AN INTEGRATED INFRASTRUCTURE ENGINEERING DECISION-MAKING PROCEDURE: A FINANCE-BASED FUZZY TIME-COST-QUALITY TRADE-OFF OPTIMIZATION MODEL OVER THE PROJECT LIFE CYCLE

By

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A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

2016

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To my family

ACKNOWLEDGMENTS

I would like to gratefully and sincerely thank my supervisory committee members, Dr. Ralph Ellis, Dr. Charles Glagola, Dr. David Prevatt, and Dr. Richard Romano, for their guidance and valuable advice throughout the course of this research.

Dr. Glagola was always there, smiling, ready for listening to my plan, research, work, or life, and for offering me most valuable advice. It was also fun to work with Dr. Glagola on a FDOT-sponsored in-place soil testing project. His wisdom inspired and motivated me.

I would have still been wasting much time working on a "perfect" dissertation without Dr. Prevatt's kind reminder that a good dissertation is a done dissertation. His suggestions on research methods and processes also enlightened me a lot.

It was Dr. Romano's game theory class that encouraged me to go further into the decision-making sciences. His instructions had substantial influence on my research. Dr. Romano's advice on my studies and research was always most illuminating.

My deepest gratitude goes to Dr. Ralph Ellis, my committee chair, for mentoring and putting faith in me. I cannot express my thanks adequately for his continuous support over the past five years. I have been amazingly fortunate to have Dr. Ellis as my advisor who gave me the freedom to explore on my own, and whose mentorship was paramount in providing valuable guidance, feedback, encouragement, and experience consistent with my long-term career goals.

Additionally, I would like to thank Dr. Duzgun Agdas and Dr. Don Lewis for many discussions on related topics that helped me improve my knowledge and thinking in the area. I am very thankful to my Ph.D. fellows and friends, Carlos, Eileen, Jae, Kevin, Kyle, Sevcan, and Sungjin: without them the whole Ph.D. life would be dull and would lack so much fun. I appreciate their friendship and wish we could spend more time hanging out together.

Lastly, sincere thanks go to my parents, my wife, and my pretty little one. I love you all.

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LIST OF ABBREVIATIONS

AEC	Architecture, Engineering, and Construction
AHP	Analytical Hierarchy Process
BCA	Benefit-Cost Analysis
CPM	Critical Path Method
CSF	Critical Success Factor
EF	Early Finish
ES	Early Start
FF	Free Float
GA	Genetic Algorithm
GAO	Government Accountability Office
IMS	Integrated Master Schedule
IRR	Internal Rate of Return
KPI	Key Performance Indicator
LF	Late Finish
LOB	Line of Balance
LS	Late Start
MADM	Multi-Attribute Decision Making
MCDA	Multi-Criteria Decision Analysis
MCDM	Multi-Criteria Decision Making
MODM	Multi-Objective Decision Making
NGO	Non-Government Organization
NPV	Net Present Value
PRISMA	Preferred Reporting Items for Systematic reviews and Meta-Analyses

SIS	Strategic Intermodal System
TBL	Triple Bottom Line
TCQT	Time-Cost-Quality Trade-off
TCT	Time-Cost Trade-off
TF	Total Float
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
TTS	Travel Time Savings

Abstract of Dissertation Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the
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August 2016

Chair: Ralph Ellis
Major: Civil Engineering

This research centers upon the study of methodology in decision making of infrastructure engineering development and management. It further proposes comprehensive finance-based time-cost-quality trade-off optimization models to help infrastructure engineering decision makers enhance their integrated decision-making procedures. After a literature review on the theory and methods of multi-criteria decision making (MCDM), two types of applications are discussed: (1) multi-attribute decision-making (MADM) optimization, and (2) multi-objective decision-making (MODM) optimization. The MADM method is proposed to be applied in the prioritization process of highway projects by constructing an index system through analysis of economic attributes, technological attributes, and environmental attributes of potential projects. The MODM method is proposed to be applied in the optimization of multiple objectives trade-off for a selected project through identification and modification of relationships among multiple objectives and through advanced optimization techniques. The former is then applied in Case Study I which aims to prioritize the Strategic Intermodal System highway projects in Florida Department of Transportation District 2, and the latter is then applied in Case Study II which provides the project sponsor with a finance-based multi-objective trade-off optimization model.

An integration of analytic hierarchy process, entropy weight, and technique for order of preference by similarity to ideal solution is modeled to solve the MADM problem, while the genetic algorithm is suggested to solve the proposed MODM model.

In addition, some critical success factors and key performance indicators for successful projects and successful project management are identified and incorporated in the proposed models with consideration of financial constraints over the project life cycle. Uncertainties and imprecisions that have often been encountered in the infrastructure engineering decision-making practice are modeled through the application of fuzzy sets theory. The two case studies have testified the effectiveness and the efficiency of the proposed models. Generally, this dissertation research provides infrastructure engineering decision makers (e.g., project sponsors and project managers) with a look into the existing methods and their applications to MCDM problems.

CHAPTER 1
INTRODUCTION

Background

Governments and other infrastructure administration agencies must make decisions, among a great many potential projects, on which projects to fund, when to fund, and how much to fund. This is especially the case in the United States where maintenance and replacement costs of aging infrastructure facilities are high and where budgets are constrained. This requires the decision-maker's efforts on rational planning and programming to accommodate the needs for budgeting and scheduling the acquisition and development of infrastructure engineering projects. Therefore, prioritization of potential projects becomes one of a decision-maker's major concerns.

Once an infrastructure engineering project is selected and bids published, architecture, engineering, and construction (AEC) firms are then faced with decisions about project selection, project management, and corporate development. The management and project managers of such organizations (i.e., project owners or sponsors such as government agencies, as well as AEC firms) wonder as to which decision would be best. While project owners must have a comprehensive view on overall project risk and return, many AEC firms are struggling with promoting their competitiveness by taking successful projects through best project management practice. Intuitively, project success, project management practice, and the firm's competitiveness are positively interrelated, while project management practice serves as a linkage that connects project success and the firm's competitiveness. This has been indicated by several studies. For example, Cooke-Davies (2002) discussed the importance of project management and operations management working together to deliver beneficial change from projects, and further depicted the corporate context for project success.

With limited budgets and expedited schedules in the infrastructure engineering industry in these days, planners, engineers, contractors, along with other decision-makers, must be equipped with speedy decision making tools and techniques in selection of optimal solutions to cope with project capital constraints and rapidly changing environment.

On the first hand, selection of appropriate projects requires prioritization of potential projects at the very beginning of the planning phase. The prioritization and selection process has considerable impacts on project risks and costs over the project life cycle. As indicated in Figure 1-1 PMBOK® (Fifth Edition, 2013, pp.40), cost of changes is lowest at the start of the project, when risk and uncertainty are usually greatest. Specifically, cost of changes tends to increase fast with the progress of the project, although the project uncertainty decreases with time. In other words, construction time can be reduced if we spend more time in planning and designing, and thus project prioritization and selection are critical to project success. Accordingly, project owners or sponsors usually play a critical role in influencing costs of project construction as the decisions they make at the very beginning of a project cycle will have much greater influence than later. Again, this makes adequate planning and feasibility studies necessary and important.

On the other hand, traditionally, a project is viewed as a successful project if it is delivered on time, within budget, and meets or exceeds the customer’s expectation. However, conflicts exist among these multiple objectives. This calls for research on time-cost-quality trade-off (TCQT) optimization analysis. Most existing studies are conducted based on some constraints with certainties. In real engineering practice, however, the existence of uncertainties is the only “certain” thing that will be encountered. For example, we cannot know for sure soil spatial variability on the job site, weather conditions, management qualities, material supplies, equipment operation status, and so on. These uncertain factors have extensive impacts on project time, cost, and quality and thus make project objectives fuzzy. In order to take such risky or uncertain project conditions into account, probability theory and fuzzy sets theory are often applied into TCQT analysis.

Besides time, cost, and quality objectives that are commonly considered in the process of project management decision-making, other significant objectives, for example, project safety and sustainability (with regard to project environment), have gradually been added to the key control objectives. Correspondingly, with the rapid development of computing techniques and computer engineering, more critical factors (e.g., construction safety, health, sustainability indicators, etc.) are also suggested to be incorporated in the optimization models. A recent trend in the literature has been emphasized that project life cycle performance should also be included in the trade-off analysis.

Usually, TCQT problems are analyzed at the project level. It should be noted that techniques above the project level are also critical to project success as well as to corporate success. A key to best project management decision making above the project level requires the integration of engineering skills with finance sciences. However, there seems a big gap between the practice of engineering and the understanding of finance. In the real world, project owners and AEC firms can make better financial decisions with the understanding of project engineering, and vice versa. In fact, integrating the scheduling and financing functions of construction project management has become a pressing need and attracted many researchers' interest (Elazouni 2009). In the recent decade, a "One Stop Shop" approach, which involves property development, design, construction and facility management, has often been provided by many of the most successful construction companies. Such an approach helps in a way that multiple project objectives are under control by one single team.

This dissertation aims to improve the infrastructure engineering decision-making procedures by developing practical finance-based models for an extensive TCQT optimization over the whole project life cycle. A framework, which integrates the positive feedback from project success through project management practice to corporate's competitiveness, is also developed. Building on existing asset management strategies, this research provides a methodology to help infrastructure development stakeholders make suitable and sustainable decisions to support project life-cycle economic activity, and is intended to offer tools to help the project financing and prioritization processes.

Problem Statement

In the real world where resources are limited, decisions have to be made on whether a project proposal should be accepted and then whether the project should be executed within a specific timeline. The goal of the project selection process is to approve or reject project proposals by analyzing project feasibility and prioritizing a group of potential projects based on established criteria that usually include time, cost, and quality requirements. Therefore, the selection process serves as the starting point of project planning. – This is important, as initiation of a project without proper planning by a state highway agency (SHA) has been identified as one of the root causes of time delays in highway construction projects (Thomas and Ellis, 2001).

During project execution, optimization for project scheduling has attracted researchers' continuous attention since the creation of Critical Path Method (CPM) in the 1950s. Concerned with the optimal allocation of scarce resources to activities over time (Karger et al., 1997), the practice of scheduling theory makes it necessary for research on multi-objective trade-off analysis during the project life cycle. Although meeting project time (or duration), cost (or budget), and quality (or scope) requirements are most frequently referred to as the basic objectives of a successful project, further identification of main critical success factors (CSFs) and key performance indicators (KPIs) for project management is of significance for the project team to prioritize the resource constraints and then to have a correct focus (Ebbesen and Hope, 2013).

The knowledge of CSFs and KPIs provides us with opportunities to add other important dimensions to the existing time-cost-quality trade-off optimization analysis. Further, the project stakeholder's financial constraints are suggested to be included in the trade-off analysis over the project life cycle. Considering uncertainties in different project phases, fuzzy sets theory can be applied to help with the project management decision-making process. The above-mentioned efforts are made so that the simulation model can be closer to real engineering practice.

Further, advanced modeling and algorithms are needed to solve such multi-objective optimization problems as time-cost-quality trade-off simulation. These include heuristics methods, linear regression, non-linear programming, neutral network, genetic algorithms, etc. Among them, genetic algorithms (including improved genetic algorithms) have been widely used in recent years and seem to have advantages in identifying optimal or near-optimal solutions to optimization and decision-making problems with large search spaces based on linear or non-linear programming.

Another motivation of this research, introducing project life cycle assessment to the multi-objective trade-off analysis, requires two-step work: firstly, identifying sustainability indicators, and secondly, integrating sustainability indicators into the existing trade-off models. Social and environmental impacts on the project life cycle should be quantified and codified in some specific way so that they can be simulated in the model.

The final motivation of this dissertation is to develop a framework for facilitation, through best project life-cycle management of the proposed finance-based fuzzy TCQT optimization model, of the positive feedback between project practice and corporate competitiveness. Application of this framework will enhance the AEC firm's competitiveness as a whole.

Research Questions

This dissertation presents, at least partially, solutions to the following questions:

- In general, what is the decision-making process for infrastructure engineering development and how does it work? (Chapter 3)
- What is the general form of a decision-making problem? (Chapter 4)
- How do infrastructure engineering project sponsors target and select a specific project? For example, how should DOTs prioritize highway engineering projects? (Chapter 5 and Chapter 7)
- What strategies and techniques do DOTs adopt for project prioritization? (Chapter 5)
- What are critical factors and/or key performance indicators for a successful infrastructure engineering project and for successful project management? (Chapter 2 and Chapter 3)
- What is the general form of a time-cost-quality trade-off optimization problem? (Chapter 3 and Chapter 6)
- How can we optimize the project plan in terms of the trade-off among project time, cost, and quality (so that a project can be delivered on time, within budget, and with acceptable quality, and can create maximum benefits and utilities for stakeholders)? (Chapter 2 and Chapter 6)
- How can we integrate financial constraints into the proposed model over the project life cycle? (Chapter 6 and Chapter 8)

Research Objectives

Based on the above research questions, the objective of this research is to improve, through multi-attribute project optimization, multi-objective trade-off optimization, and best project management practice, the decision-making process of and the connection between infrastructure engineering project success and the project stakeholder's competitiveness. The definitions of project management from different institutes and organizations are compared and summarized so that we can understand those factors or indicators that need to be focused on. Meta-analyses is suggested to be conducted to filter out, among tens of possible factors, the critical success factors (CSFs) and the key performance indicators (KPIs) for project success, project management success, and corporate's competitiveness, respectively. According to the CSFs and the KPIs, potential infrastructure projects are first prioritized based on critical criteria that are selected. Then the project time-cost-quality trade-off problem is analyzed in a wider and more general view of project life cycle as well as of project sponsor's financial constraints. Considering the many uncertainties during the project life cycle, fuzzy sets theory is applied to help with the project management decision-making process.

Chapter Organization

The chapters of the dissertation are organized as shown in Figure 1-2. Chapter 2 provides an overview of the research background and findings from literature reviews. Chapter 3 explains the research methodology. Chapter 4 summarizes the theory on multi-criteria decision-making (MCDM). Chapters 5 and 6 detail the MCDM methods by discussing applications of multi-attribute decision-making (MADM) optimization and multi-objective decision-making (MODM) optimization, respectively. Accordingly, Chapters 7 and 8 provide two case studies based on the proposed MADM and MODM techniques, respectively. Finally, Chapter 9 discusses and summarizes the research findings and offers suggestions.

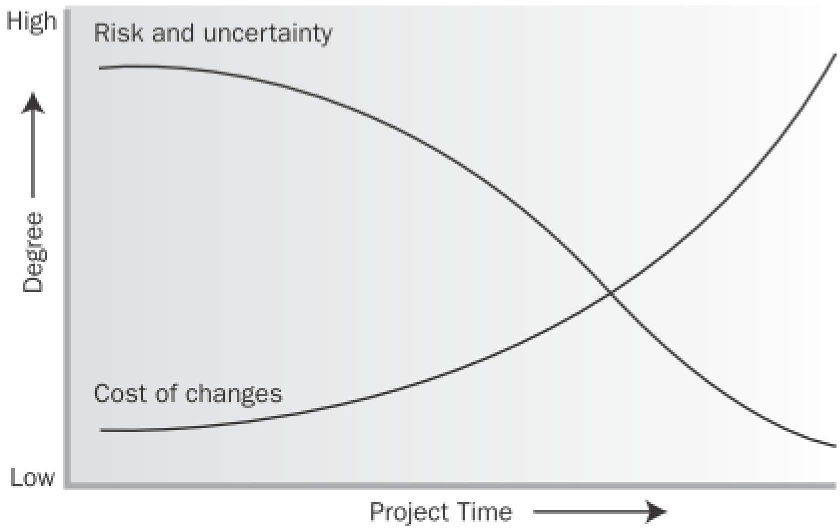


Figure 1-1. Change of Project Features with Time

Source: PMBOK® (Fifth Edition, 2013, pp.40)

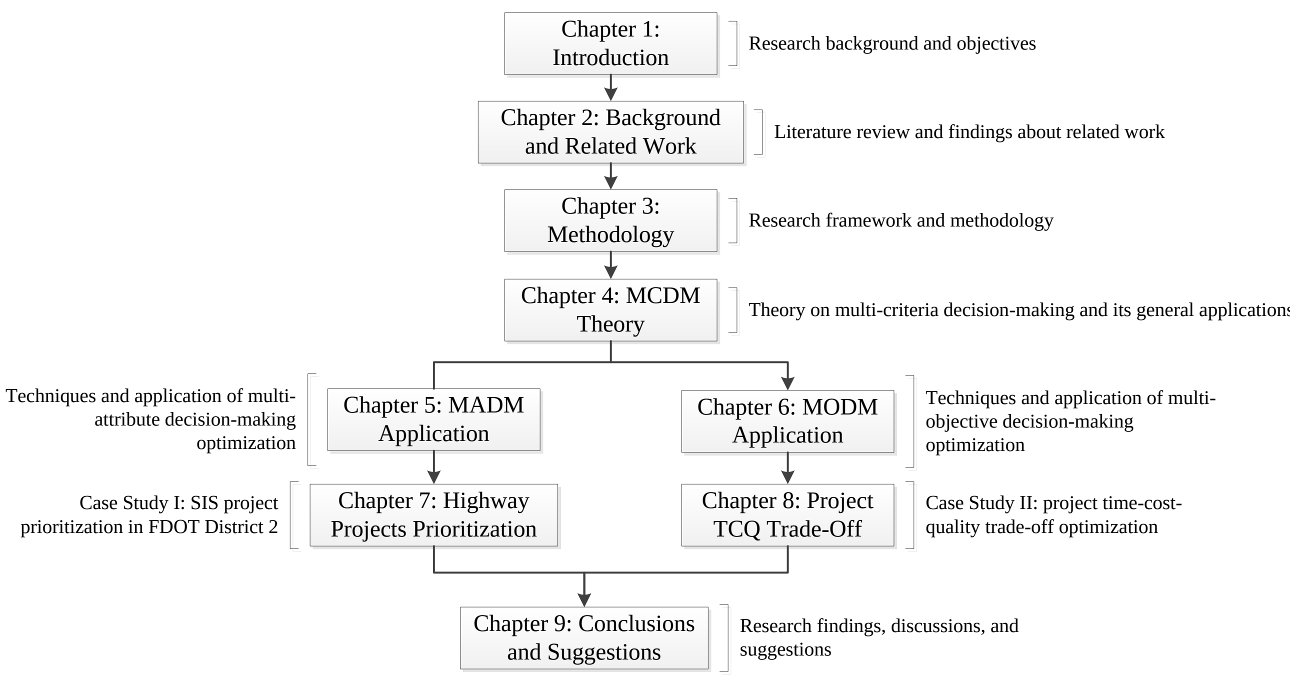


Figure 1-2. Organization of Dissertation Chapters

CHAPTER 2
BACKGROUND AND RELATED WORK

Scope of Research on Infrastructure Engineering Projects

According to Cleland and Ireland (2002), a project is "a combination of organizational resources pulled together to create something that did not previously exist and that will provide a performance capability in the design and execution of organizational strategies". With the increase in scale of engineering projects and in complexity of engineering design, it has become more and more difficult to meet pre-defined objectives of engineering and construction projects. This makes it necessary to introduce optimization theories and techniques for project control. Research has indicated a variety of critical success factors. Among those factors, however, project time, cost, and quality are still the most widely recognized objectives to control. Other significant objectives, for example, project safety and sustainability (with regard to project environment), have gradually been added to the key control objectives. Meeting those objectives require: (1) properly selecting and planning potential projects in the very beginning, and (2) reasonably managing and controlling the project execution and operation.

Accordingly, this dissertation research focuses on: (1) how to prioritize potential infrastructure projects, and (2) how to optimize the real-world multi-objectives of project time, cost, and quality over the whole project life cycle when dealing with the engineering and management of such infrastructure systems as highways, bridges, railways, water and sewage systems, energy facilities, and other civil engineering structures. These unique, large-scale, and usually multimillion-dollar-involved infrastructure engineering projects have increased in complexity manifold over the years. Frankel (2007) pointed out such challenges to America's claims of economic, social, environmental, and technological leadership as infrastructure failures, ineffectiveness, and the inability to properly plan, construct, manage, and maintain physical infrastructure. Therefore, the need has been extensively increased for properly managing the infrastructure engineering project over the whole project life cycle. In Chapters 5~8, highway engineering projects will be specifically chosen as the main reference for this dissertation research analysis. The frameworks and methodologies, however, may also be applied to the management of other infrastructure engineering projects.

The Status of Infrastructure in the United States and in Florida

The United States has been leading the infrastructure development in the world for a long time since the end of World War II. The current status of infrastructure in the United States, however, brings more and more concerns to the public. In the recent ASCE's *Report Card for America's Infrastructure* (2013), America's civil engineers gave a comprehensive assessment of the major U.S. infrastructure and the cumulative grade was only D+, indicating a poor condition with some risks. The *Report Card* is updated every four years and its categories, assessment criteria, and grading scales are listed in Table 2-1. The highway and roadway systems in the U.S. are even under a slightly worse condition, with a grade of only D for roads, and the improvement will require investment of $3.6 trillion by 2020 according to the estimation by Federal Highway Administration. In a report to the White House, the National Economic Council and the President's Council of Economic Advisers (2014) indicated that "America's transportation infrastructure is not keeping pace with demands or the needs of our growing economy, for today or for future generations". This calls for careful selection of future highway projects based on an appropriate project prioritization system, as selecting appropriate projects at appropriate times is one of the keys to achieve goals of projects regarding time, cost, quality, and other important project objectives.

The highway system faces the same challenge in Florida. In the *2012 Report Card for Florida's Infrastructure*, Florida's infrastructure was given an overall grade of C- while its highways got an above average grade of C. The funding or revenue sources have been considered one of the critical issues in both cases. This requires that decision-makers select possible future infrastructure projects very carefully in the planning phase of project management. Researchers believe that the State of Florida is facing a transportation crisis. According to the estimation by Florida Transportation Commission (2014), an additional $136.3 billion is required in order to meet the mobility needs on the Strategic Intermodal System (SIS)[1] through 2040.

In addition, in the *21st Annual Report on the Performance of State Highway Systems (1984-2012)*, Hartgen et al. (2014) used spending and performance data from state highway agencies to track and rate the performance of the 50 state-owned highway systems based on the following categories: expenditures, pavement conditions, bridge conditions, congestion, fatality, and narrow rural arterial lanes. In 2012, the highway performance ranking for Florida was only 31 out of the total 50 states, although Florida's ranking was already improved from 37 in 2009 and 33 in 2011; major issues that existed in the Florida highway system included disbursements (ranking 48th), capital and bridge disbursements (ranking 49th), maintenance disbursements (ranking 45th), admin disbursements (ranking 36th), and urban Interstate/freeway congestion (ranking 50th).

Obviously, investments in infrastructure and the performance of the infrastructure systems are interactive. Both are also affected by economic activities such as the movement of people and goods. Part of this dissertation research concentrates specifically on planning and optimization of highway engineering in the United States.

[1] Established in 2003, Florida's SIS serves as a transportation system with statewide and regionally significant facilities and services, with all modes of transportation, and with integrated transportation network. It focuses limited state resources on critical transportation facilities.

U.S. Highway System Movement

Take the U.S. highway system for example. With decades of highway construction, the United States may have established the most robust highway network and systems in the world. Accordingly, the emphasis of U.S. highway agencies has been moved from new construction to maintenance and asset management. Fwa (2006) summarized three phases of U.S. highway development (Table 2-2). The most recent improvement reflects the integration of big traffic data and mobile technologies with construction, maintenance, and management of highways and highway systems.

Different from developing countries, who rely heavily on debt sources (e.g., the World Bank) for financing of highway construction, the United States and most of developed counties have financed their highway systems primarily through both equity investment and bond issuance, in which calculation of financial risk and return has to be made. In addition, multi-objective optimization analysis should also be conducted in order to incorporate non-monetized elements with financial considerations.

Overview of Project Management

Researchers from both the academia and the industry have attempted to define project management. Commonly cited are those published by different societies, associations, and institutes related to project management, as listed in Table 2-3. Some of those definitions have been accepted as national standards.

