700.00	3,027.46	1,737.55	1	11,700.00	2,578.07	1,131.05	1	11,700.00	1,584.68	2,016.22
B-10M	CY	1	2,220.00	985.92	260.68	1	2,220.00	1,365.91	284.07	1	2,220.00	1,068.08	270.70
B-19A	LF	1	160.00	1,590.13	2,078.59	1	160.00	1,832.10	2,003.68	1	160.00	2,160.50	1,741.52
B-12F	CY	6	70.00	488.05	518.93	5	70.00	533.54	587.21	4	70.00	405.33	386.92
B-43	Each	1	5.50	2,505.80	1,334.66	1	5.50	1,664.30	1,142.28	1	5.50	1,496.00	949.90
C-14C	CY	3	40.00	28.88	3,596.28	4	40.00	35.72	3,909.00	3	40.00	34.58	2,470.49
C-14A	CY	6	20.00	760.14	6,505.04	5	20.00	828.12	4,981.34	5	20.00	469.68	4,981.34
C-14B	CY	3	20.00	741.60	5,658.12	3	20.00	432.60	5,658.12	2	20.00	747.78	4,441.32
B-26	SY	1	1,760.00	2,251.39	3,014.84	1	1,760.00	2,251.39	1,609.43	1	1,760.00	1,940.22	3,060.18
B-78	LF	1	3,660.00	454.93	1,050.17	1	3,660.00	445.55	1,240.09	1	3,660.00	492.45	1,463.53
C-2A	LF	1	110.00	0.00	1,463.62	1	110.00	0.00	1,612.69	1	110.00	0.00	1,626.24

Table 4-3 Overtime policy options

Option	Working Hours	Shifts/Day	Productivity Adjustment Factor	Cost Adjustment Factor
1	8 hours/5days	1	100.00%	100.00%
2	12 hours/5days	1	76.25%	133.30%
3	24 hours/5days	2	68.75%	153.30%
4	8 hours/7days	1	88.75%	128.60%
5	12 hours/7days	1	68.75%	152.40%
6	24 hours/7days	2	62.00%	175.25%

traffic demand on this network which can be represented by the OD trip data (see Table 3-2). The cost data in this example are estimated using the cost rates in the Means (2008) and the scope and type of work in each reconstruction project.

The model was used to analyze the above input data and was able to generate a set of optimal reconstruction plans, where each provides an optimal and non-dominated tradeoff between minimizing the network service disruption and the reconstruction costs (see Figure 4-8). The results of this analysis confirm that more public expenditures are often required to control and minimize the additional travel time during the duration of post-disaster reconstruction efforts, as shown in Figure 4-8. This tradeoff exists because minimizing the network service disruption can be accomplished by accelerating the reconstruction work in bridges that are used by higher average daily traffic. This acceleration is often associated with additional reconstruction costs due to overtime premiums and reduced productivity during overtime hours and/or additional shifts, as shown in Table 4-3. Figure 4-9 shows the significant impact of this acceleration on recovering the pre-disaster levels of service of the damaged transportation networks. For example, working for multiple shifts per day and changing the priorities of recovery projects and their contractor assignments accelerated the reopening of important roads

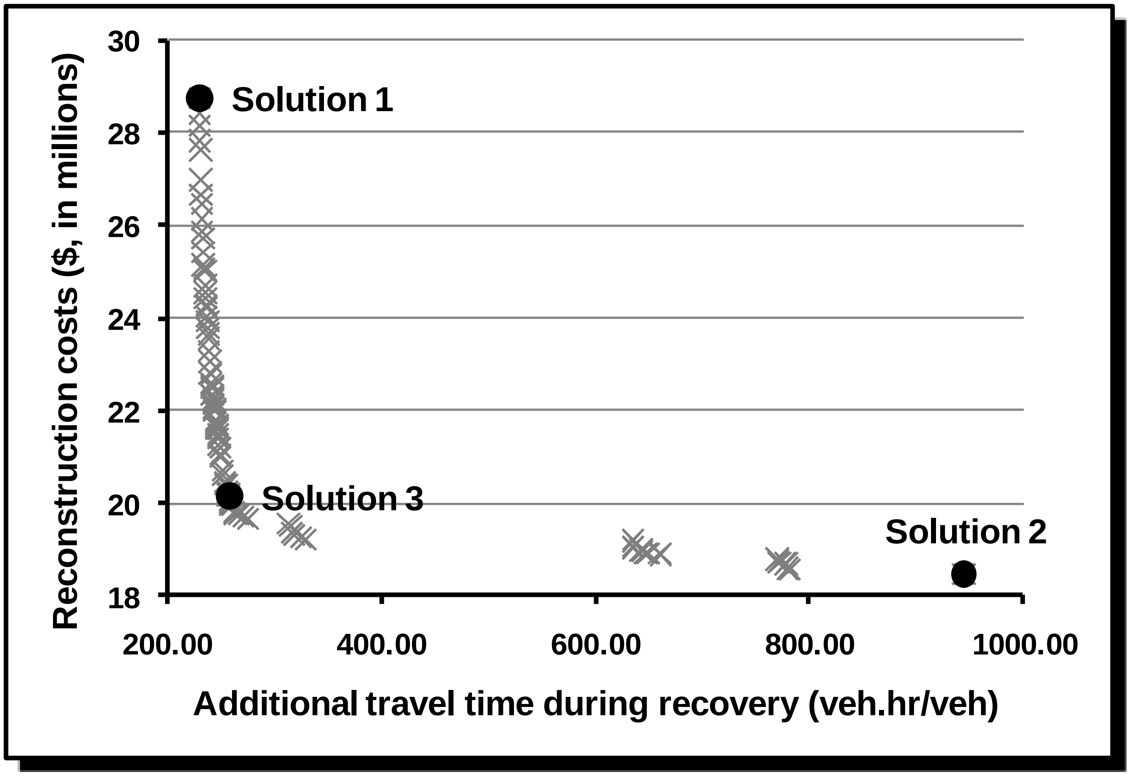


Figure 4-8 Tradeoff between service disruption and reconstruction costs

to the public, which in turn reduced network performance loss by 75.76% from 944.512 veh. hr/veh in Solution 2 to only 228.993 veh. hr/veh in Solution 1 (see Figure 4-9).

Figure 4-10 shows three solutions from the wide range of optimal solutions generated by the model and their associated reconstruction schedules. Solution 1 provided the minimum network service disruption by minimizing the total additional travel time spent by travelers on the damaged transportation network compared to pre-disaster levels. This was possible by (1) minimizing the duration of all the reconstruction projects by working two 12 h shifts per day, as shown in Figure 4-10 and (2) giving higher priority to projects that accelerate the completion of bridges that are used by higher ADT. This solution however has the highest reconstruction costs due to the overtime premiums and the adverse impact of overtime on construction productivity. On the other end of

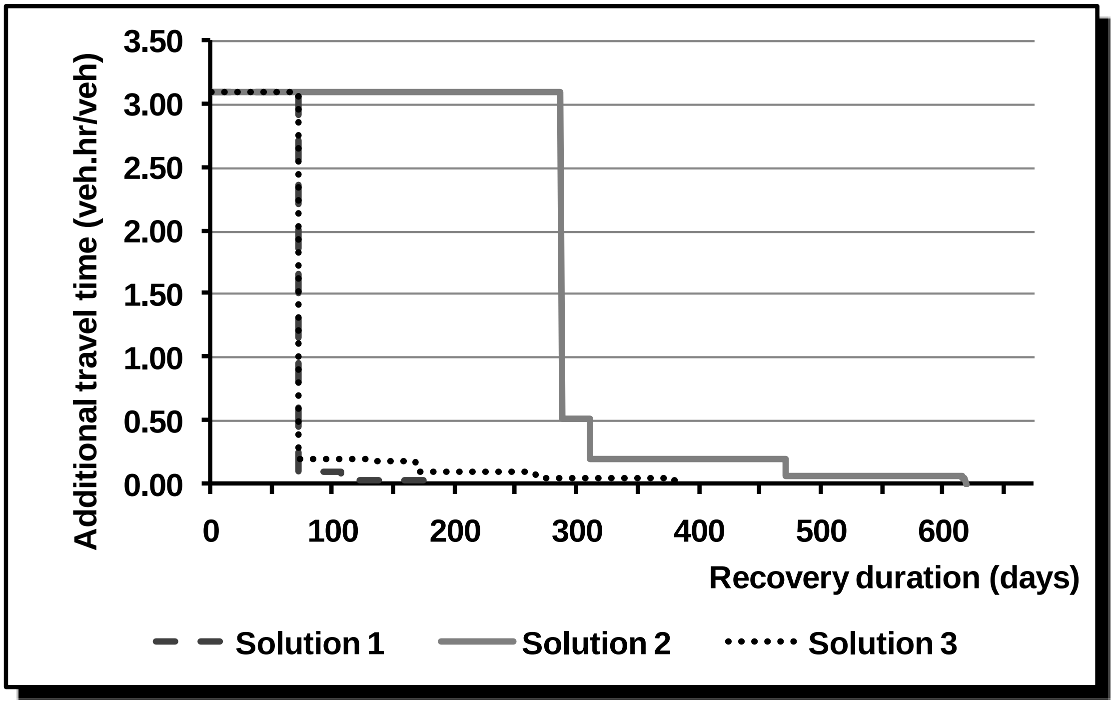


Figure 4-9 Recovery of network performance

the optimal front, Solution 2 provided the lowest possible reconstruction costs by (1) avoiding the use of overtime hours or multiple shifts and (2) awarding all the recovery projects to contractor 3, which has significantly lower costs than the other competitors. This solution however provides the maximum network service disruption mainly due to longer reconstruction durations, as shown in Figure 4-10.

In addition to the two extreme optimal solutions of 1 and 2, the model generated a set of optimal reconstruction plans that provide a wide range of tradeoffs between the two analyzed optimization objectives, as shown in Figure 4-8. Planners can analyze these optimal solutions and select a reconstruction plan that strikes an optimal balance between reducing the network service disruption and the reconstruction costs such as Solution 3. This solution provides a reduction of 72.81% in the network service disruption compared to Solution 2 with an increase of only 9.20% in the reconstruction

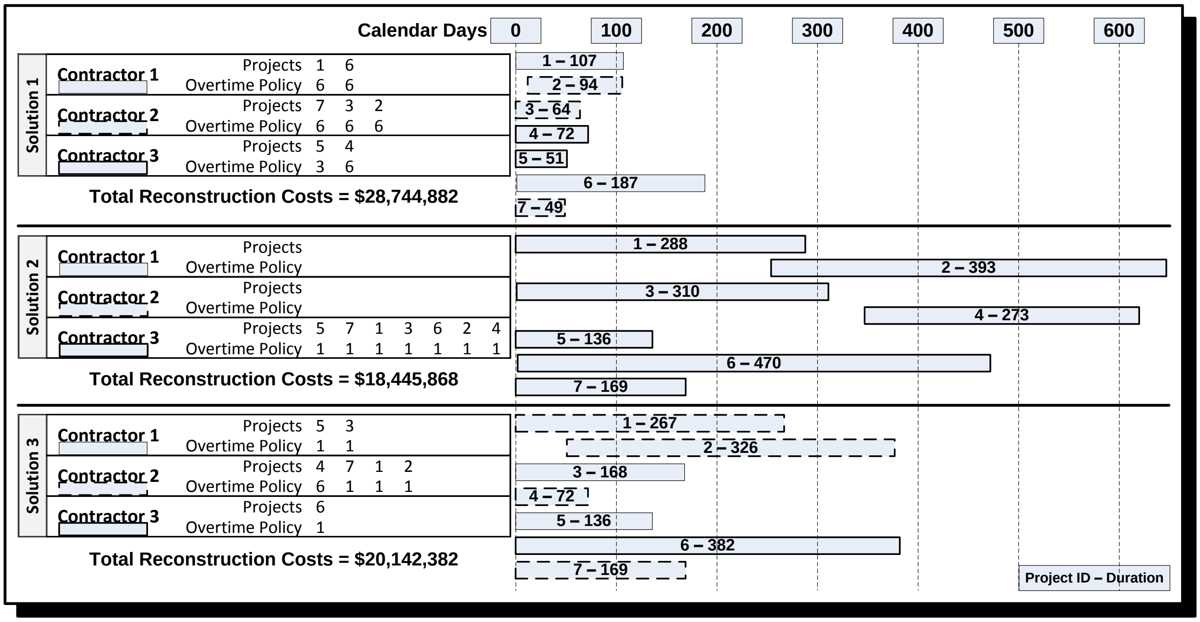


Figure 4-10 Post-disaster reconstruction schedule

costs. Similarly, Solution 3 provides a savings of 29.93% in the reconstruction costs with an increase of 12.15% in network service disruption compared to Solution 1.

The analysis of this application example emphasizes the unique and practical capabilities of the present models in facilitating the procedure of selecting and implementing the reconstruction plan(s) that best serve the societal requirements in the aftermath of natural disasters. It illustrates how these models can be effectively used to search for and identify a wide range of optimal plans for reconstructing damaged transportation networks in the aftermath of natural disasters. Each of these plans provides a unique and optimal tradeoff between the network service disruption and the reconstruction costs, as shown in Figure 4-10. Decision makers can evaluate these generated optimal tradeoffs and select an optimal reconstruction plan that satisfies the specific requirements of the reconstruction efforts being planned.

4.5 Summary and Conclusions

Resource utilization and multi-objective optimization models were developed to enable an efficient and effective reconstruction process for damaged transportation networks in the aftermath of natural disasters. The newly developed resource utilization model is capable of assigning reconstruction resources to the competing reconstruction projects according to the project priorities, contractor assignment, and overtime policy. This model is also capable of estimating both the reconstruction duration and cost of various optimal reconstruction plans. In addition, the GA-based multi-objective optimization model is capable of optimizing the post-disaster reconstruction efforts in such a way that simultaneously minimizes network service disruption and reconstruction cost. An application example is analyzed to evaluate the performance of the developed models, illustrate their use and demonstrate their capabilities in generating optimal tradeoffs between network service disruption and reconstruction cost. These capabilities are demonstrated in the ability of the developed models to consider a number of practical post-disaster reconstruction planning requirements, including: (1) considering the impact of the limited availability of resources on scheduling the reconstruction efforts for damaged transportation networks; (2) evaluating the service disruption in the damaged transportation network during the reconstruction efforts; and (3) optimizing the utilization of reconstruction resources to minimize the network service disruption in transportation networks while keeping the reconstruction costs to a minimum. These new and unique capabilities of the developed models should prove useful to decision makers and planners in emergency management agencies and should contribute to enhancing planning of post-disaster reconstruction efforts for damaged transportation networks.

CHAPTER 5
OPTIMIZING HIGHWAY REHABILITATION PROJECTS

5.1 Introduction

This chapter focuses on planning and optimizing highway rehabilitation efforts of aging transportation networks in order to simultaneously (a) maximize the net rehabilitation benefits which can be represented by the difference between the savings in road user costs and the construction and maintenance costs; and (b) minimize the impact of highway construction on network service disruption. To this end, this chapter presents the development and implementation of a new model for planning and optimizing highway rehabilitation projects that consists of four main modules that focus on: (1) estimating the cost and schedule of rehabilitation programs; (2) measuring the impact of rehabilitation efforts on network performance and road user savings; (3) analyzing the expected benefits and costs of rehabilitation; and (4) optimizing the rehabilitation efforts to identify optimal programs that simultaneously maximize the net rehabilitation benefits and minimize network service disruption (see Figure 5-1). The following sections describe these four modules in detail and present an evaluation of their performance.

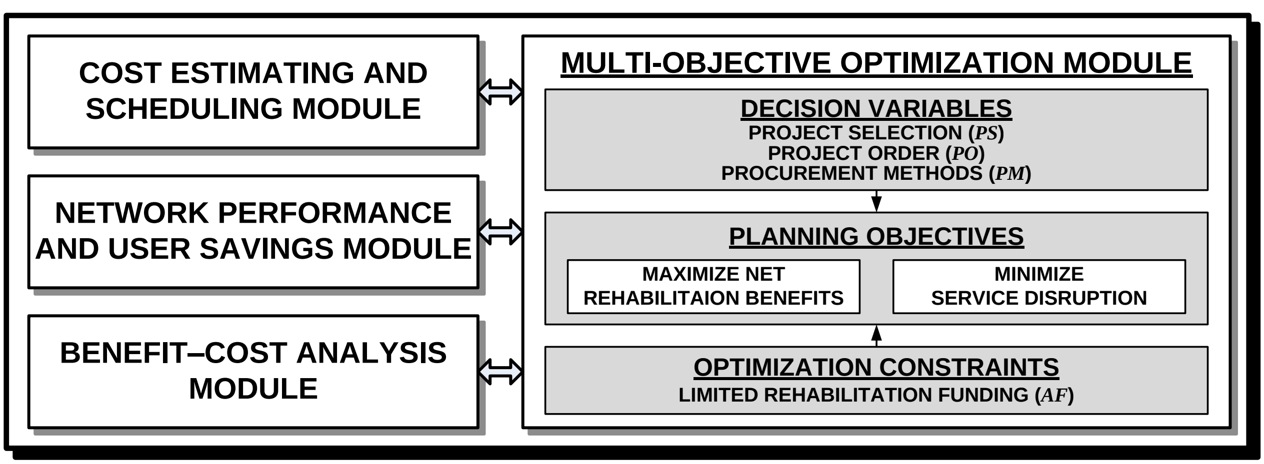


Figure 5-1 Highway rehabilitation planning and optimization model

5.2 Cost Estimating and Scheduling Module

The objectives of this module are to estimate the construction cost and calculate the schedule of a selected highway rehabilitation program. The cost estimating and scheduling module is designed to consider the impact of three main decision variables: (1) the selected rehabilitation projects; (2) the order of these projects; and (3) the procurement method adopted for each project, as shown in Figure 5-2. The project selection (PS) variable is a binary one that can be true for selected projects or false for unselected ones. Similarly, the project order (PO) variable depicts the order of execution of the competing rehabilitation projects, where projects with lower order values should be scheduled to start before projects with higher order values. Finally, the procurement method (PM) variable identifies the type of contract to be used in