These definitions clearly show that, while a variety of concepts have been made, the criteria for project success and project management success require balancing the objectives of time, cost and quality in general. Some researchers (e.g. Atkinson, 1999) refer to the three constraints as the Iron Triangle (Figure 2-1). Note that project quality and scope are used interchangeably in this research. This is reasonable because project quality is usually defined as meeting or exceeding the expectations of the customer and thus the customer gets what he or she asked for, i.e. the project scope.

Three things are worth pointing out. Firstly, in a narrower view, project management success does not necessarily lead to project success, and sometimes (at least in some cases) a successful project does not indicate excellent project management for sure. Secondly, different people have different views on project success even for the same project. In addition, debates on the Iron Triangle exist. Details are discussed as follows.

Cooke-Davies (2002) pointed out the importance of the distinction between project success and project management success. Further, he discussed and distinguished factors on project management success, on an individual successful project, and on consistently successful projects. He summarized the distinction between project success and project management success, the distinction between success criteria and success factors, and the distinction between project success and project performance. Those distinctions are demonstrated Table 2-4.

In order to differentiate views on project success from different people, Lim and Mohamed (1999) proposed to define the following two views of project success.

1. The macro viewpoint: Project end users and the general public usually evaluate the project performance from this viewpoint by asking whether the original project concept has been achieved or not at its operational phase.

2. The micro viewpoints: Project owners, sponsors, engineers, and contractors define project success mainly from this viewpoint by asking whether their respective project objectives (e.g., project time, cost, and quality) have been achieved or not at the conclusion of the construction phase.

Debates on the Iron Triangle do exist. Atkinson (1999) argued that the Iron Triangle (cost, time, and quality), which has been used usually, frequently and for a long time as a set of project management success criteria, is “no more than two best guesses and a phenomenon”. His argument was based on the ideas that time and costs are “calculated at a time when least is known about the project" and that quality is a phenomenon "which often changes over the development life-cycle of a project". He further argued that two types of errors can exist within project management, i.e. Type I errors being the sin of commission (when something is done wrong), while Type II errors being the sin of omission (when something has not been done as well as it could have been or something was missed). So he concluded that using time, cost and quality as the criteria of success is an example of a Type II error and such criteria are not as good as they could be or something is missing. He proposed the Square Route of success criteria instead.

Despite of those debates and arguments, it is still general expectation that a successful project should be delivered on time, within budget and meet quality/scope specifications. However, projects meeting such goals sometimes may not necessarily be perceived as successful projects by key stakeholders (Shenhar and Dvir, 2007; Turner and Bredillet, 2009). Other factors (safety, adaptability, and sustainability, for example) have also been considered as indicators of successful projects. In the PMBOK® Guide (Fifth Edition, 2013, pp.61), Project Management Institute provides a good summary of ten distinct Knowledge Areas of project management (Table 2-5).

Critical Success Factors and Key Performance Indicators

The PMBOK® Guide (Fifth Edition, 2013) suggests measuring project success by the following criteria:

- Product and project quality
- Timeliness
- Budget compliance
- Degree of customer satisfaction

These criteria are consistent with meeting pre-determined objectives on project time, cost, and quality. Environmental issues and construction safety have also been of major concerns in recent decades. In fact, the development of the concept of project success has been a research focus because researchers believe the setting of criteria and standards for project success measurements can benefit project managers to complete projects with the most favorable outcomes. The concept of project success, however, has remained ambiguously defined in the construction industry. Chan and Chan (2004) defined criteria of project success as the set of principles or standards by which favorable outcomes can be completed within a set specification. They argued that such definitions are dependent on project type, size and sophistication, project participants and experience of owners, etc. and developed a set of key performance indicators (KPIs) for both objective and subjective measurements.

Studies on project success factors or key performance indicators have been conducted with focuses at or above the project level, on a variety of project types, on a specific country, or on different project phases. Hyvari's survey (2006) indicated the significance of company/organization size, project size, organization type, and project managers' work experience. Jugdev and Müller (2005) presented a shift or evolution of definition of project success from the implementation phase of the project life cycle to an appreciation of success over the project and product life cycle. Chan et al. (2002) developed a framework of success criteria for design/build projects by evaluation through performance measures developed from extensive research literature. Takim and Akintoye (2002) suggested dividing successful construction project performance along procurement, process and result orientations.

Regression analysis has been used to verify the relationship between project overall performance and success factors. For example, Lam et al. (2008) developed a project success index for design-build projects in terms of time, quality, and functionality. Ling et al. (2008) used cost performance, time performance, quality performance, owner satisfaction, and profit margin as performance measures to develop models for prediction of project success levels, based on project management practices adopted by foreign AEC firms in China.

Researchers also use mathematical tools to categorize a huge number of success factors. Lu et al. (2008) grouped 35 success factors into eight clusters by factor analysis. Tabish and Jha (2012) used structural equation modeling for measurement of human factors, management actions, success traits, and project success, concluding that human factors and management actions play a key role in making the project a success. Park (2009) identified a set of 10 common factors and 188 individual factors and grouped them into eight major categories as critical success factors for whole life performance assessment of construction projects. Chan et al. (2010) grouped 18 factors necessary to conduct PPP projects into five categories. Although other factors or indicators have also been suggested, time, cost and quality remain the most considered criteria for measuring construction project success.

As early as in 1972, the U.S. Government Accountability Office (GAO, 1972) summarized the basic characteristics of credible cost estimates in their report of *Theory and Practice of Cost Estimating for Major Acquisitions*. Those characteristics, listed as follows, can still be applied to the nowadays practice:

- Clear identification of task
- Broad participation in preparing estimates
- Availability of valid data
- Standardized structure for the estimate
- Provision for program uncertainties
- Recognition of inflation
- Recognition of excluded costs
- Independent review of estimates
- Revision of estimates for significant program changes

The U.S. Government Accountability Office (GAO, 2012) also summarized ten best practices for development of a high-quality, reliable schedule that is comprehensive, well-constructed, credible, and controlled. These ten best practices are:

- Capturing all activities
- Sequencing all activities
- Assigning resources to all activities
- Establishing the duration of all activities
- Verifying that the schedule can be traced horizontally and vertically
- Confirming that the critical path is valid
- Ensuring reasonable total float
- Conducting a schedule risk analysis
- Updating the schedule using actual progress and logic
- Maintaining a baseline schedule

In addition, the Integrated Master Schedule (IMS) is also suggested by GAO for the integration of planning, resource and budget assignment, and the project schedule.

The importance of identifying CSFs and KPIs is at least two fold: first, it helps the management team develop effective strategies; and second, incorporation of CSFs and KPIs with project success prediction models improves the project control process. Russell et al. (1997) suggested using continuous variables (e.g., owner expenditures, contractor construction efforts hours expended, invoices paid by contractor, total commitments for material and equipment, cost of owner project commitments and costs of contractor project commitments, and designer project cost) for project cost and schedule predictions. They found that success predictors are different at different points of project time. Ko and Cheng (2007) further created an Evolutionary Project Success Prediction Model by integrating genetic algorithms, fuzzy logic, and neural networks into the Continuous Assessment of Project Performance software developed by Russell et al. (1996).

Time-Cost-Quality Trade-off Optimization

PERT (Program Evaluation and Review Technique) and CPM (Critical Path Method) are the most common tools associated with network analysis. They formed the foundation for scheduling optimization with regard to minimizing project cost within pre-determined project duration. Based on CPM, an early study on time-cost trade-off algorithm was conducted by Siemens (1971), in which he developed a Siemens Approximation Method (SAM). His method provided simple solutions (even suited for hand computation) to time-cost trade-offs on determining which activities to expedite and by what amount for minimizing the project cost by compressing the activity with the smallest slope (with regard to direct cost) on the critical path. Another early effort was made by Philips and Dessouki (1977) for project time-cost trade-off optimization by using the minimal cut concept. Thomas and Ellis (2001) summarized 6 major causes of construction delay: (1) utilities, (2) differing site conditions, (3) delays in environmental planning and permitting issues, (4) design errors, (5) omissions and changes, and (6) weather.

Stochastic methods are also used in the TCQT analysis. For example, Azaron and Tavakkoli-Moghaddam (2007) used an interactive approach to covert a dynamic PERT into a stochastic network of queues and then to construct a continuous-time Markov chain in the solution of multi-objective time-cost trade-off problems.

By introducing fuzzy numbers for the duration and cost of project tasks, Eshtehardian et al. (2009) proposed an optimization method for finding solutions to time-cost trade-off problems under uncertain conditions. Zhang and Xing (2010) further incorporated fuzzy numbers for project quality measurement and provided solutions to fuzzy time-cost-quality trade-off problems by using the particle swarm optimization (PSO) algorithm.

Research has also been conducted where time, cost, and quality are treated as discrete variables. Tareghian and Taheri (2006) developed three binary integer programming models for optimization of one single objective with bounds on the other two objectives at each time.

Literature has shown different types of models with regard to project quality. Existing models include the cost of quality model (Ereiesleben, 2004; Schiffauerova and Thomson, 2006; Naidu, 2008; and Abdelsalam and Gad, 2009), the quality reliability model (Shi et al., 2009), the quality earned value model, and the time-quality model (Babu and Nalila, 1996; Pollack-Johnson and Mattew, 2006; and Tareghian and Taheri, 2007).

Different modules have also been developed in trade-off models. For example, Senouci and Al-Derham (2008) presented such a model for the scheduling of linear construction projects, which consists of a scheduling module, a cost module, and a multi-objective module.

Time-cost-quality trade-off problems have attracted attention in the construction industry for many years. Frequently used as a set of project management success/performance criteria, time, cost, and quality are almost always listed as controllable objectives by each AEC project team. And thus the three objectives/criteria are sometimes called the Iron Triangle. The mutual dependency and the quantitative trade-off (assuming a higher quality index is better) among the three constraints are obvious: project quality and project time or project cost are usually positively correlated (i.e., requests for increasing project quality will increase the amount of time needed and will also cause in increase in project cost), while time and cost are usually negatively correlated (i.e., a tight/crashed time schedule requires more intensive labor and thus will lead to higher cost and usually a lower quality as well). It remains a puzzle, however, as of how to effectively quantify the three objectives in an appropriate model and then how to solve the model. The significance of such research is to maximize the project value (or in a wider extent, the social welfare) by providing better quality with less time and lower costs. Most of the existing studies, however, were conducted in a deterministic environment, and thus ignored or simplified uncertainties in real construction projects. The fact is that both the variables and objectives in project management decision making are fuzzy due to uncertain underground conditions, non-continual supply of equipment, etc. This gives possibilities for applying fuzzy logic into the tradeoff problems.

Early attempts can be dated back to late 1950s, when Kelley and Walker (1959) first developed the critical path method (CPM), an algorithm for scheduling a set of project activities. Until today it is still the most widely used tool for effective project management. Based on CPM, time-cost trade-off (TCT) analysis, as well as its extensive form, time-cost-quality trade-off (TCQT) optimization, has been conducted in recent years (see Table 2-3). The time-cost trade-off methodology is used to obtain the optimization set of time or cost under the constraint of either a budget (so called "budget problem") or a deadline (so called "deadline problem"), summarized by Brucker et al. (1999). This can be achieved by crashing those activities with more resources on the critical path, and finally a time-cost curve can be constructed over the set of feasible project durations.

In traditional studies on multi-objective engineering optimizations, deterministic values were usually assigned to each activity's time (duration), cost (budget), and quality, and both linear and non-linear programming models were developed with certain assumption of time-cost relationship (Brucker et al., 1999). Though widely used as forecasting tools, these traditional deterministic methods fail to provide the project team with sufficient information about the probability of meeting project goals. Such discrepancy with real engineering practice has long been realized, and thus uncertainty has been gradually introduced into simulation models. For example, efforts have been made on multi-objective optimization under uncertain circumstances. Those include: multi-mode trade-off optimization models; fuzzy logic based multi-objective trade-off optimization models; stochastic optimization models; etc. With the improvement of computers and computing sciences, advanced intelligent algorithms have been adopted to solve the TCQT problem, as listed in Table 2-6.

The difficulty of adding quality into the trade-off analysis is how to quantify project quality. A common strategy is to define each activity's quality in some value in a [0,1] domain and then average them to get the project quality. Obviously, this only has a relative or comparative meaning. Babu and Suresh (1996) were among the first researchers who took project quality into consideration along with TCT optimization in a deterministic CPM network. The inter-related linear programming models developed by Babu and Suresh were evaluated and applied to an actual cement factory construction project by Khang and Myrint (1999). Hegazy (1999) summarized the advantages and drawbacks of different techniques used for TCT analysis, including heuristic methods, mathematical programming models, and genetic algorithms. Peng and Wang (2009) considered renewable resources in the discrete TCT problem and accordingly drew an example of time-cost curve.

Table 2-6 listed most-cited literatures on time-cost-quality trade-off (TCQT) analyses in the past two decades. Typically, the following steps have been taken in existing studies on TCQT analysis: (1) making assumptions of the relationships among activity/project time, cost, and quality; (2) determining the variables; (3) suggesting the theoretical background and framework; (4) developing a TCQT model based on the assumptions and the framework; (5) comparing and selecting the algorithms; and (6) doing (scenario or real) case studies with numerical calculations.

Other related studies provided general forms of multi-objective optimization problems that can cover the elementary analysis of TCQT problems. For example, Konak et al. (2006) summarized the multiple-objective optimization method using genetic algorithms (GAs) from existing studies. The authors compared the components, procedures, applications, advantages and disadvantages of well-known (customized) multi-objective GAs. Xu et al. (2012) took environment impact into account for the trade-off problem. They developed a fuzzy-based adaptive hybrid genetic algorithm for analysis of the discrete trade-off among time, cost, and environment. Zheng and Ng (2005) developed a stochastic time-cost optimization model by integrating the fuzzy sets theory and non-replaceable front with genetic algorithms as a searching mechanism.

The literature indicates that since the early 1960's, various analytical methods have been proposed for TCQT optimization, and examples of these include the heuristic, linear programming, integer programming, and hybrid programming models. Again, one of the key points here is to tailor the assumptions, theories, models, and algorithms to the best need of the underlying question. The proposed dissertation research can provide new customization in the infrastructure engineering field to enrich the body of knowledge in TCQT analysis. In addition, another knowledge gap in existing literature is the missing of incorporation of other key performance indicators. Incorporating other factors, however, will greatly increase the complexity of the trade-off analysis. Therefore, effort should be made in the proposed research to cautiously select the incorporated factors and to give them appropriate mathematical expressions.

Moreover, the project life cycle performance has attracted more and more attention in the 21st century. For example, Jugdev and Müller (2005) argued that project management is perceived as providing only tactical (operational) value and not strategic value if project success is limited to the variables of time, cost, and scope. However, the definition of project success has now shifted from the implementation phase of the project life cycle to an appreciation of success over the project and product life cycle, so that project management can have strategic value when the links to product/service value exist. Assessing the project life cycle performance requires us to consider the series of project phases from its initiation to its closure. In this case, financial constraints in infrastructure engineering projects put great pressure on the project management team. In other words, financial availability has big impact on the project life cycle performance. In many organizations, however, predicting and analyzing the prospective financial performance of the project's product is performed outside of the project (PMBOK, 2013).

Measurement of Subjective Factors

In the trade-off optimization analysis, attributes such as project time and cost are relatively easy to measure. Quantification and measurement of some other attributes, however, remain ambiguously determined. Project quality is an obvious example. Some studies suggested measuring quality subjectively by using a five or seven point scale. A relatively objective way, however, could be the measurement of the degree of conformance to all technical performance specifications (Chan et al., 2002) and to customer satisfaction. Similarly, environmental performance of a given project, also quite subjective, could be measured by the environmental impact assessment score through the application of ISO14000, and by the total number of complaints received during the construction. More accurately, fuzzy sets theory can be applied to deal with such uncertainty associated with linguistic imprecision. The proposed research will add to the knowledge base creative ways of quantifying and optimizing those subjective factors or indicators in the trade-off analysis.

A Possible Fourth Dimension: Sustainability

A recent trend for similar trade-off analysis is to take project life cycle into account. For example, the newest edition of PMBOK® (Fifth Edition, 2013) has included and detailed the contents of the project management life cycle and its related processes, as well as the project life cycle, which is defined as the series of phases that a project passes through from its initiation to its closure. Life cycle assessment is a more appropriate way to tell whether a project is really successful or not. After all, a bridge could not be viewed a successful project if it would collapse in 20 years while its design life were 50 years. Meanwhile, the view of project life cycle (and also, of project management life cycle) echoes the modern concept of sustainable development. However, one of the difficulties of taking sustainability into consideration is to develop a set of criteria with both effectiveness and efficiency. The current strategy usually proposes a rating system and suggests some up-to-date best practices.

To capture the idea of sustainability in the analysis of time-cost-quality trade-off optimization is based on, to some extent, subjective judgments. The concept of Triple Bottom Line (TBL) has gained worldwide acceptance and will be integrated in the research model. The concept of TBL was created by Elkington (1998). He argued that environmental, social and economic dimensions of sustainable development should be taken into consideration by corporations, government organizations and non-government organizations (NGOs). Related to the ideas of corporate social responsibility, TBL requires that corporations pursue a balance in development among economic prosperity, environment protection, and social welfare. Traditionally, profit (or rather, the economic benefit of shareholders) is the bottom line of entrepreneurship. The point of TBL is that a corporation’s ultimate success should be measured not only by the traditional financial bottom line, but also by its social/ethical and environmental performance.

The empirical study conducted by Ebbesen and Hope (2013) indicated disagreement of how to integrate sustainability into time, cost, and quality constraints, and of how to integrate sustainability principles into projects. They suggested sustainable project management as a process to “ensure that projects incorporate sustainability principles throughout the project lifecycle and beyond”. They also summarized several recent models which extend the traditional Iron Triangle. Liu and Frangopol (2005) proposed a framework to formulate the life-cycle maintenance planning of deteriorating bridges as a multi-objective optimization problem. Genetic algorithms (GAs) and Monte Carlo simulation were applied to produce a pool of alternative maintenance solutions for the trade-off among structure condition index, safety index, and life-cycle maintenance cost.

The 1987 World Commission on Environment and Development (WECD) report (later published as a book Our Common Future) defined sustainability as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. In the civil engineering field, American Society of Civil Engineers (ASCE) suggested, as early as in November 1996, such a definition of sustainable development as “the challenge of meeting human needs for natural resources, industrial products, energy, food, transportation, shelter, and effective waste management while conserving and protecting environmental quality and the natural resource base essential for future development”. This requires the 21st-century civil engineer demonstrate an ability to analyze the sustainability of engineered systems and design accordingly.

To incorporate sustainability in the proposed trade-off analysis, however, we have to deal with at least two important things. Firstly, the concept of sustainability is too abstract and too general to be quantified and measured in the analysis, and thus identifying and adding specific, concrete and measurable indicators are of significance. Effort has been made on this issue. For example, Chen et al. (2010) identified sustainable performance criteria, composed of economic, social, and environmental criteria, for construction method selection in concrete buildings. However, there is still a lack of such identification in infrastructure engineering in existing literature, not to mention to incorporate the identified indicators in the trade-off analysis. Secondly, it is generally believed that sustainability increases costs in the short run, but can bring more benefits in the long run. This calls for the application of project life cycle assessment (LCA) and of project life cycle costing (LCC) analysis. Procedures of LCA and LCC have been suggested in existing studies (for example, see Ortiz et al. 2009), but customizing those procedures for the benefit of application in infrastructure engineering remains unsolved. In addition, issues associated with financing in LCA and LCC are often neglected or quite simplified in existing literature. One of the objectives of this dissertation is to bridge the above-mentioned knowledge gap.

Proctor et al. (2012) proposed the Asset Sustainability Index for measurement of critical investment trends of highway infrastructure. Simply put, this index is "a ratio of the amount budgeted for highway infrastructure preservation divided by the amount needed to adequately sustain infrastructure at a targeted condition over the long term".

Finance-based Scheduling

Research has been conducted to obtain a "trade-off" optimization of project management among time, cost, and quality (some scholars also discussed resources, benefits and other factors in their studies). Some studies also included and discussed allocation and leveling of resources. Other than crashing non-critical tasks, speeding up project schedules can sometimes be achieved by investing more labors, using more equipment or higher-efficient (and thus more expensive) equipment, and/or sacrificing some of the quality. Those have been discussed in existing studies.

However, project financing was neglected in most studies. This seems unusual because being short of cash flow is a common problem when project schedule is accelerated.

Chih (2010, p.54) discussed advantages of the NPV-based time-cost trade-off decision system. NPV is straightforward in concept, simple in calculation, widely accepted, and most importantly, provides linkages between project duration and cost. Lucko and Thompson Jr. (2010) pointed out the importance of accurate determination of financing fees (particularly interest) for planning and management of construction project cash flows. They considered construction project cash inflows as a quasi-random function because contractors may undertake several projects of different sizes and activities in parallel subject to different payment terms. Elazouni and Metwally (2005) discussed the feasibility of applying genetic algorithms into a finance-based scheduling model, and compared the model with an integer-programming model developed by Elazouni and Gab-Allah (2004). Both models, especially devised for contractors' bank overdraft strategies, are aimed at searching for a schedule with maximum project profits by minimizing the total project duration under a cash constraint while minimizing financing costs. Ali and Elazouni (2009) integrated cash flow models with CPM/LOB technique to devise financially feasible schedules through GAs technique for projects with repetitive non-serial activities (which feature a uniform repetition of a unit work throughout the project, e.g. multiple similar houses and high-rise buildings comprising similar floors). Elazouni (2009) also discussed the heuristic method for multi-project finance-based scheduling, subject specifically to cash constraints set up by line of credits.

Uncertainty has also been considered in the research. Afshar and Fathi (2009) developed a finance-based scheduling model for construction projects with uncertainties in cost by employing fuzzy multi-objective optimization and the elitist non-dominated sorting genetic algorithm techniques. They used the model to search the non-dominated solutions considering total duration, required credit (specifically, bank lines of credits), and financing cost as three objectives. A time-profit trade-off optimization model, developed by Senouci and El-Rayes (2009), is composed of a scheduling module, a profit module, and a multi-objective module (based on genetic algorithm). The authors detailed the three modules step by step and evaluated the impact of subcontracting option, construction material, crew size, and overtime policy on both construction time and profit.

As a practical application in the engineering projects, Orabi and El-Rayes (2011) discussed the optimization problem about the rehabilitation planning of aging transportation networks, including financial resource allocation, rehabilitation effect measurement, benefit-cost estimation, and tradeoff analysis.

All in all, there has been an increasing need for development of new approaches to model, analyze, and optimize financial constraints and cash flows in infrastructure engineering project management. A revised finance-based TCQT model is developed in this dissertation to help support financial decision-making in maximizing the net present value of a project within the project constraints.

Development of a Finance-Based Model

Integrating scheduling and financing functions of construction project management has become a pressing need and attracted many researchers' interest (Elazouni 2009). This is important because delivering the project within the agreed-upon time and cost and maximizing the project profit are two vital objectives that often determine the project success or failure. Determination of debt structure is critical for both contractors and project owners, as borrowing can temporarily cover the unbalance of cash outflow and inflow but with its financing fees impacting profitability. A trade-off needs to be optimized within the financial constraints that are often faced by the project management team. However, the vast majority of cost-optimization scheduling techniques in project management entirely discarded the financing costs. Finance-based scheduling has been suggested as a tool to minimize project indirect costs, financing costs, and consequently maximize the project profit. The concept of finance-based scheduling achieves the sought-for integration between the functions of scheduling and financing by incorporating financing costs into the project total cost as well as scheduling under cash constraints.

Researchers have developed different finance-based models with different focuses on the project perspectives. For example, models have been developed based on different project types. Kong et al. (2008) established a quantitative model, which uses a conditional credit rating transition matrix to predict default probability and uses Net Present Value (NPV) to estimate the maximum default loss. Their model was based on BOT projects, whose credit risk depends on credit ratings, market data, and financial information. Orabi and El-Rayes (2011) discussed the optimization problem about the rehabilitation planning of aging transportation networks, including financial resource allocation, rehabilitation effect measurement, benefit-cost estimation, and tradeoff analysis. Researchers have also integrated different scheduling techniques in their finance-based models. For example, Ali and Elazouni (2009) integrated cash flow models with CPM/LOB technique to devise financially feasible schedules through GAs technique for projects with repetitive non-serial activities.