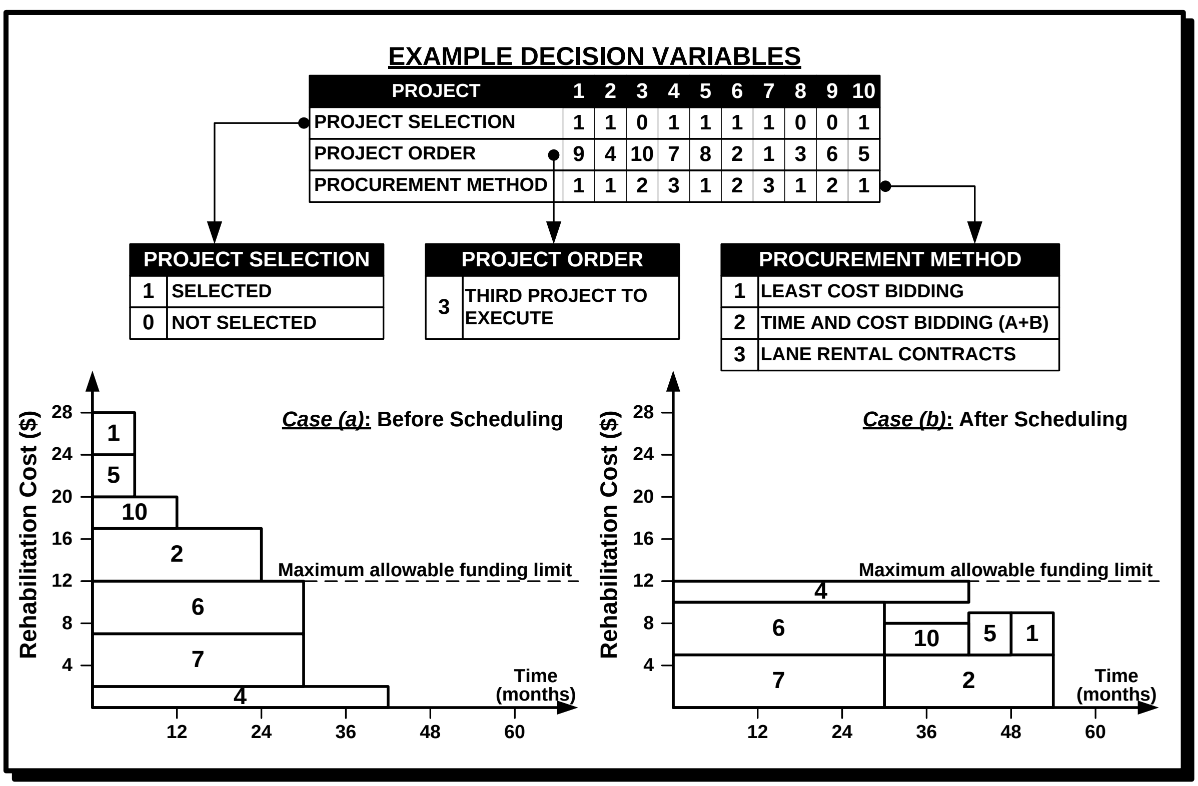


Figure 5-2 Allocation of available rehabilitation funds

each rehabilitation project. In this model, three procurement methods are considered including: (1) least cost (traditional) bidding; (2) bidding for cost and time (A+B); and (3) lane rental contracts, as shown in Figure 5-2. The procurement method selected for each project has a significant impact on the project cost, duration and service disruption. For example, utilizing A+B contracts is expected to deliver projects faster than traditional contracts but at relatively higher costs. Similarly, lane rental contracts typically cause less service disruption compared to other procurement methods. These three decision variables are discussed in more detail later in the multi-objective optimization module.

The main challenge in this module is to develop a schedule for the rehabilitation program that satisfies the budget constraints (overall available funding and allowable monthly expenditures). Figure 5-2 shows an example list of ten rehabilitation projects that are identified to improve the surface conditions of a transportation network. The example shows the selection, order and procurement variables for each of the ten suggested rehabilitation projects. Due to budget constraints, only seven of these ten projects can be rehabilitated (see Figure 5-2). If the decision maker selects to proceed with all seven selected projects concurrently, the total monthly investment required would exceed the level of available funding represented by the dashed line (case (a) in Figure 5-2). Therefore, an algorithm is developed to schedule these selected rehabilitation projects according to their order of execution in such a way that maintains the total monthly investment requirements at or below the level of available funding (case (b) in Figure 5-2). This scheduling algorithm is designed to identify: (1) the schedule of the rehabilitation program; (2) the total construction cost of this program;

and (3) the main construction milestones of the rehabilitation program that have a direct impact on the functional behavior of the transportation network, as shown in Figure 5-3. The Figure shows a flowchart for the developed scheduling algorithm that consists of the following eight steps:

1. Identify the projects selected to be funded according to the project selection variables (PS_p) of the rehabilitation program. For example, only projects 1, 2, 4, 5, 6, 7 and 10 of the example rehabilitation program shown in Figure 5-2 will be included in steps 2 through 7 which are repeated for each of these projects.
2. Select the next unscheduled project with the lowest order of execution (PO_n) from the rehabilitation projects identified in step 1. In the example rehabilitation program shown in Figure 5-2, the projects identified in step 1 will be scheduled in the following order: 7, 6, 2, 10, 4, 5 and 1.
3. Identify the cost and duration of the current project (n) based on the project's procurement method (PM_n). In the illustrated program, ($PM_7 = 3$); therefore, the rehabilitation cost and duration of lane rental contracts is used for project 7.
4. Check whether project (n) can be scheduled during planning interval ($i = 1 \text{ to } I$) without exceeding the maximum allowable funds for that interval. If the project can be scheduled while complying with the limited availability of funds, proceed to step 6; otherwise, continue to step 5. For example, scheduling project 2 cannot be scheduled in the first interval ($i = 1$) after scheduling projects 7 and 6 since it will exceed the maximum allowable funding limit. On the other hand, project 10 can be scheduled in the second interval ($i = 2$) following the scheduling of projects 7, 6 and 2 (see Figure 5 4).

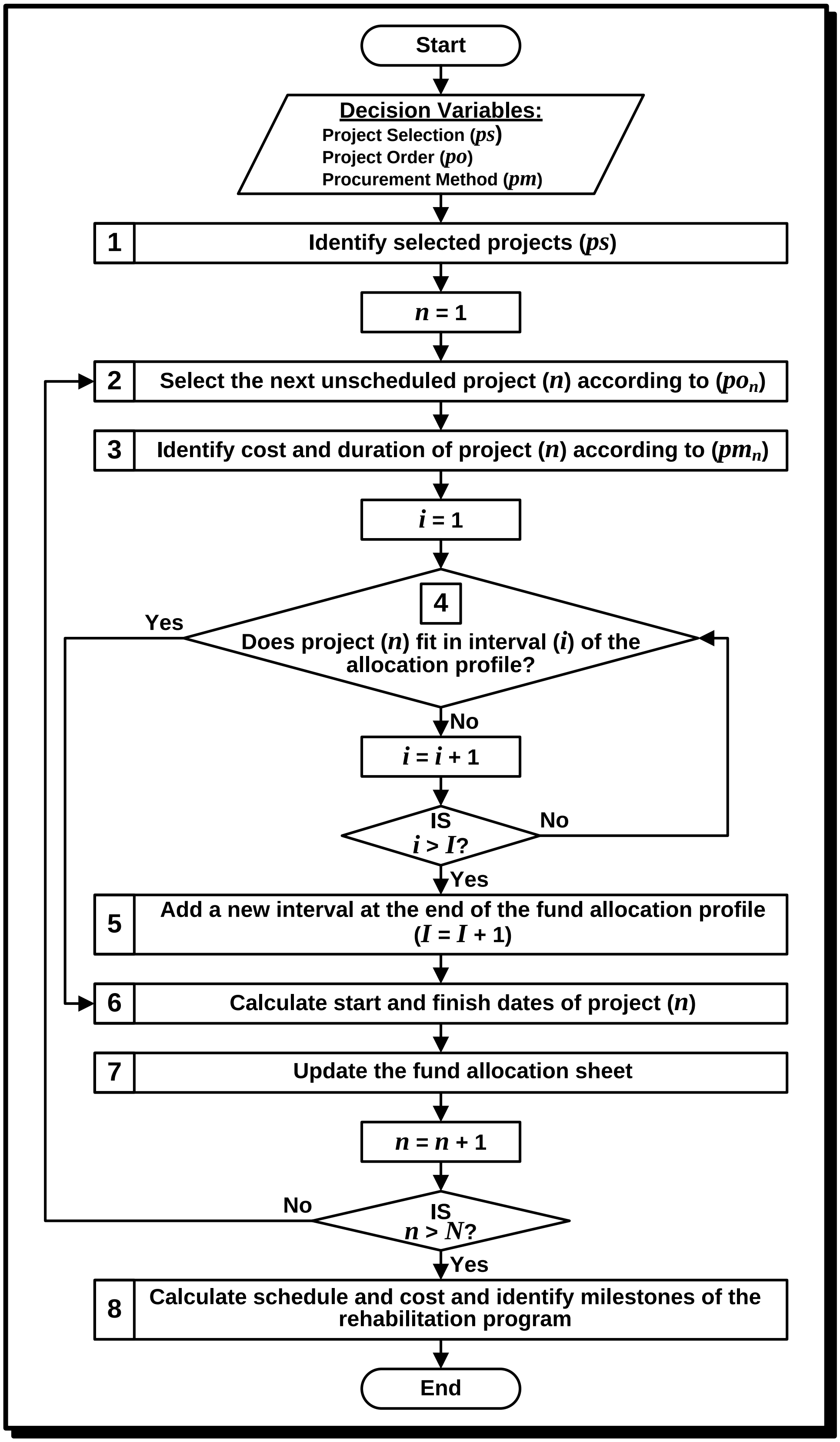


Figure 5-3 Rehabilitation program scheduling algorithm

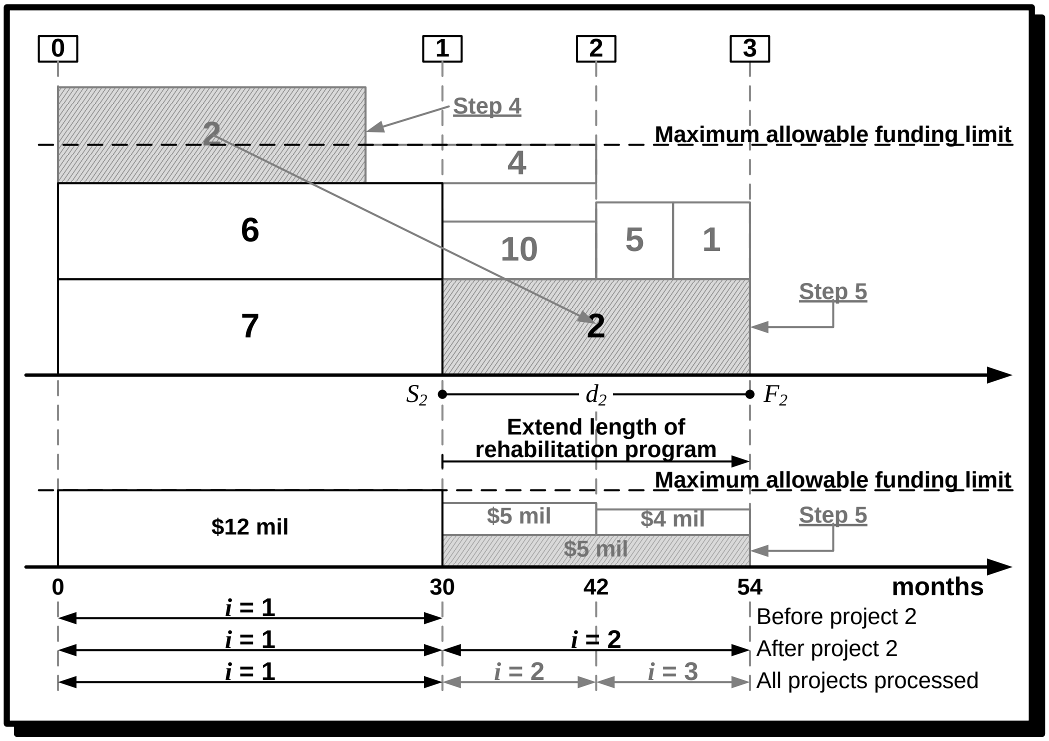


Figure 5-4 Allocation procedure for rehabilitation funds

5. Add a new interval at the end of the fund allocation profile ($I = I + 1$). The length and height of this interval are equal to the duration and monthly cost identified in step 3 for project (n). For example, the length and height of the interval added to hold project 2 ($i = 2$) are 24 months and $5 million/month as identified in step 3 (see Figure 5-4).

6. Calculate start and finish dates of project (n) based on the allocation process completed in steps 4 and 5 and using the following equations:

$$S_n = \text{Start date of the interval holding project } (n) \quad (5\text{-}1)$$

$$F_n = S_n + d_n \quad (5\text{-}2)$$

where,

F_n = Finish date of project (n)

S_n = Start date of project (n)

d_n = Duration of project (n)

7. Update the fund allocation profile to reflect the processes completed in the previous steps by reorganizing the intervals and updating their start and finish dates. This includes splitting intervals that have varying levels of committed funding such as splitting interval ($i = 2$) into two intervals ($i = 2$ and $i = 3$) with the processing of project 10 (see Figure 5-4).

8. Calculate the overall schedule and final cost of the rehabilitation program and identify the important milestones ($m = 1$ to M) at which there is a significant change to the status of the transportation network (see Figure 5-5).

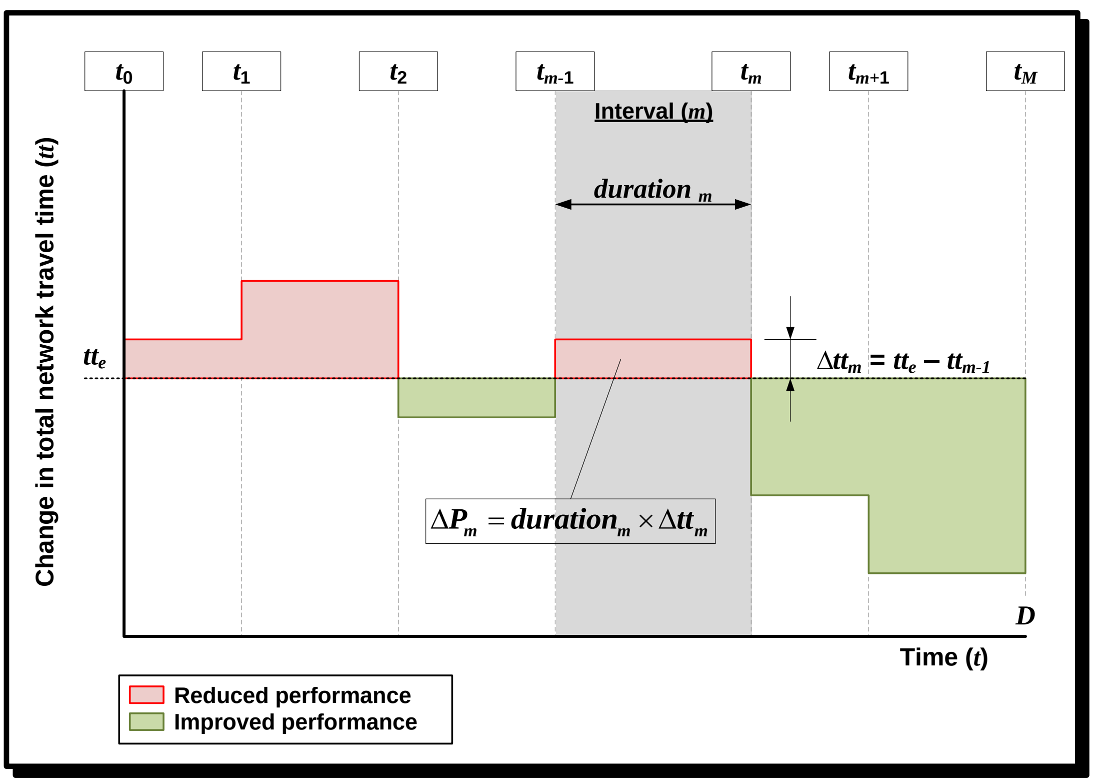


Figure 5-5 Evaluation of network performance during rehabilitation

5.3 Network Performance and Road User Savings Module

The main objectives of this module are to: (1) evaluate the impact of rehabilitation programs on the functional performance of transportation networks and estimate the expected network service disruption during rehabilitation efforts; and (2) estimate the expected savings in road user costs as a result of implementing these rehabilitation programs.

5.3.1 Impact of Rehabilitation on Network Performance

As described earlier in Chapter 3, the existing total network travel time before the start of the rehabilitation program (tt_e) is used as a benchmark to measure the impact of construction activities on the functional performance of aging transportation networks, as shown in Figure 5-5. To this end, an increase in the total network travel time indicates a reduction in performance (i.e. service disruption); while a decrease in the total network travel time indicates an improved performance (see Figure 5-5). Inherently, while travelers might experience substantial disruption to the level of service provided by the aging transportation network at the start of the rehabilitation program, this disruption is expected to significantly improve towards the end of the program (see Figure 5-5). The service disruption model presented in chapter 3 is used to measure the expected network service disruption. To this end, it is expected that significant changes in the status of the transportation network will occur at the rehabilitation milestones ($m = 1 \text{ to } M$) that were identified in the previous section and shown in Figure 5-5. The total network travel time at the end of each of these completion milestones (tt_m) is measured and compared to the pre-rehabilitation total network travel time (tt_e) in order to estimate the total change in performance (ΔP) during the implementation of the rehabilitation program. Figure 5-6 shows a six-step procedure that is developed to estimate (ΔP), as follows:

1. Estimate the existing (pre-rehabilitation) total network travel time (tt_e), represented

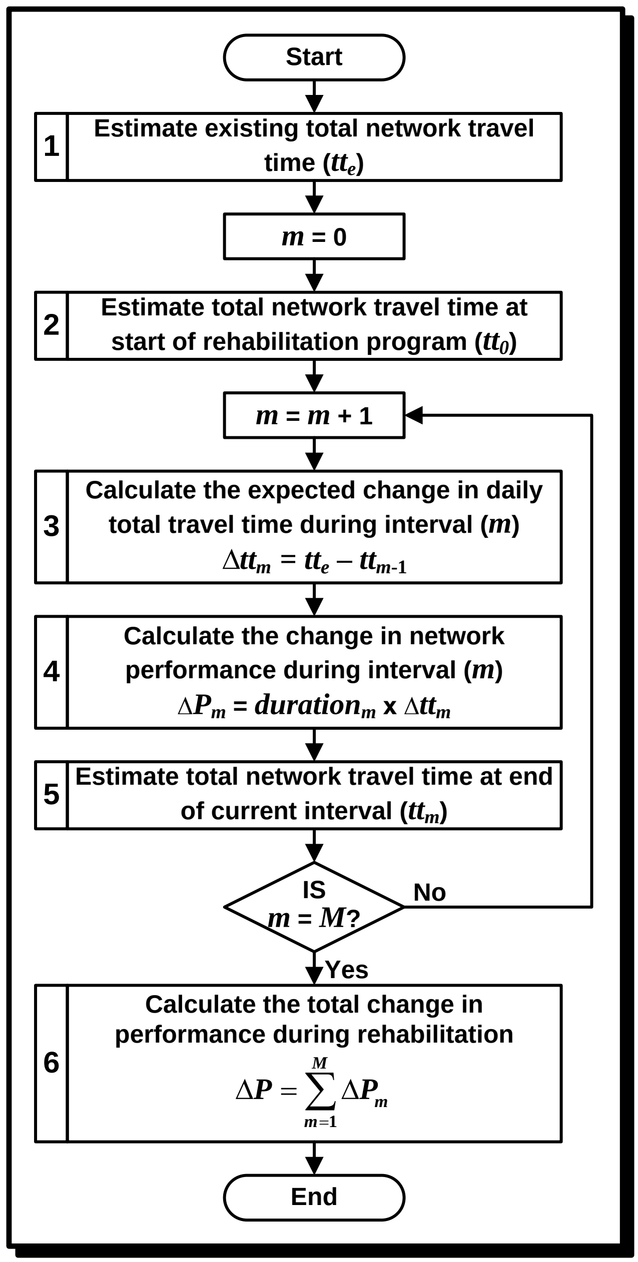


Figure 5-6 Evaluation process of the change in network performance during rehabilitation

by the horizontal dotted line in Figure 5-5, using the network service disruption model presented in Chapter 3.

2. Estimate the total network travel time (tt_0) immediately after the start of the rehabilitation program (at time t_0, as shown in Figure 5-5), which represents the expected service disruption caused by the implementation of the rehabilitation project(s) scheduled to start first. Steps 3 through 5 are repeated at the end of each interval ($m = 1$ to M) separating the rehabilitation milestones (Figure 5-5).

3. Calculate the expected change in the daily total travel time (Δtt_m) during interval (m), as follows (see Figure 5-5):

$$\Delta tt_m = tt_e - tt_{m-1} \qquad (5\text{-}3)$$

where,

tt_{m-1} = Total network travel time at the end of interval ($m-1$)

4. Calculate the change in the performance of the transportation network (ΔP_m) during interval (m) using the expected daily change calculated in step 3 (see Figure 5-5):

$$\Delta P_m = duration_m \times \Delta tt_m \qquad (5\text{-}4)$$

where,

$duration_m$ = Duration of interval (m)

5. Estimate the total network travel time at the end of the current interval (tt_m) based on the rehabilitation activities to be completed by milestone (m). The estimation of (tt_m) is needed to estimate the expected change in daily travel time (step 3) during interval ($m+1$), if applicable.