Others have proposed a variety of optimization or simulation techniques for the finance-based models. Elazouni and Metwally (2005) discussed the feasibility of applying genetic algorithms into a finance-based scheduling model, and compared the model with an integer-programming model developed by Elazouni and Gab-Allah (2004). Both models, especially devised for contractors' bank overdraft strategies, are aimed at searching for a schedule with maximum project profits by minimizing the total project duration under a cash constraint while minimizing financing costs. Elazouni (2009) also discussed the heuristic method for multi-project finance-based scheduling, subject specifically to cash constraints set up by line of credits. Afshar and Fathi (2009) developed a finance-based scheduling model for construction projects with uncertainties in cost by employing fuzzy multi-objective optimization and the elitist non-dominated sorting genetic algorithm techniques. They used the model to search the non-dominated solutions considering total duration, required credit (specifically, bank lines of credits), and financing cost as three objectives. Lee et al. (2011) developed a stochastic project financing analysis system, integrating simulation-based scheduling and cash-flow analysis as well as incorporating the contract conditions relative to payment considerations. For simplification, however, they did not take into account the effect of interest rate change. Lucko and Thompson Jr. (2010) pointed out the importance of accurate determination of financing fees for planning and management of construction project cash flows. They considered construction project cash inflows as a quasi-random function because contractors may undertake several projects of different sizes and activities in parallel subject to different payment terms.

The above-mentioned studies focused more on the financing needs and cash flow management of contractors. General strategies about the trade-off between financing and other critical project objectives have been missed. However, there has been an increasing need for development of new approaches to model, analyze, and optimize financial constraints and cash flows in infrastructure engineering project management. A revised finance-based TCQT model is developed in this dissertation to help support financial decision-making in maximizing the net present value of a project within the project constraints.

Summary

An infrastructure engineering project is typically a system of people, equipment, materials, and organizations. Good project managers (including civil engineers) must be able to see the project as a whole and drill down into the system and examine the detail of individual parts. This has been widely realized. For example, the *Summit on the Future of Civil Engineering* articulated the global vision for civil engineering in 2025 as “entrusted by society to create a sustainable world and enhance the global quality of life, civil engineers serve competently, collaboratively, and ethically as master builders, environmental stewards, innovators and integrators, managers of risk and uncertainty, and leaders in shaping public (environmental and infrastructure) policy”. The proposed research takes a system view of project management and proposes an integrated infrastructure engineering decision-making procedure accordingly.

After discussion about the current status of infrastructure development in the U.S. as well as related issues of project prioritization and project management, this chapter reviewed the time-cost-quality trade-off problem. Existing TCQT analyses focused on the trade-off in a relatively limited scope, namely, only among time, cost, and quality in the project construction phase. Other critical factors and financial constraints over the project life cycle have been neglected. The proposed research aims to analyze the TCQT problem in infrastructure engineering in a wider and more general view of project life cycle as well as of corporate’s financial constraints.

Table 2-1. Report Card for America's Infrastructure Grading Scales

Category	Assessment Criteria	Grading Scale
• Dams • Drinking water • Hazardous waste • Levees • Solid waste • Wastewater • Aviation • Bridges • Inland waterways • Ports • Rail • Roads • Transit • Public parks and recreation • Schools • Energy	• Capacity • Condition • Funding • Future need • Operation and maintenance • Public safety • Resilience • Innovation	• A (Exceptional): fit for the future • B (Good): adequate for now • C (Mediocre): requires attention • D (Poor): at risk • F (Failing/Critical): unfit for purpose

Source: ASCE (2013)

Table 2-2. U.S. Highway System Development Phases

Time	Emphasis	Achievements
1960~1985	New construction and expansion	Interstate system was completed. Management systems (for pavement, bridge, maintenance, etc.) were introduced.
1985~2000	Performance and expansion	Budgeting, staff resource allocations, outsourcing and streamlining procedures were included in investment decisions.
2000~Present	Maintenance and management	Economics and engineering are strategically integrated. IT and mobile technology are applied.

Source: Summarized from Fwa (2006), pp.17-1

Table 2-3. Definition of Project Management

Source	Organization	Definition / Concept	Other Requirements
A Guide to the Project Management Body of Knowledge (PMBOK® Guide) – Fifth Edition	Project Management Institute, Inc. (2013)	Project management is the application of knowledge, skills, tools, and techniques to project activities to meet the project requirements.	Balance the competing project constraints, which include, but are not limited to: scope, quality, schedule, budget, resources, and risks.
APM Body of Knowledge – Sixth Edition	Association for Project Management (2012)	Project management is the application of processes, methods, knowledge, skills and experience to achieve the project objectives.	A project is usually deemed to be a success if it achieves the objectives according to their acceptance criteria, within an agreed timescale and budget.
Project Management (BS 6079-1: 2010)	BSI (British Standards Institution, 2010)	Project management is planning, monitoring and control of all aspects of a project and the motivation of all those involved in it to achieve the project objectives on time and to the specified cost, quality and performance.	Specification, schedule and cost always have to be bounded to ensure ongoing viability.
ISO 21500: 2012 Guidance on Project Management	International Organization for Standardization (2012)	Project management is the application of methods, tools, techniques and competences to a project. Project management includes the integration of the various phases of the project life cycle. Project management is accomplished through processes.	Delivery as promised, faster delivery, less surprises, and improved customer satisfaction and less rework.
A Guidebook of Project & Program Management for Enterprise Innovation – Revision 3	Project Management Association of Japan (PMAJ, 2005)	Project management is the professional capability to deliver, with due diligence, a project product that fulfills a given mission, by organizing a dedicated project team, effectively combining the most appropriate technical and managerial methods and techniques and devising the most efficient and effective work breakdown and implementation routes.	The objective is to generate specific project deliverables or results that fulfill requirements of project management such as scopes, technology (quality), cost and time, and to achieve profit goals as a business.

Table 2-4. Distinctions Among Some Concepts

Project Success	vs.	Project Management Success
Measured against the overall objectives of the project		Measured against the widespread and traditional measures of performance against cost, time and quality
Success Criteria	vs.	Success Factors
The measures by which success or failure of a project or business will be judged		Those inputs to the management system that lead directly or indirectly to the success of the project or business
Project Success	vs.	Project Performance
Cannot be measured until after the project is completed		Can be measured during the life of the project

Table 2-5. PMI Knowledge Areas of Project Management

Knowledge Area	Utilization
Integration Management	▪ To coordinate various project elements effectively ▪ To identify, define, combine, unify, and coordinate various processes and activities
Scope Management	▪ To ensure all required work is enclosed ▪ To define and control what is and is not included in the project
Time Management	▪ To provide an effective project schedule ▪ To ensure the timely completion of the project
Cost Management	▪ To identify needed resources and maintain budget control
Quality Management	▪ To ensure project functional requirements are met and validated
Human Resource Management	▪ To effectively develop, organize, manage, and lead the project team
Communications Management	▪ To ensure timely, appropriate, effective internal and external communications as well as smooth project information flow
Risk Management	▪ To analyze and control potential risks ▪ To increase the likelihood and impact of positive project events and decrease such of negative project events
Procurement Management	▪ To purchase or acquire necessary resources or results from external sources
Stakeholder Management	▪ To identify stakeholders and analyze their expectations ▪ To manage and control stakeholder engagement

Table 2-6. Literature on TCT or TCQT Trade-off Analyses

Author	Topic	Model	Algorithm
Afshar et al. (2007)	TCQT analysis	Multi-objective optimization model	Multi-objective ant colony optimization
Afshar et al. (2009)	TCT optimization	Multi-objective combinatorial optimization	Non-dominated archiving ant colony
Babu and Suresh (1996)	TCQT analysis	Linear programming model	Linear programming
El-Rayes and Kandil (2005)	TCQT analysis	Multi-objective optimization model	Multi-objective genetic algorithm
Eshtehardian et al. (2009)	Stochastic TCT analysis	Discontinuous and multi-objective fuzzy time-cost model	Multi-objective genetic algorithm
Hegazy (1999)	Construction TCT analysis	Discrete time-cost relationships	Genetic algorithms
Iranmanesh et al. (2008)	TCQT analysis	Pareto optimality model with multi-execution activity mode	Fast Pareto genetic algorithm
Kalhor et al. (2011)	Stochastic TCT optimization	Fuzzy approach	Non-dominated archiving ant colony
Khang and Myint (1999)	TCQT analysis	Linear programming model	Inter-related linear programming
Li and Love (1997)	TCT optimization	Linear programming model	Improved genetic algorithm
Moussourakis and Haksever (2004)	TCT problem	Flexible mixed integer-programming model	Integer programming
Peng and Wang (2009)	TCT problem	Multi-mode resource-constrained discrete time-cost trade-off problem model	Improved genetic algorithm
Pour et al. (2010)	TCQT problem	Multi-mode discrete TCQT model	Novel hybrid genetic algorithm
Pour et al. (2012)	TCQT problem	Discrete TCQT analysis with linguistic variables	Novel hybrid genetic algorithm
Shankar et al. (2011)	Construction TCQT analysis	Discrete decision-making model	Mean risk analysis and stochastic dominance
Yang (2011)	Stochastic TCT analysis	Monte Carlo simulation	Multi-objective particle swarm optimization algorithm
Zhang and Xing (2010)	Construction TCQT analysis	Fuzzy multi-attribute utility model	Particle swarm optimization
Zheng and Mao (2010)	Construction TCQT problem	Multi-objective optimization model	Genetic algorithms
Zheng and Ng (2005)	TCT optimization	Stochastic multi-objective optimization model incorporating fuzzy sets theory and nonreplaceable front	Genetic algorithms

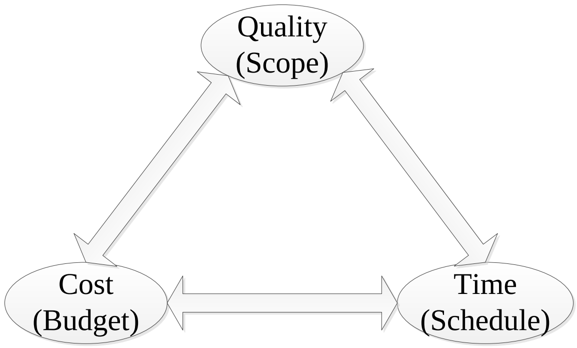


Figure 2-1. The Iron Triangle

CHAPTER 3
METHODOLOGY

Decision-Making Process

This dissertation focuses on the decision-making process in infrastructure development. As Harris (1980) indicated, decision making has two folds of meanings: (1) the study of identifying and choosing alternatives based on the values and preferences of the decision maker; and (2) the process of sufficiently reducing uncertainty and doubt about alternatives to allow a reasonable choice to be made from among them. According to Baker et al. (2001), decision making should start with the identification of decision makers and stakeholders in the decision, reducing the possible disagreement about problem definition, requirements, goals and criteria. Then, a general decision-making process can be divided into the steps indicated in Figure 3-1.

Generally, there are two types of decision-making problems: the Multi-Attribute Decision-Making (MADM) problem and the Multi-Objective Decision-Making (MODM) problem. Both types are easily self-explained. With regard to infrastructure engineering development, MADM is usually applied to project prioritization and evaluation, while MODM can be used for design and alternatives selection. Project owners or sponsors must properly make both types of decisions in order for the infrastructure project to be successful.

Research Framework

For an AEC firm, revenues from projects are the main source of corporate income and profits. Doing projects successfully is the foundation of a successful firm. Continual project success, however, depends largely on excellent project management practice. On the one hand, successful projects can provide the firm with good experience and enhance the overall reputation of the firm; on the other hand, the competitiveness and core competence enable the firm to win more successful projects. This is a positive feedback (Figure 3-2). The firm can increase the probability for project success through best project management practices, as well as by providing financial support, key resources (such as human and equipment resources), appropriate incentives, and appropriate organizational culture.

Existing studies have been conducted separately on such project management issues as critical success factors, sustainability indicators, TCQT analysis, and finance-based scheduling techniques. They have focused more on local optimization. The proposed research, however, suggests a system view on project management decision-making procedures with identification of key indicators and sustainability criteria on project success and with integration of those indicators in a more general and realistic TCQT optimization model over the project life cycle. The proposed research focuses more on global optimization.

The basic time-cost-quality trade-off (TCQT) optimization process proposed in the research will provide the project management team of the contractor with direct guidance on optimal construction planning and scheduling. Based on existing studies on TCQT problems, the incorporation of other critical factors in the research will greatly expand the existing frameworks and methodologies and enrich the body of knowledge in the multi-objective decision-making analysis. The integration of financing function and sustainability indicators over the whole project life cycle will enlarge the application of the proposed model and benefit a great many of the project stakeholders (e.g. the project owner, the government agency, and the project product end user) involved in the infrastructure engineering project. In other words, the proposed research aims to enhance the integrated decision-making procedure for different project stakeholders in the infrastructure engineering field.

This dissertation intends to first identify critical success factors (CSFs) and key performance indicators (KPIs) for project success and project management success. These criteria are inputted in the proposed project prioritization model. Models for trade-off among those factors or indicators will then be developed to optimize life cycle project management decision making processes. Financial constraints over the project life cycle will be incorporated in the model to develop financially feasible schedules with considerations of project sustainability objectives through the application of time value of money, cash flow management, and life cycle costing techniques. Fuzzy sets theory will also be employed to model project uncertainties that have often been met in the infrastructure engineering field. Common advanced intelligent algorithms will be summarized and a new algorithm for the research model will be proposed to provide solutions to the extensive TCQT optimization problem. An Excel and VBA based programming will finally be provided for the application of the proposed models. The research framework is demonstrated in Figure 3-3.

Identification of CSFs and KPIs for Project Management

Literature review indicates that the following four methodologies have often been selected for analysis of CSFs and KPIs: (1) Factor Analysis; (2) ANOVA; (3) AHP; and (4) Delphi Method. Some researchers have also performed regression analysis and case study on comparison of a variety of factors. Different mathematical tools have further been integrated in the analysis such as Fuzzy Delphi and Fuzzy AHP.

There are plenty of studies and papers on project success factors and successful project management criteria. Surveys, interviews, investigations, and other qualitative or quantitative technique have been widely used as research methods for such studies. Although different results have been obtained, some factors are extensively accepted and most cited. Therefore, a meta-analysis can be conducted to find out those factors that are often concluded.

The terminology of meta-analysis was coined by Glass (1976) with the concept of “the analysis of analyses”, referring to the statistical synthesis of results from a series of studies

(Borenstein et al. 2009). Though widely applied to biological, psychological, medical, and social sciences, meta-analysis has not been used quite often in the civil engineering industry. Kenley (1998) discussed the possible use of meta-analysis in construction management research, taking two case studies, meta-analysis of wasted time and meta-analysis of the time-cost relationship, for examples. Kenley suggested that meta-analysis should form a critical component of the research effort in the construction management research. Melo et al. (2013) conducted a meta-analysis to investigate the output elasticity of transport infrastructure in different countries. Separate studies on CSFs and KPIs for project management have been accumulated in recent decades. This gives room for the application of meta-analysis to summarize the effectiveness of those factors/indicators.

Guidelines were summarized in the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) Statement in 2009, which consists of a 27-item checklist and a four-phase flow diagram, aiming to help authors improve the reporting of systematic reviews and meta-analyses. The guidelines are reproduced here in Figure 3-4.

Research Methodology

The first model proposed in the dissertation is a project prioritization model, which composes multi-attribute decision-making techniques to objectively rank potential projects for decision-makers to prioritize projects based on the criteria obtained as well as the project performance measures. This process provides key assurance for project time-cost-quality trade-off optimization at the very beginning of the project life cycle.

The original concept of the time-cost trade-off methodology is used to reduce the project duration incrementally with the smallest associated increase in incremental cost (Gido and Clemens, 2003, p.218). This methodology is based on the assumptions that each activity has both a normal and a crash duration and cost estimates. It also assumes linear relationship between time and cost with an activity's duration being incrementally accelerated by applying more resources.

Integration of sustainability into the time-cost-quality trade-off analysis has at least two aspects of influences in the long run: firstly, a sustainable project requires investing some capitals for the improvement of the project and thus increases the total costs; and secondly, sustainability should be enclosed as one criterion for project quality. The influence of sustainability on project cost and quality will, of course, has further impact on project duration. Life-cycle costing, concerned with the interest rate, the borrowing cost, inflation, and other financial factors, is a methodology of sustainability calculation that combines both construction costs and operating costs in a model to get the net present value.

Incorporation of financial constraints is critical because infrastructure engineering projects are usually capital-intensive businesses. The time value of money has to be considered since infrastructure engineering construction often takes a long time to complete, not to mention that the much longer project life cycle should also be considered. Cash flows of the projects must be optimized to achieve the project objectives. Therefore, a finance-based model requires the application of the net present value method as well as the application of other advanced financial techniques.

Fuzzy sets theory has been widely used and accepted for modeling of project scheduling uncertainty in recent decades. Although fuzzy sets are often used to reduce the bias of ambiguous statements, the membership function of fuzzy numbers is usually defined by subjective judgment. However, researchers have claimed that fuzzy sets theory is more appropriate to model TCT or TCQT problems, given a good number of uncertain conditions in construction engineering and management. An appropriate membership function of the fuzzy sets will be suggested in the research to closely reflect decision-making processes in the infrastructure engineering practice. The fuzzy logic will then further integrated into the proposed model.

Genetic Algorithm, with growing popularity in applications in the civil engineering field, is one of the major of evolutionary computing methods and has been proven to be very powerful in solving combinational problems. As a representative of advanced intelligent algorithms, the genetic algorithm will be compared with other algorithms, and one or more algorithms will be chosen for this research to provide solutions to the proposed model.

As a last step, an Excel spreadsheet will be developed for calculation of the proposed model. As an application, case studies will be conducted to testify the effectiveness and the efficiency of the finance-based fuzzy time-cost-quality trade-off optimization model over the project life cycle. Comparisons with other existing models will also be made to verify if the proposed model can improve the integrated infrastructure engineering decision-making procedure.

Summary

In this chapter, the decision-making process has been reviewed. Based on specific decision-making features, a research framework is proposed along with innovative research methodology. Two integrated models, project prioritization model and project TCQT trade-off model, have been proposed. The following chapters will discuss in detail the proposed models as well as their applications.

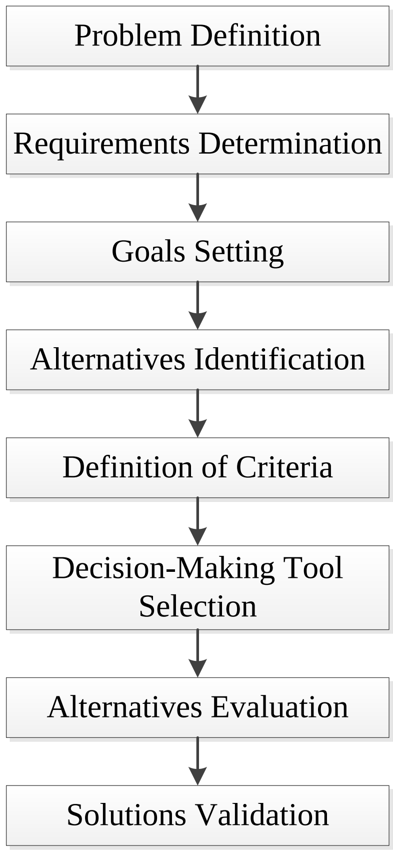


Figure 3-1. Decision-Making Process

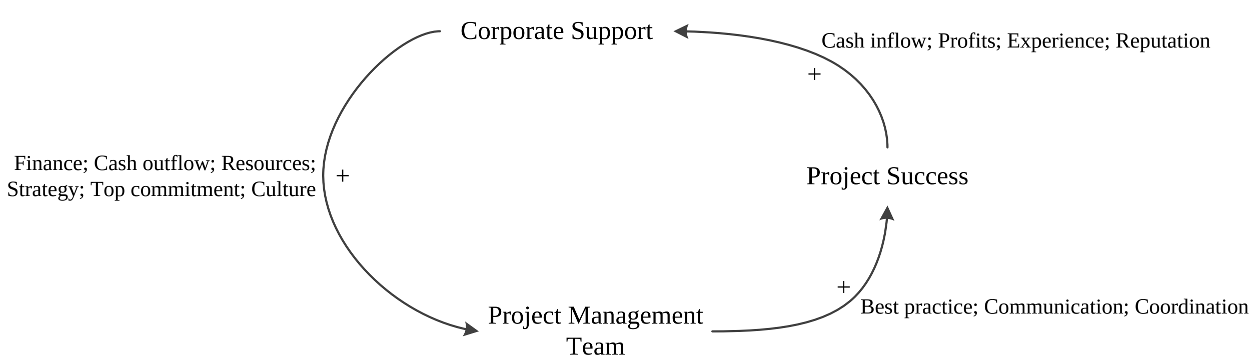


Figure 3-2. Positive Feedback in an AEC Firm

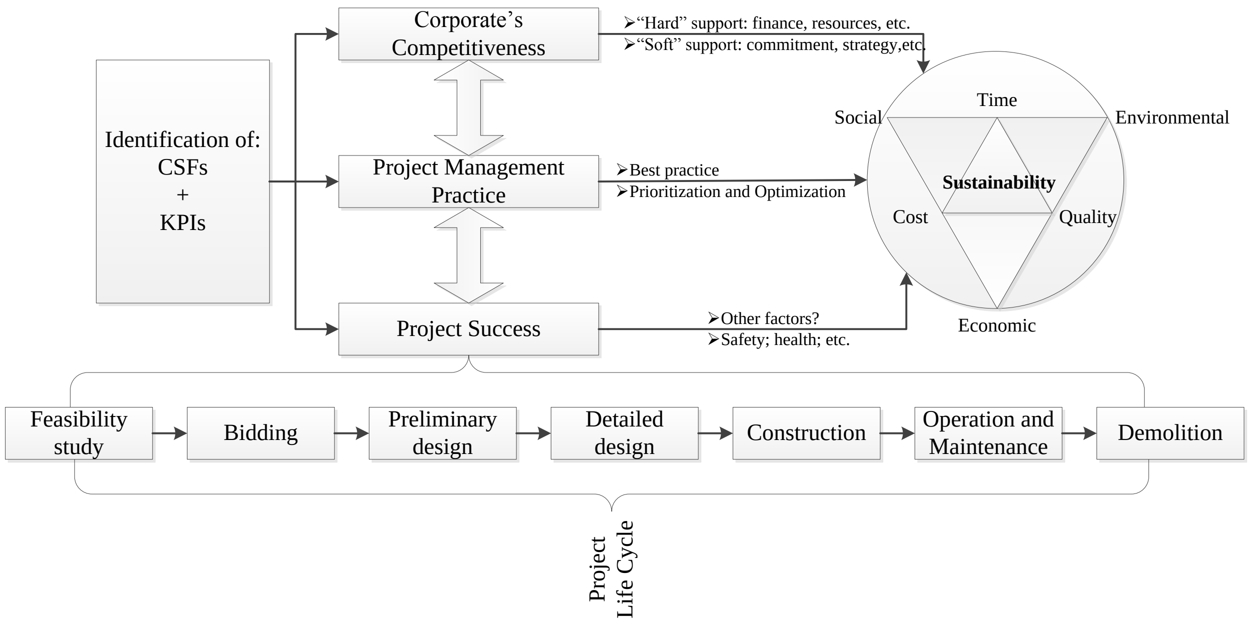


Figure 3-3. Research Framework

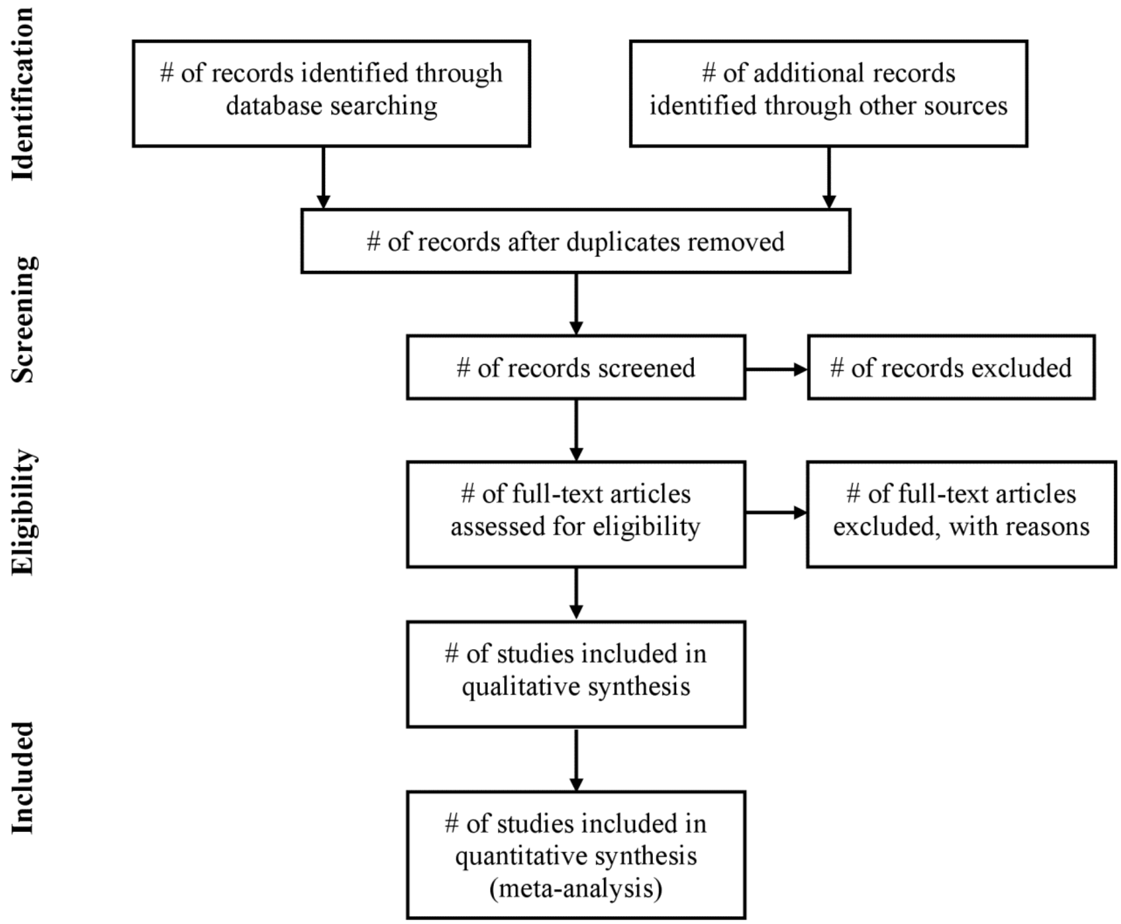


Figure 3-4. Guidelines of Meta-Analyses

(Source: Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009). Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *Annals of internal medicine*, *151*(4), 264-269.)