6. Calculate the total change in the functional performance of the transportation network (ΔP), due to the implementation of the rehabilitation program, by summing the change in performance across all the intervals.

$$\Delta P = \sum_{m=1}^{M} \Delta P_m \qquad (5\text{-}5)$$

5.3.2 Savings in Road User Costs

Estimating the expected savings in road user costs resulting from the implementation of rehabilitation efforts is essential in evaluating and comparing candidate rehabilitation programs. In this study, two types of daily road user costs are considered: direct and indirect costs. The direct cost accounts for the vehicle operating costs per mile (VOC), which takes into consideration both the distance traveled and the condition of the road (Archondo-Callao 1993; Dewan and Smith 2002). The indirect travel cost measures the cost of time incurred by truckers to reach their destination (Herbsman et al. 1995). Therefore, the traveling distance, time and road conditions between each origin-destination (OD) pair on the network after the conclusion of the rehabilitation program need to be analyzed and compared to pre-rehabilitation conditions in order to identify the net change (i.e. savings) in daily road user cost due to the rehabilitation efforts. This module also takes into consideration any deterioration or upgrades in road conditions throughout the lifecycle of the network. The flowchart in Figure 5-7 shows a five-step procedure for calculating the post-rehabilitation savings in road user cost, as follows:

1. Estimate the network traffic assignment at equilibrium before the implementation of the rehabilitation program using the Frank-Wolfe algorithm for deterministic user equilibrium assignment (Bell and Iida 1997).
2. Estimate the network traffic assignment at equilibrium after the completion of the

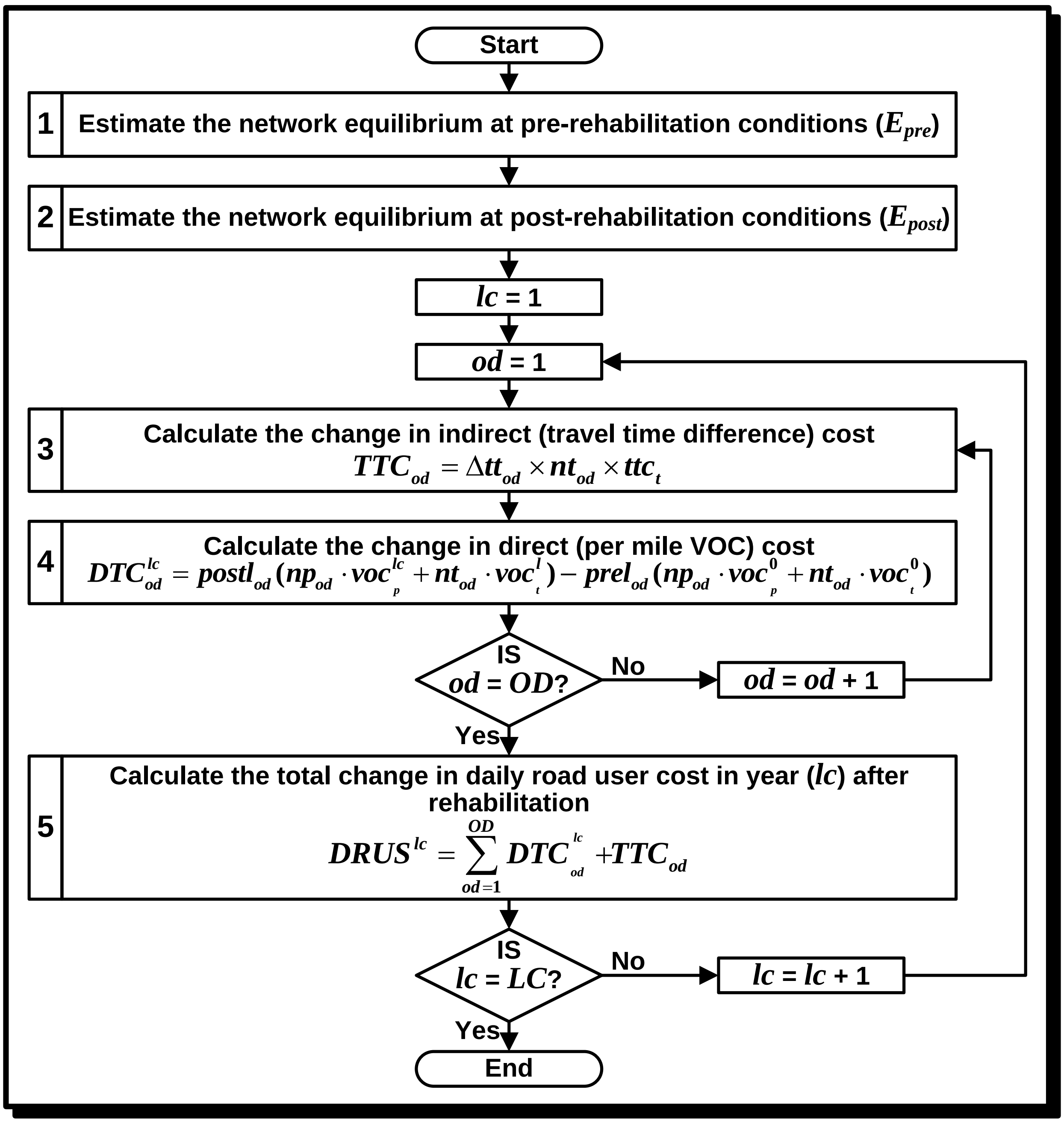


Figure 5-7 Post-rehabilitation road user savings calculation

rehabilitation program. Steps 3, 4 and 5 of this procedure are then repeated in two nested loops to estimate the daily change in road user costs for all drivers traveling between each OD pair ($od = 1 \text{ to } OD$) for each year (lc) of the network's lifecycle ($lc = 1 \text{ to } LC$) using the flow data of the traffic assignment estimated in steps 1 and 2.

3. Calculate the post-rehabilitation change in travel time (indirect) cost for the time saved/lost by truck drivers traveling between the current OD pair loading points compared to the pre-rehabilitation travel times (Herbsman et al. 1995), as follows:

$$TTC_{od} = \Delta tt_{od} \times nt_{od} \times ttc_t \tag{5-6}$$

where,

TTC_{od} = Indirect traveling cost on route between loading points (o) and (d)

Δtt_{od} = Post-rehabilitation change in time for traveling on the route between loading points (o) and (d)

ttc_t = Indirect traveling cost (cost of time) rate for truck drivers

4. Calculate the post-rehabilitation change in direct travel cost that represents the road user savings or losses in vehicle operating costs (VOC) per mile for traveling between the current OD pair loading points in year (lc) compared to pre-rehabilitation travelling distances (Archondo-Callao 1993; Dewan and Smith 2002), as follows:

$$\begin{aligned} DTC_{od}^{lc} = {} & prel_{od}\left(np_{od} \cdot voc_p^{\mathbf{0}} + nt_{od} \cdot voc_t^{\mathbf{0}}\right) \\ & - postl_{od}\left(np_{od} \cdot voc_p^{lc} + nt_{od} \cdot voc_t^{lc}\right) \end{aligned} \tag{5-7}$$

$$voc^{lc} = e^{(a+b(100-PCI_{lc}))} \tag{5-8}$$

where,

DTC_{od}^{lc} = Direct traveling cost on route between (o) and (d) in year (lc)

$postl_{od}$ = Post-rehabilitation traveling distance between loading points (o) and (d)

$prel_{od}$ = Pre-rehabilitation traveling distance between loading points (o) and (d)

np_{od} = Number of passenger vehicles traveling between points (o) and (d)

nt_{od} = Number of trucks traveling between loading points (o) and (d)

voc_{p}^{lc} = Passenger vehicle operating cost in year (lc)

voc_{t}^{lc} = Truck vehicle operating cost in year (lc)

voc_{p}^{0} = Pre-rehabilitation vehicle operating cost for passenger cars

voc_{t}^{0} = Pre-rehabilitation vehicle operating cost for trucks

PCI_{lc} = Road pavement condition index in year (lc)

a, b = Constants that are function of vehicle type

5. Calculate the daily change (i.e. savings or losses) in road user cost in year (lc) after rehabilitation by summing the direct and indirect costs estimated in steps 3 and 4 for all OD pairs, as follows:

$$DRUS^{lc} = \sum_{od=1}^{OD} DTC_{od}^{lc} + TTC_{od} \qquad (5\text{-}9)$$

where,

$DRUS^{lc}$ = Daily change (savings) in road user cost in year (lc) after rehabilitation

5.4 Benefit-Cost Analysis Module

The main objective of this module is to estimate all the benefits expected from the implementation of a rehabilitation program and compare them with the costs associated with this program. Since both benefits and costs of rehabilitation can occur at different times during the lifespan of the transportation network, it is important to perform a lifecycle assessment for the investigated aging transportation network in order to analyze the net benefits of rehabilitation accurately, (see Figure 5-8). The costs and benefits analyzed in this research study include: cost of initial rehabilitation construction works, cost of the required periodic maintenance activities, and savings in road user costs, as shown in Figure 5-8. The following subsections briefly describe each of these costs and benefits.

Rehabilitation Cost (RC **)** – is the initial cost of the rehabilitation program as described earlier in this chapter. It includes all direct and indirect costs of the planned rehabilitation projects. Depending on the length of the rehabilitation program and the decision maker's preference, this rehabilitation cost can either be included as a single cost incurred at time (0) of the network lifecycle or divided into a number of costs for which the decision maker identifies the frequency and size. For example, (RC) is included as a single initial payment in the cash flow in Figure 5-8.