CHAPTER 4
THEORY ON MULTI-CRITERIA DECISION-MAKING

Decision-making refers to the process of comparing, ranking, prioritizing, or selecting possible solutions from all the available alternatives in order to achieve optimal results. The alternatives usually have multiple attributes, while the results are expected to meet a single goal or multiple goals. The engineering processes have long been integrated with the decision-making processes, from prioritization of potential projects at the very beginning of the planning phase to determination of labors and resources at the construction phase. Generally, decision theory articulates the following key elements of decision-making processes:

- *Alternatives*: identifying all viable options or choices
- *Attributes*: characterizing the conditions and performance of alternatives
- *Objectives*: indicating expectations on the outcomes
- *Values*: quantifying the results of selected alternatives

Single Objective Optimization Model

In a typical single objective optimization model, the Benefit-Cost Analysis (BCA) is usually conducted to compare the costs and risks with benefits and rewards of alternatives for program evaluation. This analysis method involves determination of costs and benefits, assignment of monetary values to both of them, and comparison of the two. It is a relatively simple and straightforward tool for go/no-go decision making in investment and project selection. It is widely used by governments and other organizations, e.g., U.S. Army and California Department of Transportation, both of which have published guides on cost-benefit analysis. The Economic Analysis Branch of California Department of Transportation has further developed a PC-based life-cycle benefit-cost spreadsheet model of analysis of highway construction and operational improvement projects (Figure 4-1). FHWA has also developed a tool for operations benefit/cost analysis (Figure 4-2). In Florida, a Benefit-Cost Analysis

Template is suggested for roadway design (Figure 4-3). Many of those tools created spreadsheets using Microsoft Excel. In Table 4-1, a BCA worksheet is created. However, BCA has limitation on determination of monetary values of project quality and other long-term objectives. In Table 4-2, common BCA tools that have been utilized in the United States are summarized.

Note that when converting both benefits and costs to monetized values, we shall decide which type of dollars to use: constant dollars or current dollars. Constant dollars represent the purchasing power of the dollars in a specific year (i.e., base year). In other words, by using constant dollars the inflation effect has been removed, and thus real interest rates are used for calculation of discounted cash flows. Current dollars, on the other hand, are nominal dollars; they reflect the purchasing power of the dollars in the future. The link between constant dollars and current dollars is inflation.

General Multi-Criteria Optimization Model

Instead of meeting only one single goal, in most decision-making processes, decision-makers must choose from all available *alternatives*, based on a set of judgment *criteria* and a set of decision *attributes*, a possible course of action that will optimize a set of different *objectives* (Hwang and Masud, 1979). Concepts of alternatives, attributes, criteria, and objectives are self-explained, although some scholars (e.g., Hwang and Masud, 1979) provided definitions of them. A multi-criteria decision-making problem with m alternatives and n criteria can be presented in a matrix format as follows:

$$D = \begin{array}{c|c} & \overline{C_1(w_1), C_2(w_2), \cdots, C_n(w_n)} \\ \begin{array}{c} A_1 \\ A_2 \\ \vdots \\ A_m \end{array} & \begin{pmatrix} r_{11} & r_{12} & \cdots r_{1n} \\ r_{21} & r_{22} & \cdots r_{2n} \\ \vdots & \vdots & \ddots \\ r_{m1} & r_{m2} & \cdots r_{mn} \end{pmatrix} \end{array} \qquad (4\text{-}1)$$

Where: $A = (A_1, A_2, \cdots, A_m)$ is the feasible alternatives set; $C = (C_1, C_2, \cdots, C_n)$ is the evaluation criteria set; $w = (w_1, w_2, \cdots, w_n)$ is the criterion weight set; and $r = (r_{ij})$ is the performance rating set. The multi-criteria optimization then becomes a procedure to find the best or optimal alternative among the feasible alternatives set based on evaluation criteria and relative weights.

Whatever method is used, the process of solving such multi-criteria decision-making (MCDM) problems involves five major steps:

- Selection of decision variables, judgment criteria, and alternatives
- Construction of decision matrix
- Normalization of decision matrix
- Determination of criteria weights
- Prioritization of all alternatives

Final decisions can be made according to the results obtained from the above process.

Multi-Criteria Decision Analysis (MCDA) methods can be categorized in different ways based on different factors: constrained vs. unconstrained; linear vs. nonlinear; continuous vs. discrete; deterministic vs. stochastic; and single objective vs. multi-objective etc. For example, in discrete MCDA, criteria (either objectives or attributes) are countable in number and are well defined; while in continuous MCDA, mathematical programming is applied to functions that reflect multiple criteria. A common way for MCDA problems classification is to categorize them as either Multi-Attribute Decision-Making (MADM) problems or Multi-Objective Decision-Making (MODM) problems. Both categories are easily self-explained. Hwang and Yoon (1981) summarized the contrast of the features between the two. Simply put, MADM is usually applied to project prioritization and evaluation, while MODM can be used for design and alternative selection.

Multi-Objective Decision-Making Optimization

General Form

In a typical multi-objective decision-making problem, the decision-maker hopes to achieve more than one goal in selecting alternative components while satisfying the constraints and conditions that have been defined. Mathematically, such problems can be represented as:

$$y^* = f(x^*) = \max_{x \in R} f_i(x) = \max_{x \in R} [f_1(x), f_2(x), \ldots, f_k(x)]^T \tag{4-2}$$

Subject to: $x \in R = \{x | g_j(x) \le 0\},\ j = 1, 2, \ldots m$

Where: x is an n-dimensional decision variable vector. For a feasible solution of the *i*-th decision variable, x_i^*, $y_i^* = f_i^*(x)$ is an optimal value for the *i*-th objective among the *k* objectives under *m* constraints. If some objective function is to be minimized, it is equivalent to maximize its negative.

In multi-objective decision-making optimization, an optimal solution set usually does not exist that maximizes all objective functions at the same time, and thus Pareto optimal solutions are developed. When the Pareto optimal frontier is reached or approximated, any improvement in one objective will result in the worsening of at least one other objective. The final suggested alternative is then selected from the Pareto solution that possesses the most desirable trade-off properties.

One of the traditional solutions to multi-objective optimization problems first decompose the multi-objective optimization problem into a series of single-objective optimization problems and then use the solution to the preceding problem as a new constraint for the succeeding problem. The order for solving those sub-problems is based on the relative importance of each objective. Therefore, the original problem has now been decomposed as the following problem sets.

$$
\begin{aligned}
&\mathrm{P}1: \max(or \min) f_1(x) \\
&\mathrm{P}2: \max(or \min) f_2(x) \\
&\ldots \\
&\mathrm{P}n: \max(or \min) f_n(x)
\end{aligned}
\tag{4-3}
$$

Subject to $f_i(x) = f_i(x^i)$, $i = 1, 2, ..., n-1$

The Weighted Sum Method

Another approach elicits decision-maker preferences between hypothetical alternatives using multi-criteria trade-offs in order to properly aggregate the attributes into a single criterion. In this way additive objective functions are constructed. In general, the process can be formulated as follows:

1. Choose appropriate weights, $w_i(i = 1, 2, ..., m)$, for *m* objectives, $f_i(x)$.
2. Maximize $V = \sum_{i=1}^{m} w_i f_i(x)$ (4-4)
3. Subject to $\sum_{i=1}^{m} w_i = 1$

Where *V* = value function for alternative *i*, *w* = weight for objectives, $w_i \geq 0$.

The key to additive objective functions development is to determine appropriate weights for different objectives according to their relative importance. Ideally, the decision-maker has the knowledge and ability to assign weights of each objective based on the intrinsic feature of the problem. In practical use, however, the normalization of objectives is often applied to get a Pareto optimal solution. A common technique involves in use of normalization. Normalization makes the value of demand for each resource required by each task between [0, 1] and thus demand differences among tasks can be compared. Weights are then determined based on the degree of importance of each resource, or relative weights of each resource can be determined by AHP. However, in this approach, attribute weights are based on decision-makers' preferences, and thus selection of attribute weights will have significant impact on the optimization results. In other words, it might be difficult to obtain satisfied Pareto optimality for decision-makers. Pareto optimal solutions form a Pareto frontier, where any improvement in one objective has to be traded off by degrading the level of another objective.

Additive objective functions can also be constructed for multi-objective decision-making problems. In this case, three objectives are included: project quality (*Q*) is maximized, while project time (*T*) and cost (*C*) are minimized. If we use the additive objective function that combines all the objectives into a single objective function and that is to be minimized, the additive objective function (*Z*) is:

$$\min Z = r_T T + r_C C - r_Q Q \tag{4-5}$$

Where r_i is the relative weights of the project objectives (i.e., project time, cost, and quality, respectively). Determination of the relative weights relies on different calculation approaches. Common methods include:

Trade-off evaluation between pairs of objectives may also be conducted. For example, if two days increase in project time can be compensated by one unit gain in project quality, then we can determine that the relative weight of project time is 1 and the relative weight of project quality is 2.

Sensitivity analysis can be enclosed as a powerful tool. This method aims to find the ranges of optimality through development of sensitivity tables for the relative weights for which the optimal solution does not change.

Another widely-used practice for MODM optimization is through the introduction of utility theory. Utility theory can be applied to prioritizing the development and construction of infrastructure engineering projects with multiple optimization objectives (mainly with trade-off among project time, cost, and quality during the whole project life cycle). A value is assigned to the utility of a project and can be expressed as:

$$U(X) = \sum_{i} \beta_i U_i(X) \tag{4-6}$$

Where: $U(X)$ = Overall value of the utility for Project *X*; $U_i(X)$ = The utility value for Index *i* of Project *X*; and β_i = The weight of the Index *i*.

After the development of different utility functions and the assignment of the utility value and the weight for each index, the potential alternatives can be prioritized based on their overall utility values.

Specifically, when taking into consideration project constraints or boundary with regard to project time, cost, and quality, a multi-objective optimization problem can be formulated as follows:

Objective: $$\max U(x) = \frac{1}{K}\left\{\prod_{i=1}^{n}[k_i u_i h_i(x_1, x_2, ...x_m) + 1] - 1\right\} \tag{4-7}$$

Constraints: $y_i = h_i(x_1, x_2, ..., x_m)$

Time: $y_T^- \le h_T(x_1, x_2, ..., x_m) \le y_T^+$

Cost: $y_C^- \le h_C(x_1, x_2, ..., x_m) \le y_C^+$

Quality: $y_Q^- \le h_Q(x_1, x_2, ..., x_m) \le y_Q^+$

Where: $U(x)$ - Utility function; x - Decision variables; K - Normalizing parameter; y - Project objectives; $h(x)$ - Relationships between decision variables and project objectives.

At a maximum point, the partial derivatives of U must be zero:

$$\frac{\partial U}{\partial x_i} = 0 \tag{4-8}$$

With the appearance of constraints, Lagrange multipliers can be introduced for making a system of equal equations and unknowns and thus the system can be solved.

Generally speaking, multi-objective decision-making problems have been widely studied. Whichever method is used, the solution process typically includes: (1) normalization of decision-making matrix, (2) determination of criteria weights, and (3) prioritization of all alternative solutions.

Multi-Attribute Decision-Making Optimization

General Form

Given a set of plans P_1, P_2, …, P_n, each plan has its own attributes A_1, A_2, …, A_m with the weights w_1, w_2, …, w_m, respectively, where w_i confirms to the condition of normalization: $\sum_{i=1}^{m} w_i = 1$. The decision-making goal is to obtain the "best" solution among the set of plans, namely, P_{max}. The solution can be expressed as a matrix below:

$$P_{\max} = \begin{pmatrix} a_{11} & a_{12} \cdots & a_{1n} \\ a_{21} & a_{22} \cdots & a_{2n} \\ \vdots & \vdots & \vdots \\ a_{m1} & \cdots\cdots\cdots\cdots & a_{mn} \end{pmatrix} = (x_{ij})_{m \times n} \tag{4-9}$$

where a_{ij} is the value of the j-th alternative on the i-th index.

Theoretically, we hope to find an optimal solution as a representative of best solutions. A unique optimal solution does not usually exist, however, in solving multi-objective optimization problems, because we have to make trade-offs among those multiple conflicting objectives. Usually, we can only help state the preferences over different objectives and attributes, and provide the decision maker with relevant information and priority suggestions. Thus the following possible solutions are sought for:

Non-dominated Solution: A solution S_1 is dominated and thus should be eliminated if another solution is at least as good as S_1 with respect to every criterion. The remaining are non-dominated solutions for final selection once all the dominated solutions are removed.

Efficient Solution: A solution is said to be efficient (or, Pareto optimal) if there does not exist another solution such that the utility value (or other critical performance value) is larger than the utility value provided by the efficient solution. Accordingly, the set of all efficient solutions is called an efficient frontier.

Preferred Solution: In order to get a preferred solution, multi-attribute utility functions are usually developed to identify the most preferred alternative of a decision maker who has to trade off certain criteria for others.

Satisfied Solution: A satisfied solution provides the decision maker with results that meet the decision maker's requirement for each attribute level.

Ideal Solution: A solution is said to reach the (positive) *ideal point* if it provides the maximum for maximization problems and the minimum for minimization problems of each objective function. On the contrary, a negative ideal solution, or *nadir point*, provides the minimum for maximization problems and the maximum for minimization problems of each object function among the points in the non-dominated set. Therefore, the ideal solution can be expressed as:

$$A^* = (C_1^*, C_2^*, \cdots, C_m^*) \tag{4-10}$$

Where: $C_i^* = \max_i U_i(x_{ij}),\ j = 1, 2, \cdots n; U_i(\bullet)$ is the utility function of the *i*-th attribute.

On the contrary, the negative-ideal solution can be expressed as:

$$A^- = (C_1^-, C_2^-, \cdots, C_m^-) \tag{4-11}$$

Where: $C_i^- = \min_i U_i(x_{ij}),\ j = 1, 2, \cdots n.$

The ideal solution is infeasible in most cases, and thus the concept of a feasible Compromise Solution is generated, the solution that is closest to the ideal solution or farthest to the negative-ideal solution. Zavadskas et. al (2006) provided a method for evaluating the accuracy of TOPSIS ranking in multi-criteria decisions.

Quantification and Conversion of Criteria

Both qualitative and quantitative criteria are common in multi-objective optimization problems. Quantitative criteria, as its name indicates, can be measured objectively. Examples are distance, volume, velocity, etc. Qualitative criteria, on the contrary, cannot be easily measured in an objective way. Examples are color, customer satisfactory, fairness, truth, etc. As one of the oldest methods of measuring subjective variables, bipolar scaling is still popular and widely used, which establishes concepts that are opposite of one another, with degrees or steps between extreme poles (McCroskey and Richmond, 1989). When developing a bipolar scale we need to ask what (to be measured), how many (to be measured), and what scale (to be used). The order of the scale values can be different, depending on whether the criteria (attributes) are related to benefits or costs (Figure 4-4). Simply put, we assign the largest number to those that bring the best/optimum results, and the smallest number to those that bring the worst/permimum results. Accordingly, the midpoint represents the breakpoint between favorable values and unfavorable values and thus forms the basis for calibration. The bipolar scale assignment is obviously arbitrary, and thus other quantification approaches of fuzzy attributes should also be considered. Normalization is another widely used approach.

On the other hand, normalization or standardization is often applied to decision criteria, as different criteria are usually measured in different units. Normalization is especially necessary for some decision-making processes such as maximax, maximin, and simple additive weighting. Commonly-used normalization methods include:

1. Normalization based on maximum or minimum values. This is the simplest normalization method in which the original value of each element is compared with the maximum or

minimum value of all elements, depending on whether the attribute relates to benefit or cost. This normalization process can be expressed as:

For benefit attribute: $$y_{ij} = \frac{x_{ij}}{\max_i (x_{ij})} \tag{4-12}$$

For cost attribute: $$y_{ij} = \frac{\min_i (x_{ij})}{x_{ij}} \tag{4-13}$$

2. Normalization based on distance. This method uses the concept of distance as the denominator and has the following expression:

$$y_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{n} x_{ij}^2}} \tag{4-14}$$

3. Normalization based on the difference between the maximum value and the minimum value.

For benefits-related criteria: $$r_{ij} = \frac{x_{ij} - \min\limits_j x_{ij}}{\max\limits_j x_{ij} - \min\limits_j x_{ij}} \tag{4-15}$$

For costs-related criteria: $$r_{ij} = \frac{\max\limits_j x_{ij} - x_{ij}}{\max\limits_j x_{ij} - \min\limits_j x_{ij}} \tag{4-16}$$

Fuzzy numbers can also be used in the above calculation.

Determination of Criteria Weights

Determination of criteria weights is both necessary and important, because good solution to multi-objective optimization problems also depends on the proper selection of weights and utility functions to reflect the decision-maker's preferences. In practice, however, it is not easy to accurately assign weights to the selected criteria. This is due to: (1) different views of decision-makers on the criteria; (2) unequal impacts of the criteria on the decision-making process; and (3) different liabilities of the criteria. Therefore, weights need to be assigned to different criteria to catch their relative importance.

Determination of criteria weights lies in two major categories: subjective assignments and objective assignments. The former technique uses data collected from an expert system, in which the experts make subjective judgments and given their opinions on criteria weights accordingly. A typical example of subjective assignments is the Delphi method. The latter technique gathers data collected from the real practice. Common methods of objective assignments include Principal Components Analysis and Cluster Analysis.

Analytical Hierarchy Process

First developed by Saaty (1990), the Analytical Hierarchy Process (AHP) has been widely used and been accepted as a popular system analysis tool since then. One major advantage of AHP is the integration of quantitative analysis with qualitative analysis for solving multi-criteria optimization problems. In general, the process includes five steps: (1) create a hierarchy structure; (2) construct a judgment matrix; (3) compare decision elements in a pairwise manner; (4) assign relative weights to decision criteria; (5) check the consistency of the judgments; and (6) aggregate the relative weights to calculate alternative ranks. Consistency check is often neglected in practical use, but it actually is important in a way that understanding of the consistency relates the relationship and the magnitude of differences with various decisions (Tam et al., 2006). The steps of the process follow.

Step 1: create a hierarchy structure

The first step in the AHP is to form the hierarchy of the decision-making problem in terms of an overall objective, aspects and criteria (or criteria and sub-criteria), and different alternatives. The AHP model is structured in such a hierarchical way that the same assessment technique is used at each node of the hierarchy (Figure 4-5).

Steps 2 and 3: construct a judgment matrix and make pairwise comparisons

System analysis is based on information. The information collected for the AHP is the decision-maker's subjective judgments on relative importance of elements. These judgments are represented with numbers and thus form a judgment matrix. Constructing a judgment matrix is critical in the AHP. Assume Element A_k in Level *A* is related with Elements $B_1, B_2, \ldots, B_n$ in Level *B*, a judgment matrix can be developed in Table 4-3.

In Table 4-3, b_{ij} gives the relative importance or preference of B_i over B_j for Element A_k and is usually assigned values of 1, 2, 3, …, 9 (i.e., employs a scale with values from 1 to 9 to designate the relative preference of one element over another) according to their relative importance, and their reciprocals are used for inverse comparisons.

$b_{ij}=1$: B_i and B_j are equally preferred (i.e., they have equal importance);

$b_{ij} = 3$: B_i is moderately preferred over B_j (i.e., B_i is moderately favored);

$b_{ij} = 5$: B_i is strongly preferred over B_j (i.e., B_i is strongly favored);

$b_{ij} = 7$: B_i is very strongly preferred over B_j (i.e., B_i is clearly dominant);

$b_{ij} = 9$: B_i is extremely preferred over B_j (i.e., B_i is super dominant).