Maintenance Cost (MT **)** – is a periodic cost required to cover maintenance and preservation activities aimed at extending the life expectancy of the transportation network. DOTs typically apply these maintenance cycles in order to restore road conditions and delay deterioration, as shown in Figure 5-8. Decision makers identify the number and size of maintenance cycles needed to keep the road condition index within acceptable cutoff values before new network rehabilitation efforts are deemed essential (Peshkin et al. 2004). For example, the cash flow in Figure 5-8 assumes that four maintenance cycles are planned every five years to preserve the transportation network being analyzed.

Road User Savings (RUS) – is the expected saving in public cost of travel on the investigated transportation network as a result of implementing the rehabilitation program. There are a number of sources for these cost savings for the traveling public, including: (1) spending less commuting time on the transportation network as a direct result of easing traffic delays and congestions; (2) traveling shorter distances compared to pre-rehabilitation because of the availability of new travel alternatives; and (3) incurring less vehicle repair and operating costs because of traveling on roads with better quality. In this study, these cost savings are assumed to be continuous and tend

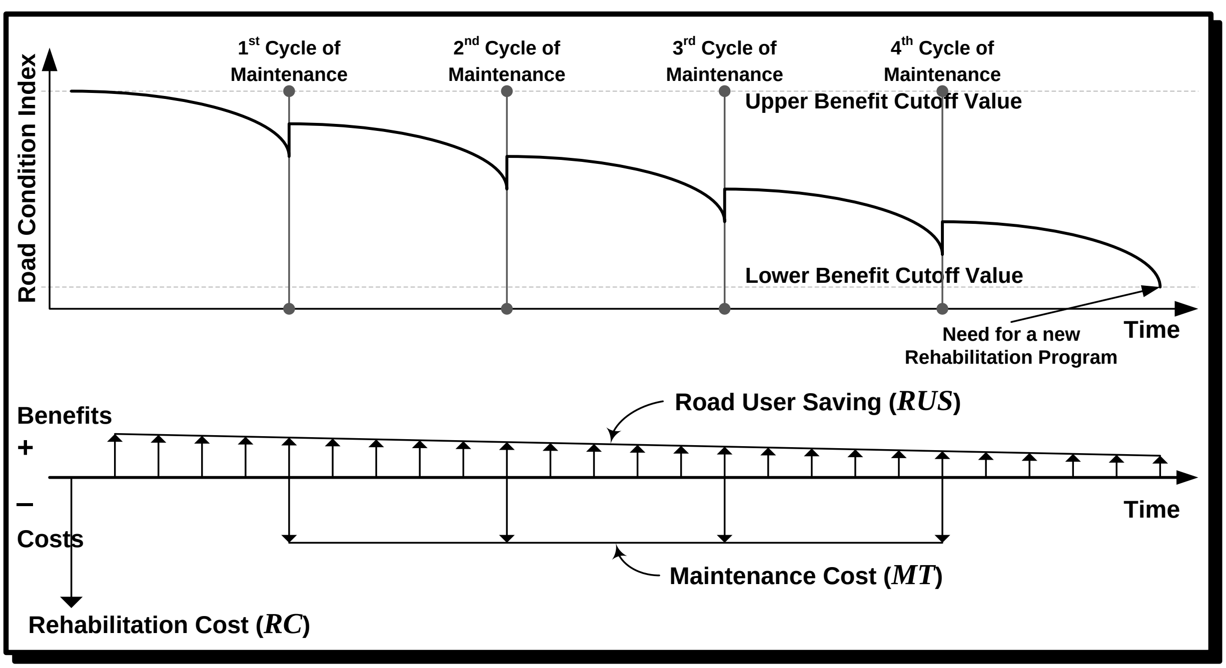


Figure 5-8 Rehabilitation benefit-cost analysis (lifecycle assessment)

to decrease over the lifespan of the transportation network as road conditions deteriorate and new rehabilitation efforts are needed, as shown in Figure 5-8. The monthly road user savings (RUS^{lc}) in any year after rehabilitation in the benefit-cost analysis is estimated by multiplying the daily savings in road user costs ($DRUS^{lc}$) estimated in Equation (5-9) for this year (lc) by 30 days.

The rehabilitation net benefits (NB) are estimated to be the net present value of the above benefits and costs at the discount rate selected by the decision maker:

$$
\begin{aligned}
NB = \sum_{lc=1}^{LC} RUS^{lc}(P \mid A, ir, 12)(P \mid F, ir, lc) \\
- RC - MT \times \sum_{c=1}^{C} (P \mid F, ir, c \times cl \times 12)
\end{aligned}
\qquad (5\text{-}10)
$$

where,

NB = Net benefit of the rehabilitation program

ir = Discount rate used for the rehabilitation benefit-cost analysis

c = Number of required maintenance cycles

cl = Frequency of highway maintenance cycles

5.5 Multi-Objective Optimization Module

The main objective of this module is to optimize rehabilitation efforts of aging transportation networks in order to satisfy the societal needs of maximizing net rehabilitation benefits while minimizing network service disruption. In order to achieve this objective, the model is designed to identify the three main decision variables of: (1)

selecting which highway rehabilitation projects should be funded; (2) prioritizing the selected projects; and (3) identifying the procurement method to be used for each rehabilitation project. Each of these important decision variables has a significant and direct impact on: (1) the rehabilitation planning objectives of maximizing net benefits and minimizing network service disruption; and (2) the observation of funding constraints on highway rehabilitation efforts, as shown in Figure 5-1. Accordingly, this model is designed to generate optimal rehabilitation program(s) each providing a unique combination of project selection, prioritization and procurement method that simultaneously: (1) maximizes net rehabilitation benefits; and (2) minimizes the expected service disruption of aging transportation networks during rehabilitation efforts. To this end, the following subsections provide a brief description of the impact of the aforementioned decision variables on the optimization planning objectives and constraints, and the optimization engine used in this research study to generate the optimal rehabilitation program(s).

5.5.1 Project Selection (ps_n)

Highway rehabilitation projects have dissimilar characteristics and could therefore have a significantly different impact on society. For example, choosing to upgrade a road that serves a high average daily traffic (ADT) can reduce the road user costs for travelers using this road upon the project completion; however, this project is expected to cause significant travel delays during rehabilitation efforts. Similarly, while undertaking huge and ambitious highway rehabilitation projects can substantially improve the cost, quality and safety of travel on aging transportation networks, these projects usually require enormous amounts of public expenditures. Decision makers need to carefully analyze and optimize the impact of these project selection decisions.

5.5.2 Project Prioritization (po_n)

The time at which each highway rehabilitation project is executed and the number and characteristics of projects that are constructed concurrently have a significant impact on the planning objectives and constraints considered in this research study. For example, the start time and duration of a rehabilitation project is important to identify when the funding required need to be available for this project and evaluate its impact on travel cost and quality. Similarly, the concurrent execution of highway rehabilitation projects has a direct and significant impact on the extent of network service disruption and the required monthly funding. Decision makers therefore need to prioritize rehabilitation projects in such a way that: (1) minimize the network service disruption during rehabilitation; and (2) comply with monthly funding limits.

5.5.3 Procurement Method (pm_n)

The procurement method used in highway projects also has a significant impact on the size of the rehabilitation programs and the extent of network service disruption. This research study considers three main procurement methods: least cost (traditional) bidding, cost and time (A+B) bidding, and lane rental contracts. Traditional bidding leads to minimizing rehabilitation costs at the expense of longer construction durations and therefore extended disruption to the level of service provided by the transportation network. Bidding on cost and time however can enable reducing projects durations but at an additional cost premium to allow for accelerating highway construction activities and roads under construction will still be closed to traffic. Finally, lane rental contracts can significantly contribute to limiting the impact of highway rehabilitation efforts on network service disruption through minimizing road closures but it usually causes construction costs to increase significantly. It is therefore important for decision makers to select and implement a combination of procurement methods for the different rehabilitation projects that strikes an optimal balance between minimizing both the cost of the rehabilitation program and network service disruption.

5.5.4 Optimization Engine

This optimization module utilizes multi-objective genetic algorithm NSGA-II (Deb et al 2001) to optimize highway rehabilitation efforts. NSGA-II was selected as the optimization engine in this model due to: (1) the multi-objective nature of the problem; (2) the non-continuous planning objective functions; and (3) the efficiency and effectiveness of NSGA-II in generating near optimal solutions for similar multi-objective optimization problems (Jeong and Abraham 2009; El-Rayes and Kandil 2005; Kandil and El-Rayes 2006; Khalafallah and El-Rayes 2006; Orabi et al. 2009). The main purpose of using NSGA-II in the multi-objective optimization model is to identify the set(s) of relevant rehabilitation planning variables that provide optimal/near optimal pairs of net rehabilitation benefits and network service disruption. Each of these variable sets represents a solution to the current problem and identifies the following rehabilitation project decisions: (1) project selection, (2) project prioritization, and (3) procurement method. The GA starts by generating a population of random solutions and pass them to the aforementioned cost estimating and scheduling module; network performance and road user savings module; and benefit-cost analysis module in order to analyze the net rehabilitation benefits and networks service disruption associated with each of these solutions using Equations (5-5) and (5-10), respectively. The GA uses the fitness of each solution in the population, in terms of satisfying the planning objectives of maximizing net rehabilitation benefits and minimizing network service disruption, to rank and sort these solutions. The genetic operations of selection, crossover and mutation are then applied on the best solutions to generate a new population of solutions that are closer to the optimal solution. This series of operations are iteratively repeated for a predefined number of generations until convergence to the optimal solution and the optimal/near optimal set of planning variables is extracted from the final population.

5.6 Model Evaluation

An application example is analyzed to evaluate the performance of the developed highway rehabilitation planning and optimization model and demonstrate its capabilities in planning and optimizing the rehabilitation efforts of aging transportation networks. The example seeks to plan and optimize the rehabilitation efforts for the transportation network in Sioux Falls, South Dakota. The topology and traffic data of this network example are summarized in Figure 3-7, Table 3-4 and Table 3-5. This transportation network is assumed to be deteriorating and need rehabilitation work at many locations throughout the network. The decision maker identified and estimated construction data for 30 rehabilitation projects to bring this aging transportation network to acceptable levels. These projects are designed to improve the pavement condition index (PCI) of many road segments that are in poor conditions and add a new lane to segments that are suffering from traffic congestion. The data of these suggested rehabilitation projects is summarized in Table 5-1 and it includes: (1) the road segments that need to be rehabilitated; (2) the current pavement condition index (PCI) of each segment; (3) the added capacity for each road segment, if applicable; and (4) the cost and duration of each rehabilitation project under the three main procurement methods considered in this research study. The funding available for this rehabilitation program is assumed to be \$70 million with a maximum allowable monthly expenditure of two million dollars. The next rehabilitation efforts for the selected road segments are planned to be performed after 35 years. In order to facilitate analyzing the benefits of the selected rehabilitation program(s) over the lifecycle of the network, it is assumed that four maintenance cycles (every seven years) are applied to the rehabilitated road segments at a cost equal to \$14 million for each cycle. In this example, decision makers and planners need to identify and implement the rehabilitation program(s) that provide optimal or near optimal tradeoffs between maximizing rehabilitation benefits and minimizing service disruption during highway construction operations. These rehabilitation programs identify three main decisions: (1) the selection of rehabilitation projects; (2) the order of execution of the selected projects; and (3) the procurement method of each project.

The developed highway rehabilitation planning model was used to analyze the above input data and was able to generate a set of optimal rehabilitation programs, where each provides an optimal and non-dominated tradeoff between maximizing rehabilitation benefits and minimizing the network service disruption during highway construction operations, as shown in Figure 5-9. The results of this analysis illustrate that maximizing the benefits of rehabilitation efforts often leads to higher levels of service disruption, as shown in Figure 5-9. This is mainly due to the extended scope of

Table 5-1 Suggested rehabilitation projects

Project	Link	PCI	ADT (*veh/day*)	Added Capacity (*veh/day*)	Traditional		A+B		Lane Rental*	
					Cost ($,mil)	Duration (months)	Cost ($,mil)	Duration (months)	Cost ($,mil)	Duration (months)
1	8	34	14,055	-	5.64	9	5.80	6	6.77	10
2	11	53	18,051	-	3.01	5	3.03	3	3.94	6
3	12	45	8,792	5,052	8.72	11	8.81	7	N/A	N/A
4	13	32	15,796	-	3.22	5	3.24	3	N/A	N/A
5	16	52	12,490	5,101	4.59	4	4.69	3	N/A	N/A
6	21	32	6,884	-	5.45	9	5.53	7	N/A	N/A
7	22	33	8,382	-	3.00	6	3.03	4	N/A	N/A
8	23	33	15,811	-	3.22	5	3.31	3	N/A	N/A
9	25	31	21,757	-	1.65	4	1.66	3	N/A	N/A
10	28	53	23,133	-	3.80	8	3.88	5	N/A	N/A
11	32	43	17,606	5,000	9.95	9	10.06	6	N/A	N/A
12	34	34	9,779	5,123	8.95	12	9.19	8	N/A	N/A
13	35	46	10,003	-	4.89	8	5.02	6	5.69	9
14	37	48	12,322	-	5.63	10	5.69	7	6.64	12
15	38	31	12,412	-	6.35	8	6.49	5	7.12	9
16	41	49	9,037	4,872	11.61	11	11.93	7	N/A	N/A
17	43	50	23,198	4,488	13.62	11	13.87	8	N/A	N/A
18	44	45	9,080	4,872	11.74	10	11.80	6	N/A	N/A
19	46	51	18,397	5,401	7.25	6	7.46	5	N/A	N/A
20	47	36	8,400	-	3.20	6	3.27	4	N/A	N/A
21	48	53	11,070	5,145	9.04	9	9.26	6	N/A	N/A
22	52	51	11,668	4,770	4.25	5	4.31	3	N/A	N/A
23	57	49	19,119	-	1.55	3	1.56	2	N/A	N/A
24	60	33	19,018	-	5.59	11	5.67	8	7.70	13
25	61	40	8,705	4,997	8.96	10	9.19	7	N/A	N/A
26	62	49	6,304	-	3.13	8	3.15	5	N/A	N/A
27	64	37	6,246	-	3.37	7	3.44	6	N/A	N/A
28	67	37	18,374	5,401	6.71	6	6.75	4	N/A	N/A
29	73	51	7,902	-	1.12	3	1.15	2	N/A	N/A
30	76	46	7,862	-	1.06	2	1.07	1	N/A	N/A

* Not available for all rehabilitation projects due to constructability and/or traffic restrictions

highway construction work that is needed to maximize the net benefits of rehabilitation efforts. Table 5-2 lists the scope of highway construction work for all 19 optimal tradeoffs and their corresponding rehabilitation programs that were generated by the model. At one end of the spectrum of generated optimal solutions, the rehabilitation program of Solution 1, which consists of only ten projects and rehabilitates a total length of 39 miles, provides the least network service disruption of -0.38 veh.hr/veh (i.e. introduces approximately 23 minutes in travel time savings for each traveler), as shown in Figure 5-9. At the other end of the spectrum, Solution 19 provides more than double the rehabilitation benefits compared to Solution 1 (See Figure 5-9). This was possible by including 26 highway miles (i.e. 67%) more than Solution 1, as shown in Table 5-2. However, this rehabilitation program causes disruption to about 83% more vehicles at an average of 5.23 veh.hr/veh in additional service disruption compared to Solution 1.

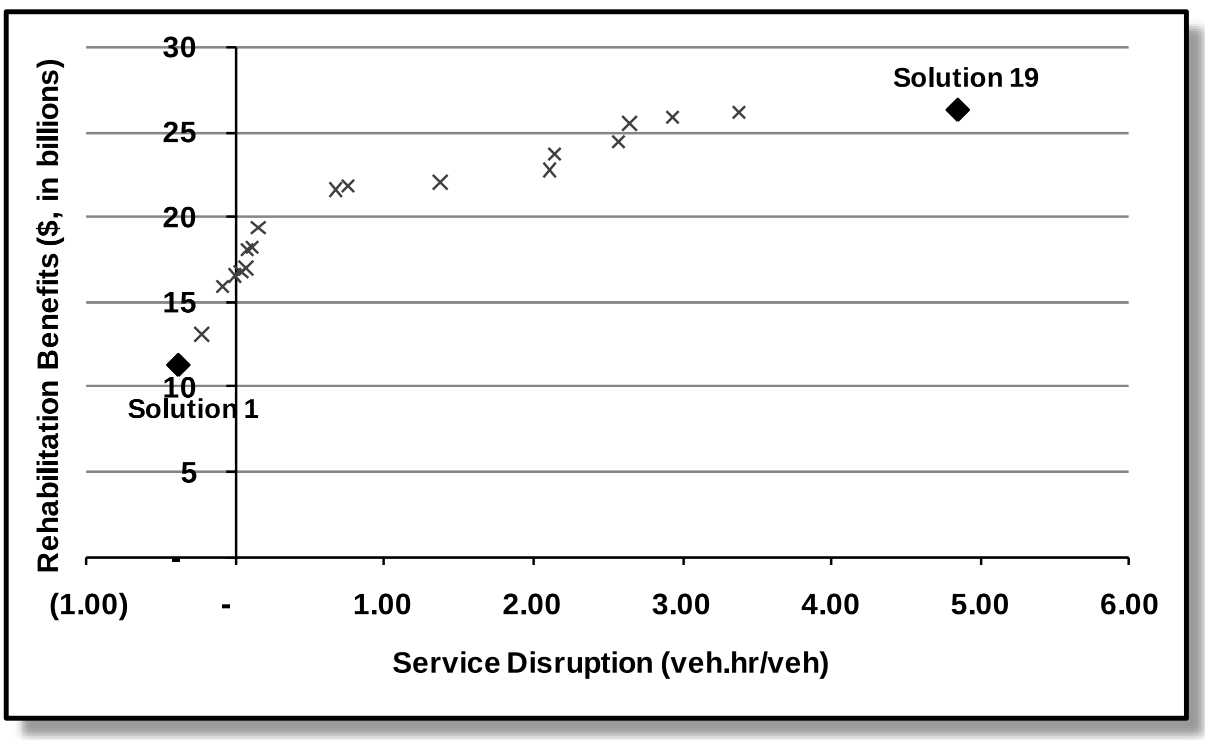


Figure 5-9 Tradeoff between service disruption and rehabilitation benefits

In addition to these two rehabilitation programs, the model generated another 17 optimal rehabilitation programs that provide a wide range of tradeoffs between minimizing service disruption and maximizing rehabilitation benefits, as shown in Figure 5-9. Planners can analyze these optimal solutions and select a rehabilitation program that strikes an optimal balance between reducing the network service disruption and increasing the rehabilitation benefits based on the conditions of the specific network.

The analysis of this example illustrates the unique and practical capabilities of the developed highway rehabilitation planning model in identifying a wide range of optimal rehabilitation programs for aging transportation networks. Each of these plans provides

Table 5-2 Scope of highway construction works of optimal rehabilitation programs

Solution	# Projects	Length of Rehabilitated Roads (miles)	Affected Average Daily Traffic (veh)	Pre-Rehabilitation Daily Direct Travel Cost ($)	Pre-Rehabilitation Vehicle Operating Costs ($/mile)
1	10	39	129,390	12,941	2.82
2	12	53	138,715	15,912	3.89
3	12	49	137,476	13,874	3.53
4	12	53	135,919	14,411	3.80
5	13	55	143,821	14,796	3.93
6	12	49	148,652	14,530	3.55
7	12	51	134,169	14,666	3.71
8	13	53	142,071	15,051	3.84
9	13	54	153,287	16,084	3.91
10	13	54	156,913	16,707	3.97
11	12	52	148,064	16,121	3.81
12	14	49	187,198	17,051	3.53
13	15	65	205,915	22,099	4.69
14	13	56	188,392	20,644	4.12
15	14	62	207,560	22,976	4.53
16	15	68	213,864	23,911	4.94
17	15	61	221,656	23,081	4.43
18	16	63	229,518	23,479	4.57
19	17	65	237,420	23,863	4.70

a unique and optimal tradeoff between the rehabilitation benefits and network service disruption, as shown in Figure 5-9. Decision makers can evaluate these generated optimal tradeoffs and select the highway construction plan that satisfies the specific requirements of the rehabilitation efforts being planned.