In the AHP, a judgment matrix is suggested to meet the following two rules:

$b_{ii} = 1$ and $b_{ij} = \frac{1}{b_{ji}} (i, j = 1, 2, ..., n)$ [2]

Therefore, we only need to assign values to $\frac{n(n-1)}{2}$ elements for a $n \times n$ judgment matrix. The matrix of pairwise comparison is so constructed that the degrees of the decision-

---

[2] In this way the consistency condition is given by $b_{ik} = b_{ij} b_{jk}, b_{ij} \in [0, +\infty]$. Another way for pairwise comparison is to assign values to $b_{ij} \in [-\infty, +\infty]$ for representation of preference difference between Criteria *i* and *j*. Then the condition of reciprocity is $b_{ji} = -b_{ij}$ and the consistency condition is given by $b_{ik} = b_{ij} + b_{jk}$. See Cavallo and D'Apuzzo (2010), accessed at: http://www.researchgate.net/profile/Bice_Cavallo/publication/239920716_A_general_measure_of_consistency_for_pairwise_comparison_matrices/links/00b4952e6d830d78b0000000.pdf

maker's preference is represented between individual pairs of alternatives. This is essentially the same if we construct a matrix of pairwise comparisons for the weight of the alternative set $A = \{A_1, A_2, ..., A_n\}$:

$$W = \{w_i / w_j\} = \begin{pmatrix} w_1/w_1 & w_1/w_2 & \cdots w_1/w_n \\ w_2/w_1 & w_2/w_2 & \cdots w_2/w_n \\ \vdots & \vdots & \vdots \\ w_n/w_1 & w_n/w_2 & \cdots w_n/w_n \end{pmatrix} = \begin{pmatrix} 1 & w_1/w_2 & \cdots w_1/w_n \\ w_2/w_1 & 1 & \cdots w_2/w_n \\ \vdots & \vdots & \ddots \\ w_n/w_1 & w_n/w_2 & \cdots 1 \end{pmatrix} \qquad (4\text{-}17)$$

Step 4: assign relative weights to decision criteria

This step aims to assign weights to all the elements in a specific level relative to the level above. It is essentially a problem of computing the judgment matrix's eigenvalues and eigenvectors, which are used by the AHP to calculate weights of aspects, criteria and sub-criteria, and alternatives for each factor based on the pairwise comparisons. A simple weighted average is then used to determine final alternative weights. Mathematically, for the judgment matrix B, we calculate eigenvalues and eigenvectors that satisfy:

$$BW = \lambda_{\max} W \qquad (4\text{-}18)$$

Where: $\lambda_{\max}$ is the maximum eigenvalue of matrix *B*, and *W* is the corresponding normalized eigenvector. The element of *W*, or w_i, is the relative weight.

When three or more items are being compared, it is important to measure the consistency of judgments. For example, if Alternative A costs two times of Alternative B and six times of Alternative C, the perfect consistency requires that Alternative B cost three times of Alternative C. Mathematically, Define the Consistency Index (*CI*) as:

$$CI = \frac{\lambda_{\max} - n}{n-1} \qquad (4\text{-}19)$$

Obviously, $CI = 0$ if the judgment matrix has perfect consistency. The consistency becomes weaker as $\lambda_{\max} - n$ (and thus *CI*) gets bigger. Therefore, we compare the *CI* with the average Random Consistency Index (*RCI*). For matrix of order 1~10, the *RCI* is listed in Table 4-4.

Define the Consistency Ratio (*CR*) as:

$$CR = \frac{CI}{RCI} \tag{4-20}$$

When $CR < 0.10$ we consider the judgment matrix to be adequately consistent (Saaty, 1980). Otherwise we may need to improve the judgments until $CR < 0.10$ is satisfied.[3]

Step 5: aggregate the relative weights to calculate alternative ranks

Aggregation of ranking all levels needs to be done from upper levels to lower levels. Assume the ranking for all the elements in the upper level, A_1, A_2, …, A_m is completed and the weights are a_1, a_2, …, a_m, respectively. Then correspondingly, for elements in the current level, B_1, B_2, …, B_n, the ranking result is:

$b_1^i, b_2^i, ..., b_n^i$ with respect to a_i.

Further assume that if B_j is irrelevant to A_i then $b_j^i = 0$. Now we can get the aggregation of ranking as follows (Table 4-5).

Obviously, the following condition is satisfied:

$$\sum_{j=1}^{n} \sum_{i=1}^{m} a_i b_j^i = 1 \tag{4-21}$$

Similarly, the consistency of the judgment matrix should be checked using the following equations:

[3] In many cases, we will need to go back to the decision makers and repeat the above-mentioned steps in order to get corrected preference statements.

$$CI = \sum_{i=1}^{m} a_i CI_i \tag{4-22}$$

$$RI = \sum_{i=1}^{m} a_i RI_i \tag{4-23}$$

$$CR = \frac{CI}{RI} \tag{4-24}$$

Where CI_i and RI_i are referred to a_i in Level B. The consistency requirement is satisfied if $CR \le 0.1$.

Entropy Weight

In the AHP method and other similar evaluation methods, determination of criteria weights is critical. One issue about the weight assignment is that the calculation contains only the information of the individual indicator and thus ignores the relationship among other objectives. The entropy method has been proposed to solve such problems (Zou et al., 2006) because the entropy weight objectively reflects the original data in a more comprehensive way. Suppose there are *m* indicators and *n* alternative objects; the entropy of the *i*th indicator is defined as

$$E_i = -k \sum_{j=1}^{n} f_{ij} \ln f_{ij}, i = 1, 2, ..., m \tag{4-25}$$

Where k is a positive constant and thus $0 \le E_i \le 1$.

Where: $f_{ij} = \dfrac{r_{ij}}{\sum_{j=1}^{n} r_{ij}}$ and $k = \dfrac{1}{\ln n}$.

Further, the entropy weight of the *i*th indicator is defined as:

$$\varpi_i = \frac{1 - E_i}{n - \sum_{i=1}^{m} E_i} \tag{4-26}$$

Again, $0 \le \varpi_i \le 1$ and $\sum_{i=1}^{m} \varpi_i = 1$.

Now, construct λ_i, to integrate the objective significance of the entropy weight, ϖ_i, and the decision-maker's subjective preference of the AHP weight, θ_i, and thus λ_i reflects a comprehensive weight of an individual indicator as follows:

$$\lambda_i = \frac{\theta_i \varpi_i}{\sum_{i=1}^{m} \theta_i \varpi_i} \tag{4-27}$$

A simpler process can also be used, which gets the average of the two weights:

$$\lambda_i = \frac{\theta_i + \varpi_i}{2} \tag{4-28}$$

Application of Fuzzy Sets Theory

In the real world, most of the time decision-makers have to choose solutions where information and data are not precisely known. Many times it is also hard for decision-makers to assign clearly defined (i.e., accurate) numbers for comparison of different alternatives. Fuzzy numbers are then suggested to be assigned to weights and criteria measurement for alternatives.

Certainly, deterministic assumptions largely simplify the problem statement and its solution, but can be so misunderstanding in the infrastructure engineering field that they might lead decision-makers to make non-optimal or even wrong decisions. Project owners and typical AEC firms cannot suffer such losses. So introducing uncertainty in the TCQT analysis is of significance. Rather, an experienced project team is able to make an example estimate such as: the activity can be finished most likely within 10 days, but definitely not less than 7 days (with a crash schedule, due to labor/equipment/budget/other constraints) and not more than 15 days (due to schedule requirements). In addition, the description and measurement of project quality are usually linguistic and thus filled with vagueness and subjectivity. In order to reflect such uncertainties, fuzzy sets theory can be applied and is viewed as one of the effective ways to solve the uncertain problem. Here a critical step for application of fuzzy sets theory is to define the membership function. Different membership functions will be considered and compared in the dissertation to find one that mostly conforms to the real infrastructure engineering practice.

The project quality relies on qualities of a series of tasks, and the task quality relies on its work activities or sub-work items, whose qualities show fuzziness as discussed in previous chapters. Therefore, it is inappropriate to use ordinary (single-value) numbers for activity (and thus project) quality evaluation. Instead, linguistic evaluation is implemented in this research. This requires converting linguistic variables, generated from experts' opinions, into fuzzy numbers. The relative, overall project quality can then be assessed from the sum product of each expert weight and each activity quality.

One of the big issues for the decision-making process in the construction industry is incomplete information caused by the complexity and uncertainty of engineering projects. This makes construction engineering decision-making a typical fuzzy multi-objective optimization problem and gives space for the application of fuzzy sets theory in the engineering field, or, fuzzy engineering decision-making. In addition, effective project financing decisions also require judgment, either objectively or subjectively, which involves figuring out a way for the project team to accept ambiguity, conflict and confusion.

Fuzzy Sets

The vagueness and uncertainty in the decision-making process can be addressed by the fuzzy set theory. First proposed and introduced by Zadeh (1965), fuzzy sets are an extension of classic crisp sets. According to Zadeh (1965), the definition of a fuzzy set is:

Let X be a space of points (objects), with a generic element of X denoted by x. Thus $X = \{x\}$.

A fuzzy set (class) *A* in *X* is classified with a continuum of grades of membership and is characterized by a membership (characteristic) function $f_A(x)$ which associates with each point in *X* a real number in the interval [0,1], with the values of $f_A(x)$ at *x* representing the "grade of membership" of *x* in *A*. Thus, the nearer the value of $f_A(x)$ to unity, the higher the grade of membership of *x* in *A*. The membership function can be generated based on experts' opinions or on opinion polls of human thoughts (Chiu & Park, 1994).

Accordingly, $\mu_{\underset{\sim}{A}} : U \rightarrow [0,1]$ is a fuzzy set on *U*. $\mu_{\underset{\sim}{A}}$ or $\underset{\sim}{A}$ is the membership function of the fuzzy set *A*. For $x \in U$, the value $\mu_{\underset{\sim}{A}}(x)$ is called the grade of membership of x in the fuzzy set *A*. As two special cases, $\mu_{\underset{\sim}{A}}(x) = 1$ indicates that the element x belongs to set A for sure, while $\mu_{\underset{\sim}{A}}(x) = 0$ indicates that the element is clearly not one of the elements in set A. Here a character tilde "~" below a symbol represents a fuzzy set.

Triangular Fuzzy Number

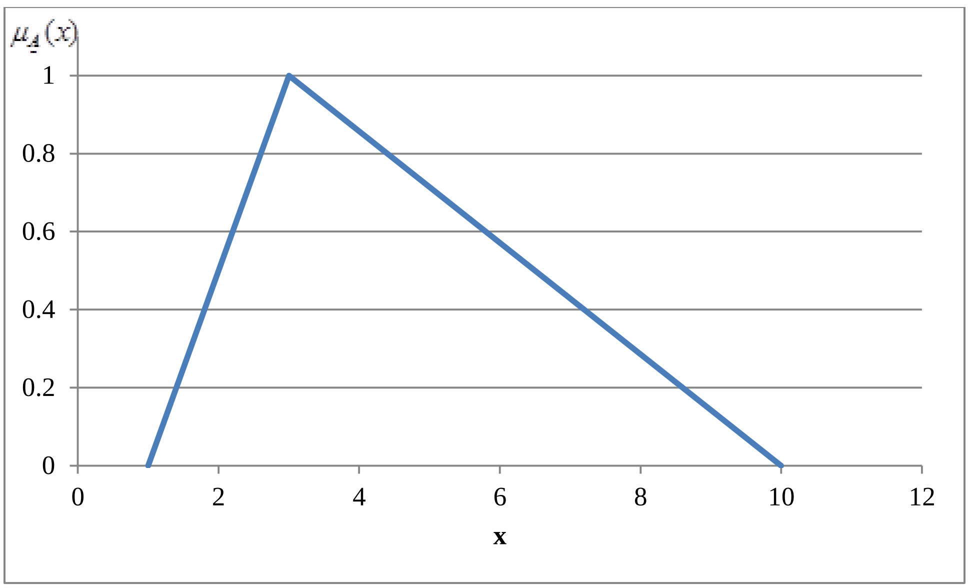
Fuzzy numbers can be obtained with different forms. One of the most widely used forms utilizes triangular fuzzy numbers. For example, a triangular fuzzy number is denoted as $\underset{\sim}{A} = (a_l, a_m, a_u)$ by using the smallest possible value, the most promising value, and the largest possible value of a fuzzy event. Its membership function can be written as follows.

$$\mu_{\underset{\sim}{A}}(x) = \begin{cases} 0, x \le a_l \\ \dfrac{x - a_l}{a_m - a_l}, a_l < x \le a_m \\ \dfrac{x - a_u}{a_m - a_u}, a_m < x \le a_u \\ 0, x > a_u \end{cases} \tag{4-29}$$

The parameter a_m is the center point, a_l and a_u are two base points. Therefore, the degrees of membership of a_l, a_m, and a_u are 0, 1, and 0, respectively. Obviously, it holds that

$a_l \le a_m \le a_u$. The larger the value of $(a_u - a_l)$ is, the fuzzier the membership. For example, the following figure shows a typical triangular fuzzy number where $a_l = 1$, $a_m = 3$, and $a_u = 10$. Therefore, its membership function is:

$$\mu_{\underset{\sim}{A}}(x) = \begin{cases} 0, x \le 1 \\ \dfrac{x-1}{2}, 1 < x \le 3 \\ \dfrac{10-x}{7}, 3 < x \le 10 \\ 0, x > 10 \end{cases}$$



The difference between a triangular probability distribution and a triangular fuzzy number rests on the aspect from different views: the former being objective probabilistic occurrence of an event, and the latter being subjective judgment in human thoughts of an event. In addition, the graded mean integration representation (GMIR) is often adopted to rank fuzzy numbers and a larger GMIR means a larger fuzzy number. For a triangular fuzzy number $\underset{\sim}{A} = (a_l, a_m, a_u)$, the GMIR can be computed as follows:

$$a = \frac{a_l + 4a_m + a_u}{6} \tag{4-30}$$

Another way of de-fuzzification is to calculate the best non-fuzzy performance (BNP) value:

$$BNP = a_l + \frac{(a_u - a_l) + (a_m - a_l)}{3} \tag{4-31}$$

One of the widely used linguistic scales introduces triangular fuzzy numbers for pairwise comparison. The meaning of such fuzzy numbers and their membership functions are listed in Table 4-6.

Operations of Triangular Fuzzy Numbers

Zadeh (1965) also discussed and defined operation rules involving fuzzy sets by extending the corresponding definitions for ordinary sets.

Let $\underset{\sim}{A} = (a_l, a_m, a_u)$ and $\underset{\sim}{B} = (b_l, b_m, b_u)$, the following operations can be performed:

Addition: $\underset{\sim}{A} + \underset{\sim}{B} = (a_l + b_l, a_m + b_m, a_u + b_u)$ (4-32)

Subtraction: $\underset{\sim}{A} - \underset{\sim}{B} = (a_l - b_u, a_m - b_m, a_u - b_l)$ (4-33)

Multiplication: $\underset{\sim}{A} \times \underset{\sim}{B} = (a_l \times b_l, a_m \times b_m, a_u \times b_u)$ (4-34)

Division: $\underset{\sim}{A} / \underset{\sim}{B} = (a_l / b_u, a_m / b_m, a_u / b_l)$ (4-35)

In addition, for a given λ-level ($0 \le \lambda \le 1$), a triangular fuzzy number, $\underset{\sim}{A} = (a_l, a_m, a_u)$, can be decomposed into an interval set as:

$$\underset{\sim}{A}(\lambda) = [a_l(\lambda), a_u(\lambda)] \tag{4-36}$$

Where: $a_l(\lambda) = \lambda(a_m - a_l) + a_l$

$a_u(\lambda) = \lambda(a_m - a_u) + a_u$

Please note that some different expressions for fuzzy number operations have also been proposed (Gani and Assarudeen, 2012). For the purpose of simplification, the above defined operations are used in this research.

Measuring Fuzziness

Fuzzy numbers need to be ranked for practical use (Cheng, 1996). A common approach to measuring fuzziness refers to the concept of distance, which measures the degree of separation between two identical objects (e.g., points, lines, surfaces, and in this case, fuzzy numbers). The smaller the defined distance, the closer two fuzzy numbers or fuzzy sets are. A variety of fuzzy distance measures have been summarized and proposed in literature (e.g., Cheng, 1996; Klir, 1987; and Tran and Duckstein, 2002). Three distance expressions that are widely used are:

Hamming Distance: $$h(\utilde{A},\utilde{B}) = \sum_{i=1}^{n} \left| \mu_{\utilde{A}}(x_i) - \mu_{\utilde{B}}(x_i) \right| \tag{4-37}$$

Euclidean Distance: $$e(\utilde{A},\utilde{B}) = \sqrt{\sum_{i=1}^{n} [\mu_{\utilde{A}}(x_i) - \mu_{\utilde{B}}(x_i)]^2} \tag{4-38}$$

Minkowski Distance: $$m(\utilde{A},\utilde{B}) = \left[\sum_{i=1}^{n} \left| \mu_{\utilde{A}}(x_i) - \mu_{\utilde{B}}(x_i) \right|^q \right]^{\frac{1}{q}} \tag{4-39}$$

Note Hamming Distance and Euclidean Distance are special cases of Minkowski Distance when $q=1$ and $q=2$, respectively.

Specifically, define the distance between triangular fuzzy numbers $\utilde{A}$ and $\utilde{B}$ as follows:

$$d(\utilde{A},\utilde{B}) = \sqrt{\frac{1}{3}[(a_l - b_l)^2 + (a_m - b_m)^2 + (a_u - b_u)^2]} \tag{4-40}$$

It does not always make sense to use distance for description of degrees of fuzziness. An improved method is further developed where (relatively) Weighted Hamming Distance is first defined:

$$h_w(\underset{\sim}{A},\underset{\sim}{B})=\frac{1}{n}\sum_{i=1}^{n}w(x_i)\left|\mu_{\underset{\sim}{A}}(x_i)-\mu_{\underset{\sim}{B}}(x_i)\right| \tag{4-41}$$

Where the weights on x_i , $w(x_i)$, shall satisfy:

$$\frac{1}{n}\sum_{i=1}^{n}w(x_i)=1$$

Take fuzzy sets $\underset{\sim}{A},\underset{\sim}{B},\underset{\sim}{C}\subset U=\{x_1,x_2,x_3\}$ for example, where x_1,x_2,x_3 denote three different project features (e.g., project location, local weather condition, and project size), respectively. Assume:

$$\underset{\sim}{A}=\frac{0.8}{x_1}+\frac{0.5}{x_2}+\frac{0.3}{x_3}$$

$$\underset{\sim}{B}=\frac{0.9}{x_1}+\frac{0.2}{x_2}+\frac{0.5}{x_3}$$

$$\underset{\sim}{C}=\frac{0.6}{x_1}+\frac{0.6}{x_2}+\frac{0.4}{x_3}$$

And $w=(1.0,1.2,0.8)$ satisfies $\frac{1}{n}\sum_{i=1}^{n}w(x_i)=\frac{1}{3}(1.0+1.2+0.8)=1$.

To compare the similarity between a new Project A and completed Projects B and C, we can calculate weighted hamming distances as follows:

$$h_w(\underset{\sim}{A},\underset{\sim}{B})=\frac{1}{3}\times(1.0\times0.1+1.2\times0.3+0.8\times0.2)=0.207$$

$$h_w(\underset{\sim}{A},\underset{\sim}{C})=\frac{1}{3}\times(1.0\times0.2+1.2\times0.1+0.8\times0.1)=0.133$$

Since $h_w(\underset{\sim}{A},\underset{\sim}{C})<h_w(\underset{\sim}{A},\underset{\sim}{B})$, it is probably a wise decision to predict features of Project A based on those of Project C.

Generally, the multiplication or division of two triangular fuzzy numbers does not necessarily results in triangular fuzzy numbers. In the fuzzy decision-making process, however, we still view such results as triangular fuzzy numbers.

There are also some other methods commonly used for comparison of fuzzy sets, such as degree of optimality, α-cut, fuzzy scoring, and linguistic expression.

Fuzzy Modeling

Some commonly-used multi-objective decision-making problem solving techniques are (Konak et al., 2006; other literature):

- Simple Additive Weighting (SAW): This method begins with constructing and normalizing the decision-making matrix. Then optimal values of each parameter and attributes weights are determined. After calculation of the weighted normalized matrix and determination of simple additive weighting optimality criterion, the final results of alternatives ranking can be obtained according to the SAW criterion values. For example, Shevchenko et al. (2008) used this method for analysis of investments risk alternatives in construction. The mechanism for SAW calculation is relatively simple:

$$W_i = \sum_{j=1}^{n} w_j r_{ij} \tag{4-42}$$

Where: W_i - Weighted score for alternative *i*; w_j - Weight for criterion *j*; r_{ij} - Rating score for alternative *i* on criterion *j*.

- Weighted Sum Method (WSM): Simply put, an alternative (A_i) is scored for the product sum of the performance of each alternative under each criterion (a_{ij}), among n criteria, multiplied by its relative weight (w_j). And thus the alternative, A^*, with the highest score, is selected:

$$A^* = \max \sum_{j=1}^{n} a_{ij} w_j \tag{4-43}$$

It is understandable that the WSM is a suitable application to single objective decision-making problems where all measurement units are identical. It is not an accurate approach, however, to multi-criteria decision-making optimization.

- Weighted Product Method (WPM): In essence, this method is a revised WSM. Instead of calculating product sum scores, WPM compares alternatives one pair at a time according to the following defined ratios:

$$R(A_K / A_L) = \prod_{j=1}^{n} (a_K^j / a_L^j)^{w_j} \tag{4-44}$$

Where: n - number of decision criteria; a_K^j - value of Alternative K in terms of the *j*-th criterion; a_L^j - value of Alternative L in terms of the *j*-th criterion; w_j - weight assigned to the *j*-th criterion.

An advantage of the WPM over WSM lies in the elimination of measurement units to make different measures comparable.

- Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS)
- The Analytical Hierarchy Process (AHP)
- The Simple Multi-Attribute Rating Technique (SMART)
- Analytic Network Process (ANP)

The vagueness in the decision-making process makes it necessary to introduce fuzzy logic for decision assistance. Because of its effectiveness and calculation efficiency, recently, fuzzy TOPSIS have attracted researchers' interest and have been applied in the analysis of multi-criteria decision-making (Saghafian and Hejazi, 2005; Shih et al., 2006; Wang and Lee, 2007; and Behzadian et al., 2012). As a common step, when using TOPSIS, relative closeness from each alternative to ideal solution has to be determined and then compared; therefore, the distance between two fuzzy numbers must be pre-defined if a fuzzy TOPSIS is used. Literature has also proposed different equations for fuzzy numbers distance calculation.

Fuzzy AHP

Analytic Hierarchy Process (AHP), first developed by Saaty (1990), is now widely used as a multi-objective decision-making tool. AHP shows effectiveness in relevant factor selection and ranking in a hierarchic structure through a way of combining both qualitative and quantitative analyses. Saaty (1990) suggested what to include in the AHP when constructing hierarchies: appropriately thorough representation of the problem; consideration of the environment; identification of attributes; and identification of participants. Zahedi (1986) summarized in which areas AHP was applied, suggested extensions of AHP, and addressed criticisms of AHP.

Essentially, AHP reflects strategic thinking of human beings in which subjective judgment is quantized through analysis. Degrees of importance for each relevant factor are compared in such a hierarchic way that a complex decision-making problem is decomposed. Saaty (1990) suggested that the key to decision-making problems should be evaluation and selection of behaviors, schemes, and objectives, in which objectives need to be ranked and then good objectives need to be selected. Further, the fuzzy AHP takes into consideration fuzzy numbers, based on the decision-maker’s emphasis, in the judgment matrix to make pairwise comparisons.

As has been discussed in the previous section, a consistency check is required in the application of AHP. Because lack of consistency in the decision-making process (e.g., inconsistency in preference relations among attributes) often brings inconsistent conclusions, failure in the consistency check will lead to re-assignment of comparable ratios. Fuzzy numbers will further increase the likelihood of inconsistency.

In a crisp context, the preference transitivity is straightforward:

$$\left.\begin{matrix} a > b \\ b > c \end{matrix}\right\} \Rightarrow a > c$$

In a fuzzy model, the preference transitivity is anticipated as:

$$\left.\begin{matrix} \underset{\sim}{a} > \underset{\sim}{b} \\ \underset{\sim}{b} > \underset{\sim}{c} \end{matrix}\right\} \Rightarrow \underset{\sim}{a} > \underset{\sim}{c}$$

Basically, in the fuzzy context, this is saying that if an alternative a is preferred to alternative b and is b to c, then a should be preferred to c. In the real decision-making process, however, such easy preference transitivity can be seldom guaranteed. Herrera-Viedma (2004) summarized two widely-used preference relations: multiplicative preference relations and fuzzy preference relations.