5.7 Summary and Conclusions

A highway rehabilitation planning and optimization model was developed to enable an efficient and effective rehabilitation process for aging transportation networks. This model incorporates four new modules that bring in an array of capabilities in highway rehabilitation planning and optimization. First, the newly developed cost estimating and scheduling module is capable of calculating the schedule of a given rehabilitation program and estimating its costs under both overall and monthly budget constraints. Second, the network performance and road user savings module is capable of evaluating the impact of rehabilitation programs on the functional performance of transportation networks; estimating the expected network service disruption during rehabilitation efforts; and estimating the expected savings in road user costs resulting from the implementation of these rehabilitation programs. Third, the benefit-cost analysis module performs an analysis of all benefits and costs associated with rehabilitation programs in order to identify the net rehabilitation benefits. Finally, the GA-based multi-objective optimization module is capable of optimizing highway rehabilitation efforts in order to simultaneously maximize net rehabilitation benefits and minimize network service disruption. An application example is analyzed to evaluate the performance of the developed model, illustrate its use and demonstrate its capabilities in generating optimal tradeoffs between net rehabilitation benefits and network service disruption. These capabilities are demonstrated in the ability of the developed rehabilitation planning and optimization model to consider a number of practical highway rehabilitation requirements, including: (1) considering the impact of the limited availability of funding on planning rehabilitation efforts for aging transportation networks; (2) evaluating the expected service disruption and road user savings during and after completion of rehabilitation efforts; (3) estimating the expected net benefits of rehabilitation programs; and (4) optimizing the allocation of financial resources to maximize net rehabilitation benefits and minimize network service disruption. These new and unique capabilities should prove useful to decision makers and planners in departments of transportation (DOTs) and should contribute to enhancing the planning of rehabilitation efforts for aging transportation networks.

CHAPTER 6
CONCLUSIONS

6.1 Conclusions

The research study presented in this dissertation focused on optimizing highway reconstruction and rehabilitation projects. In order to achieve this goal, a number of research developments were introduced to support decision making in planning highway construction works, including: (1) a service disruption model that assesses the impact of highway construction projects and operations on the functional performance of damaged and aging transportation networks; (2) models for planning and optimizing post-disaster reconstruction of damaged transportation networks; and (3) a planning and optimization model for the rehabilitation efforts of aging transportation networks.

First, a highway service disruption model was developed to support measuring and evaluating the expected disruption in the level of service provided by aging transportation networks during highway reconstruction and rehabilitation projects. The model is capable of analyzing the impact of construction projects and their dynamic nature on the functional performance of damaged and aging transportation networks during reconstruction and rehabilitation efforts. This model also incorporates a deterministic travel assignment algorithm in order to consider the impact of individualistic rationality of travelers in selecting which route/detour to use at different phases of the construction efforts. Accordingly, the developed model is capable of analyzing the functional performance of aging transportation networks and identifying the level of service disruption experienced by road users as a result of implementing specific reconstruction plans or rehabilitation programs. These new and unique capabilities of the service disruption model should prove useful to decision makers and planners in departments of transportation (DOTs) and should contribute to improving the planning and optimization of highway reconstruction and rehabilitation efforts.

Second, resource utilization and multi-objective optimization models were developed to enable the optimization of the reconstruction efforts for damaged transportation networks in the aftermath of natural disasters. The newly developed resource utilization model is capable of assigning reconstruction resources to competing reconstruction projects according to the project priorities, contractor assignment, and overtime policy. The resource utilization model is also capable of estimating both the reconstruction duration and cost of various optimal reconstruction plans. In addition, the multi-objective optimization model provides the capability of optimizing post-disaster reconstruction efforts in order to simultaneously minimize network service disruption and reconstruction cost. These new and unique capabilities of the developed models should prove useful to decision makers and planners in emergency management agencies and should contribute to enhancing the planning of post-disaster reconstruction efforts for damaged transportation networks.

Third, a highway rehabilitation planning and optimization model was developed to enable the optimization of the rehabilitation work for aging transportation networks. This model incorporates four new modules that provide new capabilities in highway rehabilitation planning and optimization. First, the newly developed cost estimating and scheduling module is capable of calculating the schedule of a given rehabilitation program and estimating its costs under both overall and monthly budget constraints. Second, the network performance and road user savings module is capable of evaluating the impact of rehabilitation programs on the functional performance of transportation networks; estimating the expected network service disruption during rehabilitation efforts; and estimating the expected savings in road user costs resulting from the implementation of these rehabilitation programs. Third, the benefit-cost analysis module performs an analysis of all benefits and costs associated with rehabilitation programs in order to identify the net rehabilitation benefits. Fourth, the GA-based multi-objective optimization module is capable of optimizing highway rehabilitation efforts in order to simultaneously maximize net rehabilitation benefits and minimize network service disruption. These new and unique capabilities should prove useful to decision makers and planners in departments of transportation (DOTs) and should contribute to enhancing the planning of rehabilitation efforts for aging transportation networks.

The aforementioned research developments contribute to the advancement of current practices in highway construction planning and can lead to: (1) accelerating the completion of highway reconstruction and rehabilitation projects and minimizing the service disruption experienced by travelers during the construction work; (2) optimizing the allocation of limited budgets and financial resources to competing highway projects; and (3) improving the utilization efficiency of construction resources in highway projects and therefore increasing their productivity. Accordingly, these developments hold a strong promise to provide significant benefits to society, departments of transportation (DOTs) and contractors.

6.2 Research Contributions

The contributions of this research include:

1. Developing an innovative service disruption model that is capable of capturing the functional behavior of aging and damaged transportation networks during rehabilitation and reconstruction projects, respectively. The model provides also the capability of estimating the total disruption to the level of service provided by these networks during highway construction projects.
2. Formulating a resource utilization model that is capable of sharing limited reconstruction resources among competing post-disaster reconstruction projects for damaged transportation networks.
3. Developing a novel multi-objective optimization model for post-disaster highway reconstruction projects that is capable of minimizing network service disruption and reconstruction costs, simultaneously.
4. Formulating new highway construction scheduling algorithms that are capable of: (i) considering the impact of limited budgets and financial resources; (ii) estimating expected road user savings; and (iii) analyzing the benefits-costs of rehabilitation programs for aging transportation networks.
5. Developing a new multi-objective optimization model for highway rehabilitation projects that is capable of simultaneously maximizing total net benefits and minimizing network service disruption of rehabilitation programs.

6.3 Recommendation for Future Research

This research study has presented new models for planning and optimizing highway construction projects. These models are effective and efficient and can be used in enhancing the planning process for highway reconstruction and rehabilitation projects. However, a number of future research areas are recommended in order to enhance the research developments of this study and expand their potential applications, including: (1) measuring the service disruption of highway construction projects; (2) planning post-disaster reconstruction of damaged transportation networks; (3) planning the rehabilitation efforts of aging transportation networks; and (4) reducing the computational efforts of optimizing highway construction projects.

6.3.1 Measuring the Service Disruption of Highway Projects

This research study was able to analyze and measure the impact of highway construction projects on the network service disruption for damaged and aging transportation networks. Future research is however needed in order to enhance the efficiency and accuracy of service disruption measurement, including:

1. Time series forecasting can be used to predict travel behavior during highway construction based on collected data from live traffic cameras. These forecasted traffic behaviors can be used in a dynamic traffic assignment approach to improve the reliability of estimating link flows compared to the current study that assumes static traffic demand.
2. Transportation networks may not reach the user equilibrium state following major events that change the network status (Yang and Liu 2007). Accordingly, future

research can investigate the use of alternative methods to user equilibrium in estimating link flows.

6.3.2 Planning Post-Disaster Reconstruction of Damaged Networks

The resource utilization model presented in Chapter 4 of this study is capable of allocating limited resources to competing reconstruction projects based on the set of optimal decision variables identified, which provided for effective sharing of resources among competing reconstruction projects. This effective resource utilization can be improved by: (1) relaxing the assumption that limits the interruption of projects once they are started to enable further optimization of projects cost and duration; and (2) integrating the optimization of resource utilization at the activity level for all reconstruction projects with the optimization of resource utilization among competing projects in order to optimize the cost and duration of individual projects as well as for the entire reconstruction efforts.

6.3.3 Planning the Rehabilitation Efforts of Aging Networks

The highway rehabilitation planning modules presented in Chapter 5 of this research study are capable of providing new and unique capabilities in planning rehabilitation efforts of aging transportation networks. The potential applications of these planning modules can be expanded in the future by:

1. Expanding the scope of rehabilitation benefits to include business growth, job creation and other relevant socioeconomic benefits.
2. Including additional procurement methods for highway construction project such as nighttime construction and A+B with incentives to the three methods already

considered in this study. This can be accomplished by introducing these methods as additional alternatives, or by redesigning the existing alternatives to accommodate the special conditions of these other procurement methods. For example, lane rental bidding and be remodeled to include nighttime construction.

6.3.4 Reducing the Computational Cost of Optimizing Highway Projects

This research study was capable of optimizing reconstruction and rehabilitation efforts of damaged and aging transportation networks and generating highway construction plans that provide optimal tradeoffs between minimizing network service disruption and maximizing the societal benefits. These optimization models however require long computational time mainly due to the time required to analyze transportation networks. This computational time increases as the size of the analyzed transportation network increases. Accordingly, future research can investigate the following methods that can be used to reduce the aforementioned computational time:

1. Develop and implement the research developments presented in this study in a parallel computing framework that can combine the computing capabilities of several personal computers to help reduce the computational time (Kandil and El-Rayes 2006b).
2. Design and apply new data processing and storage structures that allows for optimizing data handling among the different modules in order to minimize the computational overhead. For example, the storage and handling of solution data in the NSGA-II optimization engine can be redesigned to prevent reprocessing and analysis of previously evaluated solutions.

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