1. In a multiplicative preference relation, the preference of alternative a_i over a_j is defined by the ratio, r_{ij}, of their preference intensity with 1~9 scale (Saaty, 1990). Hence, $r_{ij} = 1$ represents that a_i is no different from a_j, while $r_{ij} = 9$ represents that a_i is maximally better than a_j. Obviously such a preference relation is assumed multiplicative reciprocal:

$$r_{ij} \cdot r_{ji} = 1 \quad \forall i, j \in \{1, 2, ..., n\}. \tag{4-45}$$

2. In a fuzzy preference relation, the preference of alternative a_i over a_j is defined by the preference degree, p_{ij}, an element characterized by a membership function. Hence, $p_{ij} = 0.5$ represents that a_i is almost as good and important as a_j ($a_i \sim a_j$), while $p_{ij} = 1$ represents that a_i is maximally better than a_j. Generally, $p_{ij} > 1/2$ indicates that a_i is preferred to a_j ($a_i \succ a_j$), and such a preference relation is assumed additive reciprocal:

$$p_{ij} + p_{ji} = 1 \quad \forall i, j \in \{1, 2, ..., n\}. \tag{4-46}$$

Fuzzy TOPSIS

TOPSIS was first developed by Hwang and Yoon (1981). TOPSIS selects the alternative that is the closest to the ideal solution and farthest from negative ideal solution. The solution is considered optimal when it is closest to the positive ideal point and farthest to the negative ideal point. The original TOPSIS used ordinary single-value numbers for both evaluation and weight assignments. The Washington State Department of Transportation adopts TOPSIS for benefit-cost analysis calculation of highway mobility project prioritization. WSDOT estimates benefits on the basis of 24-hour user travel time savings and costs on the basis of expenses of ROW, engineering, construction, and operation and maintenance. TOPSIS has been improved by many researchers to fuzzy TOPSIS, taking into account fuzzy effects in the practical decision-making procedures. Fuzzy TOPSIS has been applied to a variety of decision-making areas. For example, Moradpour et al. (2011) used the method for ranking highway construction project risks and their questionnaire resulted in a weight vector of

$\vec{w} = (quality, \cos t, time) = (0.384619, 0.331426, 0.283956)$.

In essence, the selection of the optimal alternative in the TOPSIS process is based on the highest score from the following equation (Finnie *et al.*, 2007):

$$C_i^* = \frac{\sqrt{\sum_{j=1}^{n}\left(\frac{w_j(x_{ij} - \min x_{ij}}{\sum_{i=1}^{m} x_{ij}}\right)^2}}{\sqrt{\sum_{j=1}^{n}\left(\frac{w_j(x_{ij} - \max x_{ij}}{\sum_{i=1}^{m} x_{ij}}\right)^2} + \sqrt{\sum_{j=1}^{n}\left(\frac{w_j(x_{ij} - \min x_{ij}}{\sum_{i=1}^{m} x_{ij}}\right)^2}} \tag{4-47}$$

Where: x_{ij} = the score *x* for the alternative *i* under the attribute *j*; and w_j = the weight of attribute *j*.

Application of fuzzy TOPSIS is discussed step by step as follows.

Step 0: Finding attribute weights and attribute ratings, and construct decision table.

Denote the *j*th criterion for the *i*th alternative as $\underset{\sim}{y}_{ij}\,(i = 1, 2, ..., m;\ j = 1, 2, ..., n)$. In other words, with *m* alternatives and *n* criteria, the decision (evaluation) matrix is:

$$\underset{\sim}{X} = \begin{pmatrix} \underset{\sim}{y}_{11} & \cdots & \underset{\sim}{y}_{1n} \\ \vdots & \ddots & \vdots \\ \underset{\sim}{y}_{m1} & \cdots & \underset{\sim}{y}_{mn} \end{pmatrix} \tag{4-48}$$

Define attribute ratings as follows (for linguistic variables and fuzzy scores of the ratings of alternatives): The range of fuzzy scores for the ratings of alternatives have been pre-defined as

[0,1] and thus already been standardized; otherwise the decision matrix have to be further standardized. Similar to the determination of criteria weights , Weighted Arithmetic Averaging (WAA) operators are also applied to get the weighted fuzzy evaluation scores:

$$\underset{\sim}{y}_{ij} = e_1 \underset{\sim}{y}_{ij1} + e_2 \underset{\sim}{y}_{ij2} + ... + e_m \underset{\sim}{y}_{ijm} \tag{4-49}$$

where e_i is the WAA vector.

Step 1: Standardize the Decision Matrix. This step transforms various attribute dimensions into non-dimensional attributes, which allows comparisons across criteria. For standardizing, each column of decision matrix is divided by the root of sum of square of respective decision attributes.

Step 2: Construct weighted standardized decision matrix by multiplying attributes weight to each rating.

The weighted standardized decision (evaluation) matrix is now:

$\underset{\sim}{v}_{ij} = \underset{\sim}{y}_{ij} \times \underset{\sim}{w}_j$ where $\underset{\sim}{w}_j$ is the weight for the *j*th criterion.

Step 3: Determine ideal solution and negative ideal solution. (A set of maximum values for each criterion is ideal solution.)

Positive ideal solution (based on benefit): $\underset{\sim}{A}^+ = (\underset{\sim}{v}_1^+, \underset{\sim}{v}_2^+, ..., \underset{\sim}{v}_n^+)$ (4-50)

Negative ideal solution (based on cost): $\underset{\sim}{A}^- = (\underset{\sim}{v}_1^-, \underset{\sim}{v}_2^-, ..., \underset{\sim}{v}_n^-)$ (4-51)

Step 4: Determine separation from ideal solution.

Distance to the positive ideal solution: $D_j^+ = \sum_{j=1}^{n} D(\underset{\sim}{v}_{ij}, \underset{\sim}{v}_i^+)$ (4-52)

Step 5: Determine separation from negative ideal solution.

Distance to the negative ideal solution: $D_j^- = \sum_{j=1}^{n} D(\underset{\sim}{v}_{ij}, \underset{\sim}{v}_i^-)$ (4-53)

Step 6: Determine relative closeness to ideal solution.

$$CC_j = \frac{D_j^-}{D_j^+ + D_j^-} \tag{4-54}$$

Barnes and Rutherford (1997) identified such closeness as Priority Index when they developed the State of Washington highway mobility project ranking procedure by using TOPSIS.

Step 7: Rank the order.

Summary

In a typical multi-criteria optimization problem, there are a variety of attributes (associated with alternatives) and/or objectives (both interactive and contradictive with one another), under a set of constraint resource conditions. Solution to such a problem reflects the decision-making process, in which the "best" decision is suggested when choices are made from a set of alternatives with multiple, potentially conflicting criteria. Trade-offs always exist in such project management decision-making processes: We have to put more labor or provide highly-priced, advanced equipment on the project to achieve the project quality requirement within a shorter time; otherwise we have to wait longer for the project or task to complete. Challenges that are often encountered in the multi-criteria decision-making process include selection of proper criteria, evaluation of alternatives, assignment of attributes weight, and determination of strength of preferences.

In this chapter, theory on multi-criteria decision-making was discussed. As a widely-used method for single objective optimization, benefit-cost analysis tools were first summarized. Two types of multi-criteria decision-making problems, multi-objective decision-making optimization and multi-attribute decision-making optimization, were then discussed in detail. Lastly, fuzzy set theory was introduced along with its application in the decision-making field.

Table 4-1. Benefit-Cost Analysis Worksheet

Action *i* (Short Term / Long Term)	Using / Doing	Not Using / Not Doing
Benefits + Rewards		
Costs + Risks		

Table 4-2. Summary of Widely-Used BCA Tools

Document	Agency	Year	Real rate	Category	Impact (costs or benefits)	Tools
Economic Analysis Primer	USDOT	2003	7%	Agency costs	Design and engineering	HERS-ST (Highway Economic Requirements System) by FHWA
					Land acquisition	
					Construction	
					Reconstruction/Rehabilitation	
					Preservation/Routine maintenance	
					Mitigation	
				User costs/benefits associated with work zones	Delays	
					Crashes	
					Vehicle operating costs	
				User costs/benefits associated with facility operations	Travel time and delay	
					Crashes	
					Vehicle operating costs	
				Externalities	Emissions	
					Noise	
					Other impacts	
Macro-economic Analysis of Florida's Transportation Investments	FDOT	2015	4%	Costs	Travel time	The Regional Economic Models, Inc. (REMI) economic simulation model
					Vehicle operating costs	
					Accident cost	
					Increased capacity	
					Modal shifts	
					Capacity spending	
					Operations and maintenance	
					Administration and support	
				Benefits	Reduced cost of doing business	
					Household cost savings	
					Modal shifts	
					Income	
					Jobs	
					Gross state product	
					Personal travel user benefits	
					Safety	

Table 4-2. Continued

Document	Agency	Year	Real rate	Category	Impact (costs or benefits)	Tools
Benefit-Cost Analysis Analyses Guidance for TIGER Grant Applicants	TIGER	2014	3%	Quality of life	Land use changes that reduce VMT	TIGER BCA Resource Guide
					Increased accessibility	
					Property value increases	
				Economic competitiveness	Travel time savings	
					Operating cost savings	
				Safety	Prevented accidents, injuries, and fatalities	
				State of good repair	Deferral of complete replacement	
					Maintenance and repair savings	
					Reduced VMT from not closing bridges	
				Environmental sustainability	Environmental benefits from reduced emissions	
WSDOT Mobility Project Prioritization Process	WSDOT	2000	4%	Benefits	Travel time savings for passenger and freight movement	
					Operating savings	
					Accident reduction	
				Costs	Construction	
					Environmental retrofit	
					Preliminary engineering	
					Annual operating and maintenance	
Benefit-Cost Analysis for Transportation Projects	MnDOT	Online	Not specified, but used 3.6% in an example	Benefits	Travel time savings	
					Vehicle operating cost savings	
					Safety	
				Costs	Capital costs	
					Major rehabilitation costs	
					Routine annual maintenance costs	
					Remaining capital value	
California Life-Cyce Benefit/Cost Analysis Model	Caltrans	2009	4%		Travel time savings	Cal-B/C
					Vehicle operating cost savings	
					Project costs	
					Safety (Accident cost savings)	
					Emissions reductions (air quality and greenhouse gas benefits)	
Major Corridor Investment-Benefit Analysis System	INDOT	1998	7%		Travel time savings	NET-BC
					Safety cost savings	
					Vehicle operating cost savings	
					Business cost savings	
					Business attraction impacts	
					Tourism impacts	
					Construction	
					Operations and maintenance	

Table 4-3. Pairwise Comparisons

A_k	B_1	B_2	…	B_n
B_1	b_{11}	b_{12}	…	b_{1n}
B_2	b_{21}	b_{22}	…	b_{2n}
…	…	…	…	…
B_n	b_{n1}	b_{n2}	…	b_{nn}

Table 4-4. RCI values for different values of n

Order	1	2	3	4	5	6	7	8	9	10
RCI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Table 4-5. Aggregation of Ranking

Level A	A_1 a_1	A_2 a_2	… …	A_m a_m	Aggregation of Ranking in Level B
B_1	b_1^1	b_1^2	…	b_1^m	$\sum_{i=1}^{m} a_i b_1^i$
B_2	b_2^1	b_2^2	…	b_2^m	$\sum_{i=1}^{m} a_i b_2^i$
...	…	…		…	…
B_n	b_n^1	b_n^2	…	b_n^m	$\sum_{i=1}^{m} a_i b_n^i$

Table 4-6. Triangular Fuzzy Numbers for Pairwise Comparison

Importance strength	Fuzzy number	Membership function	Linguistic variables
1	$\underset{\sim}{1}$	(1,1,3)	Equally important
3	$\underset{\sim}{3}$	(1,3,5)	Weakly important
5	$\underset{\sim}{5}$	(3,5,7)	Strongly more important
7	$\underset{\sim}{7}$	(5,7,9)	Very strongly important
9	$\underset{\sim}{9}$	(7,9,9)	Extremely more important

Table 4-7. Application of Fuzzy Methods

Author (Year)	Methodology	Fuzzification and Decision-Making Techniques	Application
Pan (2008)	Fuzzy AHP	Fuzzy importance scale by a combination of triangular and trapezoidal fuzzy numbers α-cut representing degrees of uncertainty	Bridge construction method selection
Huang et al. (2008)	Fuzzy AHP	Integration of degree of optimism with triangular fuzzy numbers for consideration of decision risks	Government-sponsored R&D project selection
Gumus (2009)	Fuzzy AHP and TOPSIS	Criteria obtained with modified Delphi method Extent analysis	Hazardous waste transportation firms evaluation
Amiri (2010)	AHP and Fuzzy TOPSIS	Group working for structuring decision hierarchy, AHP for criteria weights, and fuzzy TOPSIS for project selection	Oil-fields development project selection
Sun (2010)	Fuzzy AHP and Fuzzy TOPSIS	Vagueness and subjectivity handled with linguistic values by using triangular fuzzy numbers	Company performance evaluation

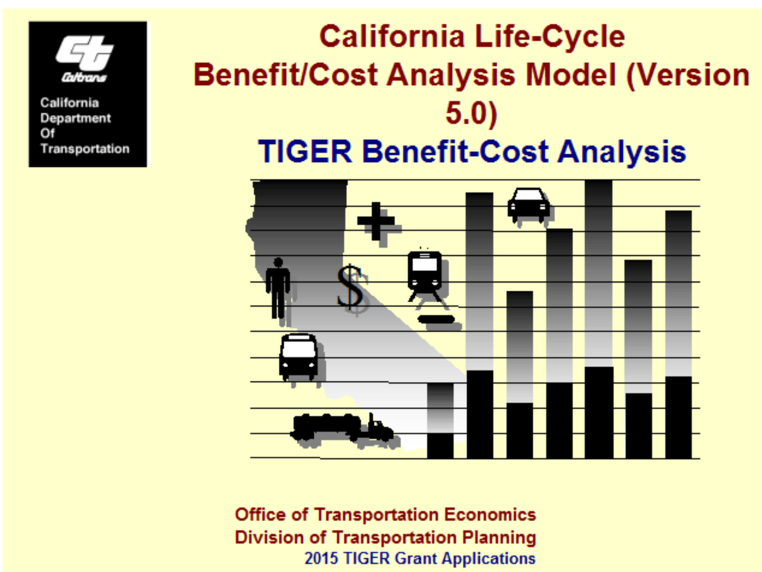


Figure 4-1. Cover Sheet of California Life-Cycle Benefit/Cost Analysis Model

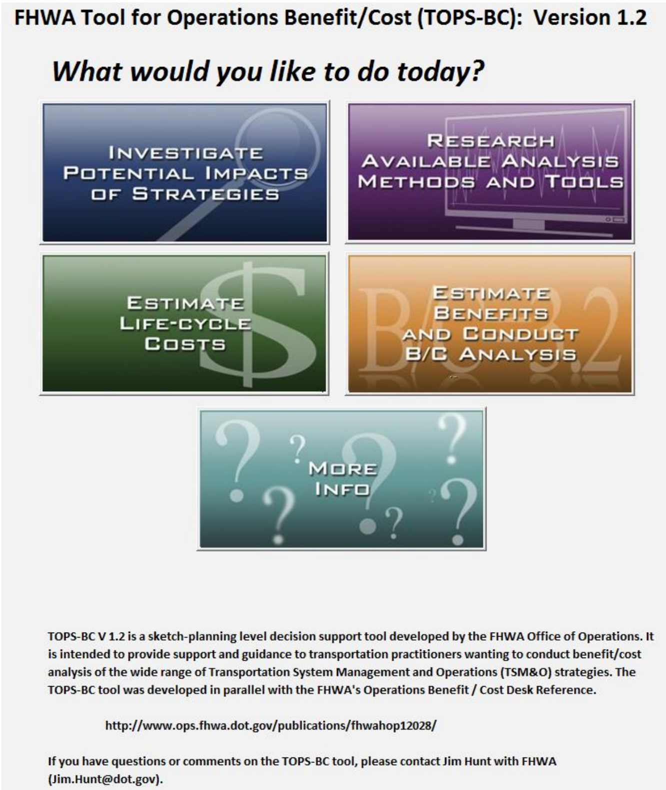


Figure 4-2. Cover Sheet of FHWA Tool for Operations Benefit/Cost

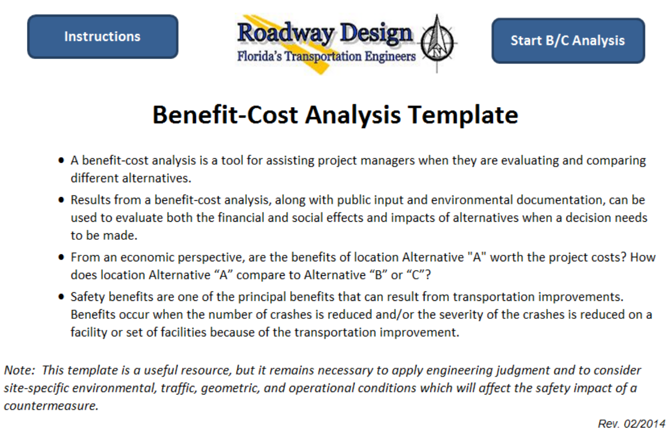


Figure 4-3. Cover Sheet of FDOT Benefit-Cost Analysis Template

				Benefits				
Small	1	2	3	4	5	6	7	Large
				Costs				
Large	1	2	3	4	5	6	7	Small

Figure 4-4. Example of Order of Scale Values

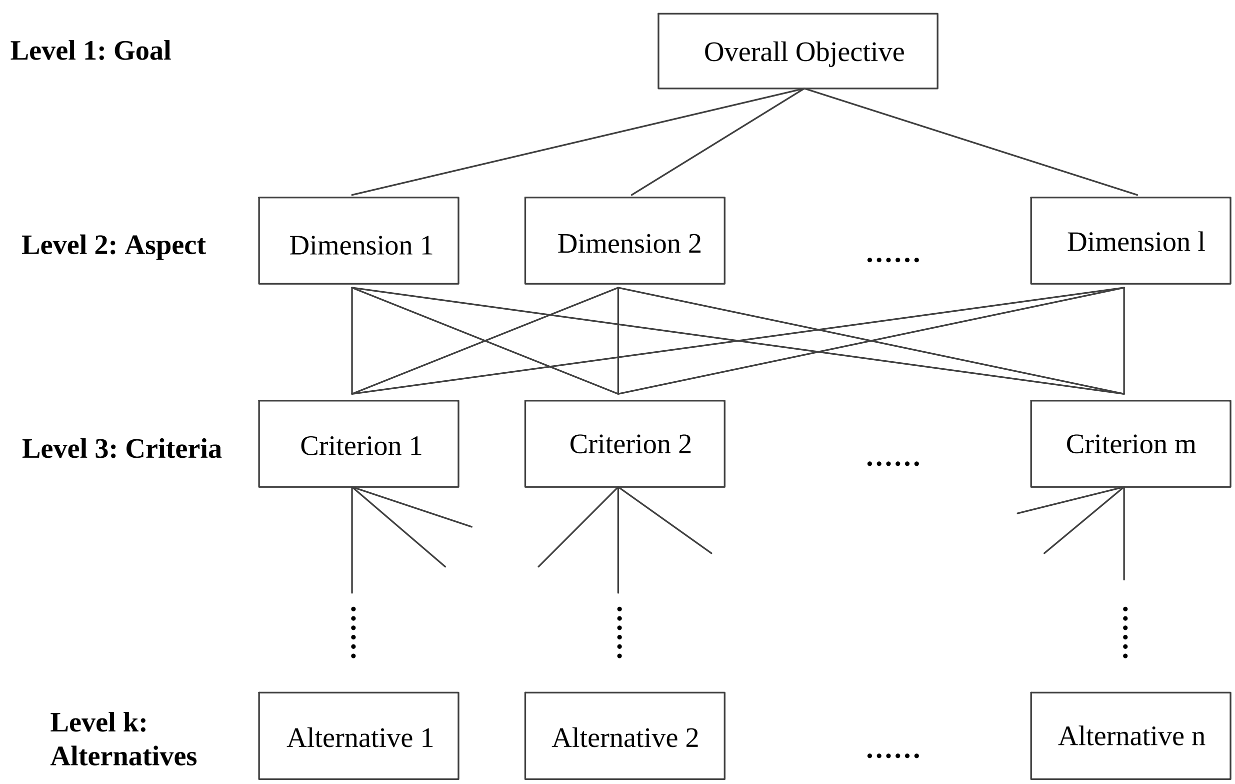


Figure 4-5. AHP Hierarchy Structure

CHAPTER 5
APPLICATION OF MULTI-ATTRIBUTE DECISION-MAKING OPTIMIZATION: PRIORITIZATION OF HIGHWAY PROJECTS IN FLORIDA

The Needs for Project Prioritization

When deciding allocation of available funds, transportation agencies must keep in mind the budget constraints imposed both locally and nationally. Gaps almost always exist between the required funds and the available funds. Decision makers must evaluate comprehensively the impact of infrastructure engineering projects on investments, operation expenses, network, traffic level of service, as well as on land development and environmental conditions. Take highway engineering projects for example: Prioritization of potential highway projects development plays an important role on the significance of the impact stated above. Prioritizing project development, or comparing a variety of potential project and then choosing a specific one, is essentially a multi-attribute optimization problem. Therefore, research must be done with regard to economy, technology, and environment. A case in point in Florida is the *Long Range Transportation Plan*, in which the North Florida TPO (Transportation Planning Organization) defines the goals and objectives as enhancing economic competitiveness, livability, safety, mobility and accessibility, equity in decision making, and system preservation. They further provide details about the performance measures and benchmarks for the above goals and objectives.

Usually, benefit-cost analysis (BCA) is conducted to evaluate the financial performance of highway projects by calculations of net present value (NPV), internal rate of return (IRR), payback period, and other economic indicators. In addition, multi-criteria performance should also be assessed with incorporation of non-monetized elements.

Accurate projection of future trip and travel demand is critical to the highway and transportation planning process. The four-step process (NCHRP, 2012) has long been the conventional method for transportation demand estimation. The process begins with estimation of trip generation from socio-economic characteristics, land use patterns, and transportation system characteristics, and is then followed by trip distribution and mode choice, and is concluded with network assignment such as link flows, speeds, travel times, and transit ridership. Further, FDOT (2013) based the process for construction opportunities prioritization on highway capacity, preservation, and safety. The Strategic Investment Tool (SIT) is developed and used by FDOT to rank capacity projects on Strategic Intermodal System (SIS) facilities. The following sections describe main project attributes and objectives and how we analyze them.

Economic Attribute Analysis

The project economic analysis can be done through a benefic-cost analysis for evaluation of the rationale and feasibility of potential projects. This provides the foundation of investment analysis, plan comparison, and project prioritization. In such an analysis the roadway network must be considered as a whole. The difficulty of economic analysis for transportation projects also lies in their impacts on not only direct users but also indirect users, and thus we must conduct such analyses in a view of system management over the project life cycle. Kockelman et al. (2013) summarized the impacts of investment in transportation infrastructure (Table 5-1).

Principles for Federal Infrastructure Investments (1994) requires systematic analysis be conducted of expected benefits and costs (including both quantitative and qualitative measures) for investment/performance analysis of transportation systems. Although the methods used for benefit-cost analysis are different among the Highway Economic Requirements System (HERS), the National Bridge Investment Analysis System (NBIAS), and the Transit Economic Requirements Model (TERM), all of the three models introduce and incorporate benefit-cost analysis into the investment/performance evaluation. FDOT published *Macroeconomic Analysis of Florida's Transportation Investments* in January 2015, which provides methodology for economic effect analysis for highway investments. The following figure (Figure 5-1) briefly summarizes the analysis approach.

In a report prepared for Utah Department of Transportation Research Division, Schultz and McGee (2009) conducted an economic development analysis and developed a project evaluation and prioritization method. The scoring system they proposed for economic development assessment consists of four aggregate criteria and one bonus criterion, a total of 110 points (Figure 5-2). Environmental, congestion, and safety objectives were further added to the succeeding economic evaluation framework. They suggested picking a set of indices for different project types from the following possible indices on a project-by-project basis:

- AADT
- Truck AADT
- v/c ratio
- v/c ratio improvement
- safety index
- functional class
- transportation growth
- vehicle-hours-saved
- B/C ratio
- Adjacent interchange v/c ratio
- Average adjacent interchange distance

Investment in highway and transportation system helps the competitiveness of local and regional economic growth in such a way that labor productivity and market access are improved by decrease in travel time and cost, as well as by increase in reliability.

Project Life Cycle Costs

The life cycle costs of a highway project are composed of investment costs and operation expenses. Investment costs are costs incurred during the planning, engineering, and construction phases of the project. Operation expenses cover costs incurred during the operation, maintenance, and renovation phases, and may also include the demolition costs if necessary.

Transportation Equity Act for the 21st Century provides a definition of Life-Cycle Cost Analysis as "a process for evaluating the total economic worth of a usable project segment by analyzing initial costs and discounted future costs, such as maintenance, user, reconstruction, rehabilitation, restoring, and resurfacing costs, over the life of the project segment". ASCE (2014) also suggests using an LCCA-driven cost-effectiveness ranking to inform the STIP (Statewide Transportation Improvement Program) and TIP (Transportation Improvement Program). In addition, FHWA requires LCCA be applied "only to compare design alternatives that would yield the same level of service and benefits to the project user at any specific volume of traffic". The LCCA process begins with establishment of alternatives and follows by determination of activity timing and estimation of agency and user costs; after computation of life-cycle costs, the results are finally analyzed. In most evaluations, construction costs and maintenance costs are sufficient to consider, since they typically account for most of the project life cycle costs. According to FHWA, user costs, based on capacity flow analysis, can be estimated from vehicle operating costs, delay costs, and crash costs. In addition, the FHWA suggests including 5~10% project contingency to account for unforeseen changes.

Project Economic Benefits

Corresponding to the project life cycle costs, the project economic benefits should also cover the whole life cycle of the project. Main categories of benefits are listed as follows.

- Vehicle operation cost savings
- Benefits due to reduce in mileage
- Benefits due to reduce in operation expenses
- Benefits of time saving due to increase in vehicle velocity
- Benefits due to decrease in truck travel time
- Benefits due to decease in congestion
- Accident cost savings
- Environmental cost savings

Above-mentioned are examples of direct benefits. Major indirect benefits include land use impacts, employment, and other non-user benefits. Other categories of benefits or costs have also been studied. Examples of such categories include changes (positive or negative) in the environment and changes (loss or improvement) of recreational facilities.

Among these economic benefits, travel time savings (TTS) is usually the principal benefit of a highway project. USDOT (2003) suggested using the value of travel time savings (VTTS) in all DOT benefit-cost analyses. There has been no unique formula for VTTS calculation; however, per person-hour values are often recommended as a percentage of total earnings. An estimate for travel time savings (TTS) can be made as follows:

$$TTS = \left(\sum_{i=1}^{m} \frac{q_i l_i}{s_i} - \sum_{j=1}^{n} \frac{q_j l_j}{s_j} \right) \times 365 \qquad (5\text{-}1)$$

Where: q_i, q_j = Traffic volumes on the *i*-th and *j*-th roads on current and future roadway networks, respectively.

l_i, l_j = The lengths of the *i*-th and *j*-th roads on current and future roadway networks, respectively.

s_i, s_j = The average speeds on the *i*-th and *j*-th roads on current and future roadway networks, respectively.

The value of travel time reflects the opportunity cost for a traveler in terms of dollar values that the traveler is willing to pay for savings of time. The USDOT recommends a 2013 U.S. per person-hour dollar value of $13 for local travel and of $19 for intercity travel, combining both personal and business travels.

Economic Analysis

Net Present Value: Net present value (NPV) is the present value of all cash flows, both positive (i.e., cash inflows) and negative (i.e., cash outflows), associated with the project investment and expenses. In other words, it is the present value of the benefits minus the present value of the costs over the project life cycle. The higher the NPV, the more attractive and desirable the project being evaluated is. Given the project life cycle of n years, the NPV can be expressed as follows:

$$NPV = \sum_{i=1}^{n} \frac{B_i - C_i}{(1+r)^i} \qquad (5\text{-}2)$$

Where *r* is the interest rate per period.

If in Year *t*, *NPV = 0*, then we say *t* is the payback period. If a specific *r** satisfies the equation NPV = 0, then we call *r** the internal rate of return (IRR) of the project.

Benefit-Cost Analysis: As has been discussed in Chapter 4, the Benefit-Cost Analysis (BCA) is usually conducted to compare the project benefits and rewards with project costs and risks in order to evaluate alternatives. Table 5-2 lists some components of such analysis.

Specifically for transportation project, the USDOT proposes a ten-step BCA process:

1. Establish objectives
2. Identify constraints and specify assumptions
3. Define base case and identify alternatives
4. Set analysis period
5. Define level of effort for screening alternatives
6. Analyze traffic effects
7. Estimate benefits and costs relative to base case
8. Evaluate risk
9. Compare net benefits and rank alternatives
10. Make recommendations

Main benefits and costs associated with transportation projects are listed in the Table 5-3.

Inflation has to be adjusted when we conduct the BCA. The Federal Highway Administration provides National Highway Construction Cost Index, or NHCCI (former Bid Price Index, or BPI), for inflation adjustments. Specifically:

Base year dollars = Data year dollars x Base year price index / Data year price index (5-3)

Data year dollars = Base year dollars x Data year price index / Base year price index (5-4)

Table 5-4 further lists the key highway financials in the United States. The data were extracted in 2010.

Technological Attribute Analysis

The purpose of technological objective analysis is to evaluate the quality of the network by identifying the impact of the potential project development on the improvement of network traffic quality and level of service.

Change in Network Connectivity

Connectivity reflects the relative degree of connectedness within a transportation network. Connectivity is a measure of accessibility without regard to distance: The higher the connectivity, the lower the isolation and the higher the accessibility. Places with high connectivity are often considered important since they are the best connected. Consequently, changes in the highway network connectivity reflect the impact of new projects on the existing network. The highway network changing ratio (NCR) can be calculated as follows:

$$NCR = \frac{C - C_0}{Invest} \qquad (5\text{-}5)$$

Where: C = Degree of network connectivity with the new project

C_0 = Degree of network connectivity without the new project

Invest = Total construction costs and operation and maintenance expenses

The degree of network connectivity in a specific area, C_i, can be estimated as:

$$C_i = \frac{L / \varepsilon}{H \times N} \tag{5-6}$$

Where: L = Total highway mileage within the area

H = Average distance between two nodes

N = Number of total nodes in the area

ε = Linear coefficient

Change in Accessibility

Highway node accessibility reflects the mean travel time (or distance, or expenses) from a certain point in the area through the highway network to a certain destination. Highway systems must provide expected levels of accessibility, "the measure of the capacity of a location to be reached by, or to reach different locations" (Rodrigue et al., 2013). Accessibility can be measured by the degree of a node, the total accessibility matrix, the Shimbel accessibility matrix (aka. The D-matrix), or the valued graph matrix.

Accessibility mainly relies on location and distance. Location can be identified by the combination of its population, economic activity level, tourist attraction, etc. Distance can be measured by length, time, cost, or energy spent.

Environmental Attribute Analysis

Construction and operation of highways may inevitably cause damages to the environment, and thus integration of environmental impact assessment (EIA) into highway development is crucial. Development of highways, from land acquisition through road construction to operation and maintenance, can bring many potential adverse impacts on the environment. An EIA process is typically composed of three key elements as shown in Figure 5-3 (Fwa 2005, p.3-1~p.3-22).

Similarly, environmental objective analysis needs to enclose analysis for both potential costs and benefits to the environment brought by the new project. Externalities also need to be estimated in terms of costs associated with controls over waste materials, pollution, noise, etc. Sustainability appraisal methods can be applied to such analysis. Ugwu et al. (2006a, 2006b) proposed a framework for infrastructure projects sustainability assessment, using both the weighted sum model and the additive utility model. Their procedure leads to the Sustainability Index (SI) of infrastructure projects and the highest corresponding value of SI is thought to be preferred as it maximizes the sustainability of a design proposal. Here they define the SI as a crisp, additive/commutative utility value of performance measurement based on sustainability appraisal decision matrix in terms of indicators of environment, health and safety, economy, societal, resource utilization, and project administration.

The statutory authority of the Federal Highway Administration (FHWA) developed a framework with six principles for the National Environmental Policy Act (NEPA) review purpose in transportation decision making. Generally, the NEPA process begins with identification of purpose and need and consideration of project impacts, followed by development and evaluation of alternatives. The process also requires interagency coordination and public involvement. Mitigation of adverse project impacts is the final step of the NEPA process. Obviously, such a decision-making process has to be based on correct prediction about transportation demand as well as on reasonable judgment for roadway deficiency, and this is a critical component of the big picture for highway engineering projects decision making.

When using BCA as a method to assess the environmental impact, Heinzerling and Ackerman (2002) argued that BCA usually leads to biased and misleading results for environmental protection analysis. Specifically, they held the view that cost-benefit analysis suffers from four fundamental flaws:

1. The standard economic approaches to valuation are inaccurate and implausible.
2. The use of discounting improperly trivializes future harms and the irreversibility of some environmental problems.
3. The reliance on aggregate, monetized benefits excludes questions of fairness and morality.
4. The value-laden and complex cost-benefit process is neither objective nor transparent.

Instead, they recommended some alternatives to the use of BCA for environmental protection, such as technology-based regulation, market-based regulation, and environmental right-to-know programs.

According to Šaparauskas and Turskis (2006), an indicator can be used for input of sustainable construction evaluation, among other things, only if it is available, reliable, and measurable. They further developed procedures of applying Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) or Simple Additive Weighting (SAW) for construction sustainability assessment.

Goh and Yang (2013) identified, between traditional models with benefit-cost analysis and life-cycle cost analysis and proposed models with sustainability-based financial decision support analysis, the knowledge gap, including difficulties in measuring sustainability, inconsistency in measurement standard, ambiguity in identifying sustainability related costs and impacts, and omission of social and environmental related costs. They also summarized from the literature three sustainability-related cost categories for highway infrastructure as agency costs, social costs, and environmental costs; each of them has several main components and sub-factors.

Generally, EIA must be carried out in all the project phases for development of sustainable highways and must be fully integrated with different project phases.

Safety

The FDOT Mission Statement reads "The department will provide a safe transportation system that ensures the mobility of people and goods, enhance economic prosperity and preserves the quality of our environment and communities".[4] Safety, as FDOT's top priority, has been continuously improved due to the efforts of FDOT and many other organizations. The Highway Safety Improvement Program (HSIP) provides methodology for highway safety improvement projections.

A simple way to look into project safety is to evaluation project alternatives by estimating monetary value of project benefits, number of total crashes reduced, number of fatal and incapacitating injury crashes reduced, number of fatal and injury crashes reduced, and cost-effectiveness index (Layton, 2010).

Development of an Index System for Highway Engineering Projects Priority Ranking Principles

The factors to be considered in the projects priority ranking should reflect the objectives of the road investment program (Thagesen 2003, p.65). Those factors should be measurable and be able to indicate the significance of the project. Therefore, the following principles should be considered when constructing an index system for highway engineering projects priority ranking.

Fwa (2005, p.1-11 and p.1-12) listed some of the common reasons that lead to project failure in developed countries, such as poor public relations, unrealistic budgets, inappropriate design, lack of cooperation, wrong placement of expertise, distrust, as well as sensitive environmental and social issues.

[4] http://www.dot.state.fl.us/publicinformationoffice/moredot/mvv.shtm, accessed April 24, 2015

Pertinence: The index system must be pertinent to the solution to the highway network requirement. In the United States, sufficiency ratings have been developed in most states to help determine which highway sections should be improved under budgetary constraints. For example, the 2014 Florida Statutes (Chapter 335, Section 335.07) requires that the FDOT adopt a sufficiency rating system for roads on the State Highway System and the determination of rating be based on structural adequacy, safety, and service and further on a series of considerations (Figure 5-4). Please note that road improvement costs are not taken into account; sometimes this is believed a drawback of the sufficiency rating method.

Based on the sufficiency rating or other similar rating scales, a priority index (PI) can be developed as follows together with consideration of incremental costs:

$$PI = \frac{(R_i - R_e) \times w}{C} \tag{5-7}$$

Where: R_i = improved condition rating; R_e = existing condition rating; w = importance weight; and C = incremental costs.

Practice of State DOTs: Many State DOTs have adopted some form of project prioritization process, although the applied prioritization criteria vary. Table 5-5 shows the application developed by DelDOT.

The North Carolina Department of Transportation (NCDOT) developed highway scoring criteria[6] for strategic transportation investments prioritization, measured on a 0 to 100 point scale (Table 5-6).

Construct of a Comprehensive Index System

There are a great number of factors that can influence the priority of highway engineering projects construction, and thus selection of appropriate factors has to be made so that the selected

[6] https://connect.ncdot.gov/projects/planning/STIData/Highway_CriteriaSummaryReport.pdf

ones can accurately reflect the project condition in different aspects, such as necessity, importance, benefits, costs, and traffic impacts of the construction of the highway engineering project. Šelih et al. (2008) used facility rating, facility age, indirect costs, and project cost as criteria and calculated utility values to rank highway infrastructure rehabilitation projects within budget constraints. Ziara et al. (2002) proposed a risk-based AHP model for infrastructure projects prioritization by using project importance, sector importance, finance suitability, execution suitability, operation suitability, reliability, and consequence of failure as multiple criteria.

Degrees of Urgency: Flow ratio (v/s) can be used as a measurement of degrees of urgency. It is the ratio of the actual flow rate or projected demand v on an approach or lane group to the saturation flow rate s.

Degree of saturation is used to compare traffic demand with the total capacity of a road. It is calculated as a ratio of demand to capacity on each approach to the junction. A 100% degree of saturation (i.e., equal demand and capacity) indicates that no further traffic is able to progress through the junction. Values over 85% are typically regarded as suffering from traffic congestion, with queues of vehicles beginning to form.

Classification of Roadways: As early as in 1989, FHWA developed a classification system of roadways according to their functions. The revised functional classification categories, identified by FHWA (2013), consist of four roadway classes:

- Local roads: have low operating speeds, serve local residences and businesses, and provide access to collectors.
- Collectors: have intermediate travel speeds, channel traffic from local roads to arterials, and trade off the demands between land access and mobility.
- Minor arterials

- Principal arterials (including interstate highways, freeways, and expressways): provide mobility (i.e., safe, reliable, and efficient travel) between towns and cities, and are used for long distance travel at high speeds.

Obviously, such a classification system partly reflects the degree of urgency of different roadways and thus potentially indicates the construction priority in a sense. This gives us an opportunity to assign coefficients (α) to different classes of roadways in order to reflect their priorities. The following coefficients have been assumed in this dissertation:

- Local: $\alpha = 0.5$
- Collector: $\alpha = 1.0$
- Minor arterial: $\alpha = 1.0$
- Principal arterial (including interstate highways, freeways, and expressways): $\alpha = 1.5$

The degrees of urgency for the highway engineering projects are obtained by calculating the weighted average of the degree of saturation and the coefficient of the roadway classification.

Also note the distinction between highways in Florida (which include all roads in Florida) and highways on the Florida State System (which consists of highways maintained by FDOT). A variety of terminology exists for highway construction projects.

Degrees of urgency can also be connected with the status of congestion. FDOT (2011) identified congested roadways and bottlenecks on Florida SIS by using a combination of planning time index and frequency of congestion. Here congested roadways and bottlenecks were quantified by the duration, extent, intensity, and reliability of the congestion.

Importance of Highway Engineering Projects: The importance of highway engineering projects also needs to be taken into account when we prioritize the development and construction of the projects. It makes sense that priority should be given to those highway projects that have large impacts on the roadway network, the function of the network, and the level of service. The degree of importance of the roadway can be reflected by the importance of the nodes that connect different roads or links.

The importance of the nodes indicates the contribution of the corresponding area to traffic demands, and such contribution can be decomposed of both direct traffic demand statistics (e.g., freights) and indirect social economic statistics (e.g., population, average vehicles per household, per capita GDP, average income, etc.). Therefore, the degree of importance of the nodes can be expressed as follows:

$$D_i = \frac{1}{m}\sum_{j=1}^{m}(\frac{a_{ij}}{a_{\bar{j}}} \times e_j) + \frac{1}{n}\sum_{j=1}^{n}(\frac{b_{ij}}{b_{\bar{j}}} \times f_j) \tag{5-8}$$

Where: D_i = The degree of importance of Node i, $i = 1, 2, ..., s$

a_{ij} = The *j*th traffic statistics of Node *i*, $j = 1, 2, ..., m$

b_{ij} = The *j*th social economic statistics of Node *i*, $j = 1, 2, ..., n$

$a_{\bar{j}}$ = The average of the *j*th traffic statistics, $a_{\bar{j}} = \frac{1}{s}\sum_{i=1}^{s} a_{ij}$

$b_{\bar{j}}$ = The average of the *j*th social economic statistics, $b_{\bar{j}} = \frac{1}{s}\sum_{i=1}^{s} b_{ij}$

e_j, f_j = The weights of each statistics

Further, the importance of the link between Nodes i and j can be determined as follows:

$$L_{ij} = \frac{D_i}{N_i} + \frac{D_j}{N_j} \tag{5-9}$$

Where: L_{ij} = The degree of importance of the link between Nodes i and j

D_i, D_j = The degrees of importance of Nodes i and j, respectively

N_i, N_j = The numbers of links that are directly connected with Nodes i and j, respectively

Economical Assessment of Highway Construction: As a critical part of highway construction feasibility analysis, the economical feature of highway construction must be assessed. The cost-benefit analysis should be conducted on the basis of traffic demand forecast and engineering characteristics. Among others, NPV and IRR are usually calculated with regard to the highway construction economical assessment.

A case in point is Florida’s Turnpike system, which uses the following key performance indicators:

- Affordability Index: a measure of toll revenue to annual vehicle miles traveled.
- Operating Expense Percentage: a calculation of operations and maintenance expense as a percentage of revenue.
- System Transportation Asset Reinvestment (STAR): a ratio of income before contributions to toll revenue.

Traffic Effects of Highway Construction: The traffic effects of highway construction are reflected by the degree to which the roadway network system is improved in terms of level of service. Such improvements include the improvements on both the degree of congestion and the travel time. In other words, we want to know the impacts of construction of a specific highway on the improvements of the roadway network operation efficiency and quality.

The impact on the roadway network operation efficiency can be assessed by the change in total travel time. Reduce in total travel time is obviously a sign of traffic improvement and can be estimated.

We must notice that the investment level can have huge impact on the level of improvement, and thus we may want to know the total time savings per dollar value, i.e., the roadway network operation efficiency improvement rate:

$$r_O = \frac{\Delta T}{I} \tag{5-10}$$

Where r_O is the efficiency improvement rate, and I is the invested dollar amount of money. Similarly, we can calculate the roadway network congestion improvement rate, based on the calculation of the congestion degree for the roadway network.

Preference for mode choice is often designated by a utility function composed of both trip cost and trip time. A typical utility function for a specific transportation mode can be simply developed as a linear relationship as follows:

$$U_i = K - \beta C_i - \delta T_i \qquad (5\text{-}11)$$

Where: U_i, C_i, T_i = Utility, trip cost, and trip time for mode I, respectively

K = Constant

β, δ = Relative weights of each service variable

Apparently, a passenger is most likely (and thus has the largest probability) to choose the trip mode with the highest utility.

A logit model further estimates the probability, P_i, that a user with a utility value, U_i, will select mode i from n modes being considered.

$$P_i = \frac{e^{U_i}}{\sum_{j=1}^{n} e^{U_j}} \qquad (5\text{-}12)$$

Highway maintenance costs can be budgeted according to historical trends for remedial maintenance and according to the pavement management system (PMS) outputs for preventative maintenance. The estimated annual costs ranges for remedial and preventative maintenances are \$1,000~\$5,000/lane-kilometer and \$4,000~\$8,000/lane-kilometer, respectively, and the sum of both costs can account for 1%~4% of the initial highway construction costs (Fwa, 2005). Selecting a specific value from both ranges should depend on the age of the road, the importance, the traffic levels, the location, etc. In a National Cooperative Highway Research Program (NCHRP) report, Markow (2011) suggested a full cost determination process.

Summary

The main goal of the prioritization process is to select projects that will generate maximum value, both monetary and non-monetary, resulting from trade-off optimization under budget constraints. To simplify the process, we assume that the best design alternative for each project has been submitted and been used in the process. Projects to be prioritized should be those listed in the long-range planning and in the future work program and thus the prioritization is an on-going process. In practice, the most widely-used prioritization methods include NPV, IRR, B/C ratio, incremental B/C analysis, cost effectiveness measures, as well as optimization methods.

The purpose for ranking highway engineering projects priorities is to effectively and efficiently use the highway development capital. Specifically, we aim to achieve a trade-off optimization of project time, cost, and quality for the whole project life cycle. We expect to achieve optimum economic benefits and optimum highway network traffics with least and reasonable capital investment for highway planning, construction, operation, and maintenance.

Based on those economic, technological, environmental, and safety attribute, an index system for highway engineering projects priority ranking has been developed in this chapter. Chapter 7 will follow on the proposed index system with a case study.

Table 5-1. Importance of Transportation Infrastructure

Category	Possible Indicators
User Impact	Traveling costs reflected by time, safety, comfort, and reliability
Economic Impact	Changes in employment, personal income, property values, business sales volume, and business profit
Government Fiscal Impacts	Changes in public revenues and expenditures
Other Social Impacts	Air quality and other environmental conditions

Table 5-2. Components of Benefit-Cost Analysis

Benefits	Costs
Increase in personal income	Construction costs
Increase in personal auto benefits	Operations and maintenance costs
Increase in consumer surplus	General overhead and administration costs

Table 5-3. Benefits and Costs Associated with Transportation Projects

Agency Costs	User Costs/Benefits Associated with Work Zones	User Costs/Benefits Associated with Facility Operations	Externalities
Design and engineering	Delay	Travel time and delay	Emissions
Land acquisition	Crashes	Crashes	Noise
Construction	Vehicle operating costs	Vehicle operating costs	Other impacts
Reconstruction/Rehabilitation			
Preservation/Routine maintenance			
Mitigation (e.g., noise barriers)			

Source: USDOT (2003)

Table 5-4. Key Highway Financials in the United States

Revenue Sources		Expenditure	
Source	Percentage (%)	Type	Percentage (%)
General funds:	26.5	Capital outlay:	48.8
Motor-fuel taxes:	26.0	Maintenance and traffic services:	23.8
Bonds:	14.9	Highway patrol and safety:	8.8
Motor-vehicle taxes:	12.2	Administration:	7.9
Tolls:	4.3	Bond retirement:	6.0
Other:	16.1	Interest on debt:	4.8

Data Source: USDOT (2013)

Table 5-5. DelDOT Project Prioritization Process

	Criteria	Weight	Description
DelDOT[7]	Safety	33.0%	The ability of the transportation system to allow people and goods to move freely, without harm
	System operating effectiveness	24.8%	The ability of the transportation system to efficiently move people, goods and services without excessive delay or inconvenience
	Multi-modal mobility, flexibility/access	15.6%	The ability of a project to provide efficient movement of people and goods between destinations by motor vehicle, pedestrian, bicycle and transit modes
	Revenue generation/economic development/jobs & commerce	7.9%	The ability of a project to facilitate or support business development and employment
	Impact on the public/social disruption/economic justice	7.2%	The assessment of the project on the transportation system as it relates to existing communities and population centers
	Environmental impact/stewardship	6.5%	The effect of the transportation system on energy use and the natural environment
	System preservation	5.0%	Fix It First/State of Good Repair addresses the improvement of the physical condition of existing transportation assets

[7] See: https://www.deldot.gov/information/pubs_forms/CTP/pdf/DelDOT_project_prioritization_criteria_summary.pdf

Table 5-6. NCDOT Project Prioritization Process

Criteria	Formula	Weight
Congestion	(Existing traffic volume/Roadway capacity ratio*100*60%) + (Existing traffic volume/1000*40%)	Statewide mobility – 30% Regional impact – 25% Division needs – 20%
Benefit/Cost	Travel time savings/Project costs	Statewide mobility – 30% Regional impact – 25% Division needs – 20%
Economic competitiveness	Number of long-term jobs created (50%) + Value added in dollars based on productivity change in division economy (50%)	Statewide mobility – 10%
Safety	For segments: (Crash density*33%) + (Severity index*33%) + (Critical crash rate*33%) For intersections: (Crash frequency*50%) + (Severity index*50%)	Statewide mobility – 10% Regional impact – 15% Division needs – 10%
Multimodal	((V/C Ratio [STRAHNET] x 100) x 25%) + ((V/C Ratio [Route to Transportation Terminal] x 100) x 25%) + (Truck Volumes / 100 x 50%)	Statewide mobility – 20%
Accessibility / Connectivity	Measured by county tier designation, upgrade roadway function, and commute times	Regional impact – 10%
Lane width	The existing lane width – DOT design standard lane width	Regional impact – 10% Division needs – 10%
Shoulder width	The existing paved shoulder width – DOT design standard paved shoulder width	Regional impact – 10% Division needs – 10%

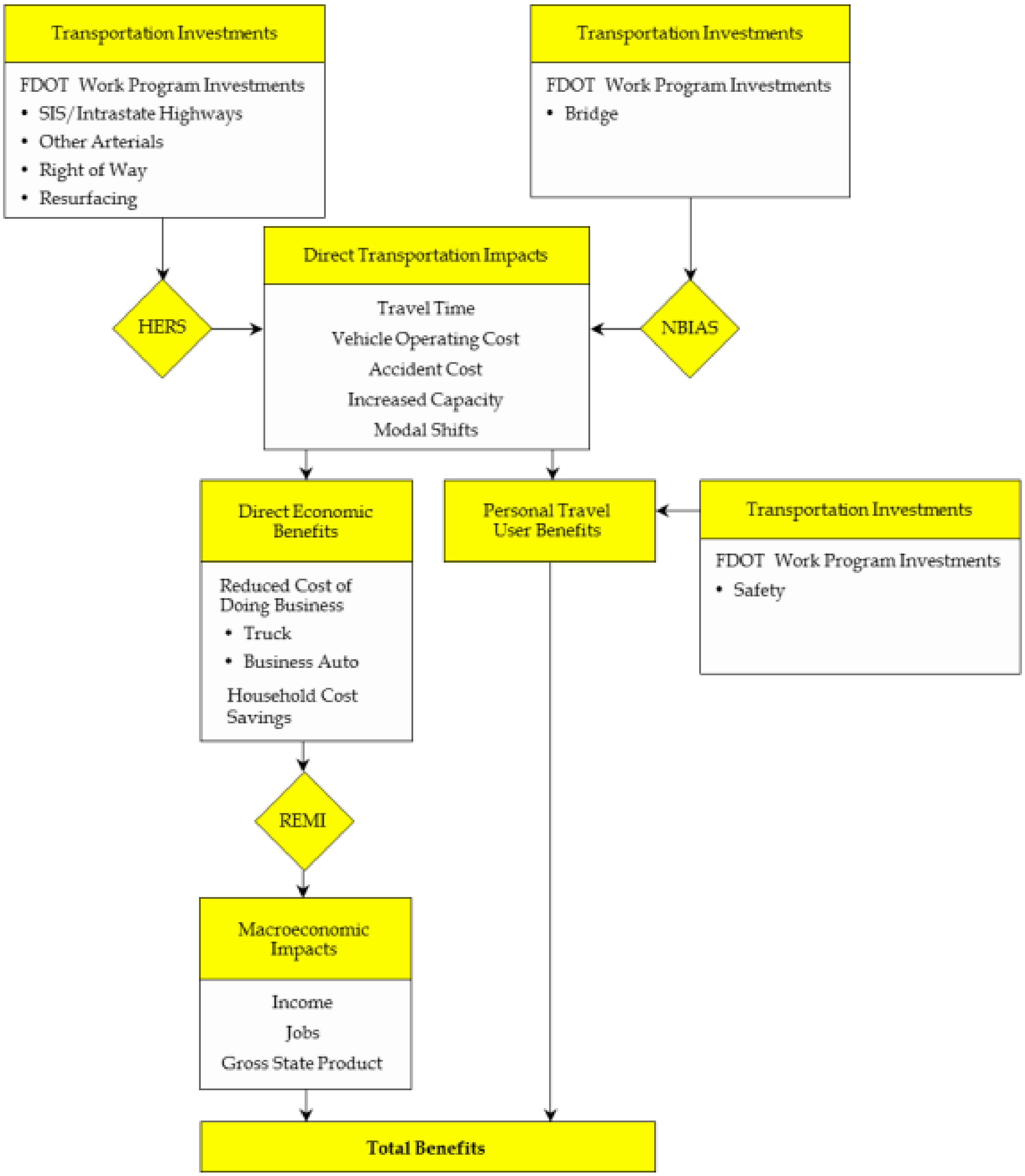


Figure 5-1. FDOT Highway Analysis Approach

Source: FDOT

Criteria	Points Possible
1) Population and Education	
Two sub-criteria are analyzed: 1) population within a 20-mile radius of the project and 2) education within a 40-mile radius of the project	10 points each
Total Points Possible	*20*
2) Existing Infrastructure	
Evaluated by proximity to the roadway project. Six different types are evaluated: 1) electrical power (transmission lines), 2) culinary water, 3) railway mainline/spur, 4) freeway interchange, 5) industrial level sewer, and 6) advanced communications	5 points each
Total Points Possible	*30*
3) Economic Attractiveness	
Four sub-criteria are analyzed: 1) recent economic success of area, 2) economic hot spots, 3) size (cost) of the project, and 4) expert feedback	10 points each
Total Points Possible	*40*
4) Tourism	
Evaluated by proximity to a tourist attraction (Non-urbanized[1] area radius is 50 miles and urbanized[2] area radius is 10 miles) as well as achievement of state goals and the roadway project classification	
Total Points Possible	*10*
Total Points Available	**100**
Bonus: Economic Choke Points	
Evaluated based on the priority given by the UDOT region or district	
Total Points Possible	*10*
Total + Bonus	**110**

[1]Non-urbanized: Areas with a population of less than 50,000

[2]Urbanized: Areas with a population of more than 50,000

Figure 5-2. Scoring System Developed by Utah Department of Transportation

Source: Schultz and McGee (2009)

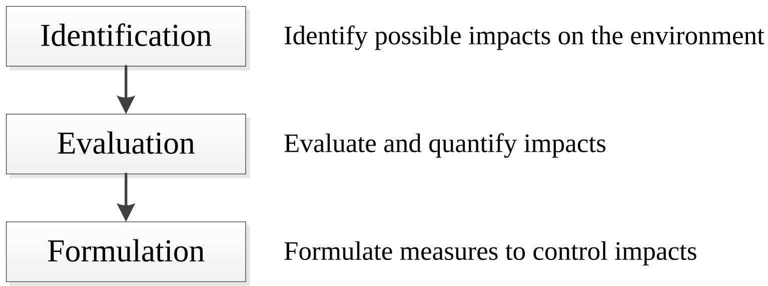


Figure 5-3. EIA Process

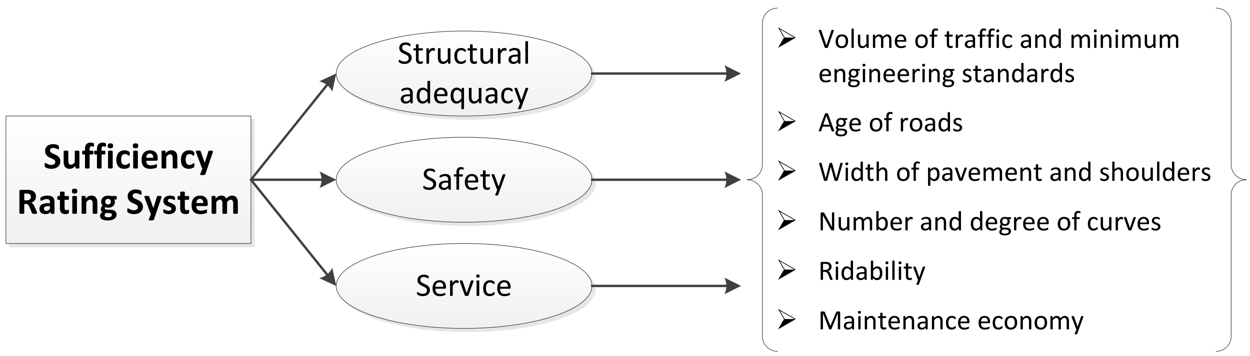


Figure 5-4. Sufficiency rating system for roads on Florida State Highway System

CHAPTER 6
APPLICATION OF MULTI-OBJECTIVE DECISION-MAKING OPTIMIZATION: PROJECT TIME-COST-QUALITY TRADE-OFF ANALYSIS

Basic Assumptions and Notations

A general linear, deterministic time-cost-quality trade-off analysis is based on the following assumptions:

- Direct cost is negatively related with project/activity time.
- Indirect cost (general overhead and administration expense) is positively related with project time.
- High project/activity quality is achieved when the project/activity is executed within reasonable (efficiency) time.
- A job task can be completed with a variety of modes, and each mode varies in time, cost, and quality due to the selection of crews, materials, equipment, and other fuzzy factors.

Linear relationships are also assumed in the linear model analysis.

The following notations will be used:

- n : number of activities
- s_i : early start date of activity *i* (assume $s_1 = 0$)
- t_i : duration of activity *i*
- t_i^N : normal (accepted longest) time for activity *i*
- t_i^C : crash time for activity *i*
- c_i^N : normal cost for activity *i*
- c_i^C : crash cost for activity *i*
- q_i^N : normal quality for activity *i*
- q_i^C : crash quality for activity *i*
- T : total time (duration) of the project

- C : total project cost
- Q : overall project quality

Given these assumptions and notations, linear relationships between project time and cost and between project time and quality can be drawn in Figures 6-1 and 6-2.

Basic Problem Statement

The duration of each activity *i* is bounded by its normal time and by its crash time:

$$t_i^C \le t_i \le t_i^N \tag{6-1}$$

For each activity *i*:

$$s_i + t_i \le s_{i+1} \tag{6-2}$$

Total project duration:

$$T = \sum_{i \in CP} t_i \tag{6-3}$$

where *CP* is the activity set on the critical path.

Total project cost:

$$C = \sum_{i=1}^{n} (a_i t_i + b_i) \tag{6-4}$$

where $a_i = \dfrac{c_i^C - c_i^N}{t_i^C - t_i^N}$ and $b_i = c_i^N - a_i t_i^N = \dfrac{c_i^N t_i^C - c_i^C t_i^N}{t_i^C - t_i^N}$ according to the (negative) linear relationship between project cost and time.

Overall project quality:

$$Q = \sum_{i=1}^{n} (f_i t_i + g_i) \tag{6-5}$$

where $f_i = \frac{q_i^C - q_i^N}{t_i^C - t_i^N}$ and $g_i = q_i^N - f_i t_i^N = \frac{q_i^N t_i^C - q_i^C t_i^N}{t_i^C - t_i^N}$ according to the (positive) linear relationship between project quality and time.

The linear programming model is developed to get the Pareto optimal solution set by minimizing *T* and *C* and maximizing *Q*. For different budget constraints and quality tolerances, minimizing *T* yields the shortest project completion times. Similarly, minimizing *C* yields the lowest project cost given completion due dates and quality tolerances. Maximizing *Q* yields the best project quality subject to a function of budget levels and project duration.

Further Development of Models

The basic problem statement is based on the assumption of linear relationships, and without consideration of other indicators and uncertainties that have often been met in real engineering practice. It is also limited in the construction phase of a project. Further development of optimization models should take into account those constraints.

Revision to the Cost-Time Linear Relationship

The expression of project cost (*C*) in the above section assumes increasing cost linearly by reducing project time. This is questionable in two major aspects: firstly, in a project, while direct cost is probably negatively related with activity time (and thus crash cost is higher than normal cost), indirect cost (e.g., general overhead and administration expense) increases with project time.

As a starting point, a simplified non-linear expression for activity i's direct cost, c_i^D , is:

$$c_i^D = a_i^D t_i^2 + b_i^D \tag{6-6}$$

Where a_i^D and b_i^D can be obtained from the corresponding time-cost curve.

A simplified expression for the project's indirect cost (C^{ID}) is:

$$C^{ID} = \rho T \tag{6-7}$$

where ρ is the indirect cost rate ($/day) and is a constant.

The total project cost is now:

$$C = C^{ID} + \sum_{i=1}^{n} c_i^D = \rho T + \sum_{i=1}^{n} c_i^D \tag{6-8}$$

Revision to the Quality-Time Linear Relationship

The quality-time relationship is not linear because of at least two reasons: Firstly, optimal quality can seldom be obtained if the project is "crashed" (i.e., the project duration is close to crash time) or delayed (i.e., the project duration is close to the longest accepted time); and secondly, the overall project quality is not simply a sum of each activity's quality. More reasonable assumptions should be made that optimal activity quality can be achieved when the activity is finished within some commonly expected time, and that the overall project quality can be expressed by a reliability function of each activity's quality.

As a starting point, a simplified method introduces the weight of activity i's quality relative to the overall project quality, determined by historical data or expert opinions. Therefore, the adjusted expression of overall project quality is:

$$Q = \sum_{i=1}^{n} w_i (f_i t_i + g_i) \tag{6-9}$$

Where $w_i > 0$ and $\sum_{i=1}^{n} w_i = 1$.

Other, more complicated expressions of *Q* will be discussed in the dissertation. For example, a reliability function can be applied to define activity *j*'s quality (q_j) based on its precedence's quality (q_i):

$$q_j = [1 - \prod_{i \in j_{pre}} (1 - q_i)] q_i \tag{6-10}$$

where j_{pre} is the set of activity *j*'s precedence activities.

Application of Time Value of Money

Infrastructure engineering projects are usually capital-intensive, requiring large amounts of money and other financial resources. Cash flows of the projects and the impact of time value of money, although often neglected, must be optimized within the constraints of time, cost, and quality objectives. Essentially, financing and its impact on project profits should be treated as a cost accrued, which most optimization models fail to reveal. The net present value (NPV) method is usually believed an effective way to count the time value of money.

NPV is defined as the discounted sum of all expected future revenues minus the initial cost and the discounted sum of all expected future costs (Hirst 2001; Newan et al. 2004). The concept of NPV has been employed by a number of researchers to solve project scheduling and time/cost trade-off problems.

Based on expressions discussed above, the present value of the project cost (C_{PV}), under a discount rate of r, is:

$$C_{PV} = \rho T \times \frac{(1+r)^T - 1}{r(1+r)^T} + \sum_{i=1}^{n} [c_i^D (1+r)^{-(s_i + \frac{t_i}{2})}] \tag{6-11}$$

Now the cost objective is to minimize C_{PV}.

Of course, a more accurate way to deal with financing costs requires developing a cash flow model of each activity at each project phase over the project life cycle. A comprehensive finance-based scheduling (in terms of time-cost-quality trade-off optimization) model over the project life cycle will be presented in this dissertation.

Existing literature implies continuous changes among project time, cost, and quality; however, they often perform in a discrete way in practice. Meanwhile, one of the optimization objectives is to minimize project costs; however, minimum costs do not necessarily indicate maximum benefit for decision-makers. Most of the existing models also do not take the time value of money into consideration.

Decisions on project time-cost-quality trade-offs affect, both directly and indirectly, the contractor's net benefit, based on which the contractor adjusts his/her objectives about project time, cost, and quality.

The project duration is T (in years). The price (value) in the contract is V. The payment, P_i, occurs at the end of the ith month. The pre-payment percentage is ρ_1 and thus the pre-payment is $\rho_1 V$. Similarly, assume the percentage for quality (performance?) bond is ρ_2 and thus the performance bond (quality warranty?) is $\rho_2 V$, which will be paid at Time t_i (in years).

The net present value of the contract value, V, is:

$$NPV = \rho_1 V + \frac{\rho_2 V}{(1+r)^{t_i}} + \sum_{i=1}^{12T} \frac{P_i}{(1+r)^{i/12}} \tag{6-12}$$

Now we consider bonus and punishment allocated by the project owner. Bonus and punishment have been applied by the project owner for the purpose of project control. They should not be neglected by the contractor, as the dollar amount of bonus and/or punishment may have big impact on the contractor's net benefit and also on the overall project quality. The payment method of bonus and punishment, along with the impact of time value of money, are analyzed and modeled in this research.

Assume the project deadline is D (or rather, the project is required to be completed within D days). The contract price, V, will be paid in full to the contractor if the project is completed within the timeline $[D-d_B, D+d_P]$. If the project is completed at time *T* before time $(D-d_B)$, the contractor will receive an additional amount of money, $\gamma_B V(T-D+d_B)$, as bonus. If the project is completed at time *T* after time $(D+d_P)$, however, the contractor will get punished by an additional amount of money, $\gamma_P V(T-D-d_P)$, as punishment.

The multi-objective optimization function of the total project can be summarized as:

$$Z = \min\{T, C, -Q\} \tag{6-13}$$

Introducing Multiple Attribute Utility Functions

Utility analysis has also been conducted to help make better decisions by building mathematical models of a decision-maker's preferences. A basic multiple attribute utility function (*U*) for the time-cost-quality trade-off analysis can be written as:

$$U = \sum \varpi_P u_P = \varpi_T u_T + \varpi_C u_C + \varpi_Q u_Q \qquad U \in [0,1]; u_P \in [0,1] \tag{6-14}$$

where: ϖ_P is the weight for the performance *P* (time *T*, cost *C*, or quality *Q* in this case) and $\sum \varpi_P = 1$.

u_P is the single attribute utility function for the performance *P*. For a risk-neutral person, the utility function can simply be defined as:

$$u_P = \alpha_P y + \beta_P \tag{6-15}$$

where α_P and β_P are constants and can be determined based on the best and worst performances, and y denotes the performances for an alternative.

Zhang and Xing (2010) suggested the following form of utility function for the TCQT analysis:

$$u_T = \frac{T^N - T}{T^N - T^C} \qquad u_C = \frac{C^C - C}{C^C - C^N} \qquad u_Q = \frac{Q - Q^C}{Q^N - Q^C} \tag{6-16}$$

For the consistence purpose, the above expressions use superscripts N and C to denote normal and crash schedules, respectively.

Now the solution to the TCQT problem is to find the optimal alternative that has the largest multiple attribute utility, namely:

$$\max U = \max(\varpi_T u_T + \varpi_C u_C + \varpi_Q u_Q) \tag{6-17}$$

Project Time-Cost-Quality Optimization

Project quality relies on the quality of each task. Completing a task within different time schedules, however, results in different levels of quality. The following assumptions are made:

- Reducing normal time of a task will degrade the task quality.
- Lengthening normal time of a task, however, will not necessarily upgrade the task quality; conversely, a slightly degraded quality is expected.

Therefore, the quality level for the *i*-th task can be calculated as:

$$q_i^{out} = [1 - \prod_{j=1}^{m} (1 - q_j^{in})] \times q_i, i = 1, 2, \ldots, n \tag{6-18}$$

Where q_i^{out} is the output quality level for the *i*th task. q_j^{in} is the input quality level of the *j*th predecessor and task I has m predecessors. Please note that $q_1^{in} = 1$.

Further, the fact that project time, cost, and quality compose an Iron Triangle gives indication that changes to any of the three variables will affect the other two. Specifically:

- Reducing project time will most likely result in increase in cost and decrease in quality.
- Reducing project cost will most likely result in increase in time and decrease in quality.
- Increasing project quality will most likely require increase in both cost and time.

Two more presumptions are made before analysis is conducted in the following chapters:

- Orders of each task as well as its predecessors and successors remain the same. Therefore, if time for each task is known, the project time can be calculated with the Critical Path Method.
- Quality (or rather, level of quality) is relatively scaled and rated within [0,1], with 0 representing the minimum quality level and 1 representing the maximum quality level. This makes the level of project quality comparable under different engineering conditions.

A variety of time-cost trade-off models have been proposed by researchers with the development and progress of network program techniques. Two categories are generally referred to in the literature: One assumes unconstrained resources with constrained schedule; the other assumes unconstraint time with constrained resources. The first category is more practical and is the focus of this research.

It is also necessary to propose different expressions for direct cost and indirect cost, as they change with project time not in the same mode (way).

Generally speaking, shortening project duration, no matter how it is achieved, will increase direct costs, as more labors or equipment have to be used, or labors have to work overtime. Assuming a quadric relationship, a curve for direct costs vs. project time can be plotted.

On the other hand, indirect costs (mostly overheads and general administration expenses) decrease with the decrease in project time. A linear relationship between indirect costs and project time is assumed in this research.

Therefore:

$$c_i = c_{ni} + \alpha t_i + \beta_i (t_{ni} - t_i)^2 \qquad (6\text{-}19)$$

Where: c_{ni} is the normal cost. T_{ni} is the normal duration for task *i*. t_i is the actual duration for task *i*.

Summary

In this chapter, a project time-cost-quality trade-off optimization model is proposed based on the multi-objective decision-making theory discussed in Chapter 4.

Compared with single-objective decision problems, multi-objective problems are much more complicated, as those multiple objectives are potentially such conflicting that measures for improving one objective would most likely worsen the performance of other objectives. Therefore, instead of seeking for a unique optimization solution (as is the case for single-attribute decision problems), we have to put effort to find an optimization set, i.e., the Pareto optimality, for multi-objective optimization problems (Zio and Bazzo, 2012).

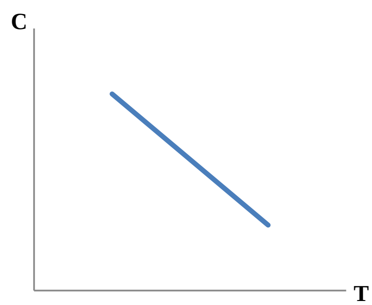


Figure 6-1. Linear Relationship Between Time and Cost

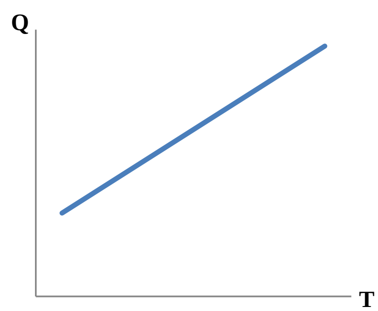


Figure 6-2. Linear Relationship Between Time and Quality

CHAPTER 7
CASE STUDY I: SIS HIGHWAY PROJECTS PRIORITIZATION IN FDOT DISTRICT 2

In this case study, potential highway development projects on Strategic Intermodal System (SIS) highway routes in FDOT District 2 are selected as samples. Participants in the decision-making process may include stakeholders representing FDOT, planning authorities, and local government agencies. Project goals, criteria, weights, and alternatives should be established by those stakeholders. This case study does not, however, incorporate all direct inputs from those stakeholders because the purpose of this case study is to evaluate the efficacy of the proposed model. Therefore, the inputs here rely to a large extent on the researcher to serve the above stakeholder roles.

Case Description

In July 2014, the FDOT adopted the Strategic Intermodal System (SIS) 1st Five-Year Plan, a work program representing "a financially feasible planning document that consists of all SIS funded projects for the current fiscal year and ensuing four years". A typical page of the Plan is extracted and displayed in Figure 7-1. The information about project limits, location, major improvement, and phasing costs is listed for each project in the Plan. The project's unweighted Strategic Investment Tool (SIT) scores are also summarized. The SIT is used for project prioritization and selection purposes by measuring the following six major goals in a total of 120 points (Figure 7-2): (1) safety & security; (2) maintenance & operations; (3) mobility & connectivity; (4) economic competitiveness; (5) livable communities; and (6) environmental stewardship. In essence, Florida's SIS was established to help allocate limited State resources to those critical projects that were picked based on the evaluation and prioritization processes, and in such processes SIT was developed as one of the tools for determining highway project priorities. The SIT highway and connector measures are listed as follows. Figure 7-3 illustrates the decision-making process of FDOT and its partners for funding SIS investments.

In comparison, High Country Rural Planning Organization (RPO) of North Carolina Department of Transportation (NCDOT) proposed a project solicitation and ranking process NCDOT, 2015) to evaluate STIP transportation projects. For highways, RPO assigns a total of 100 points to 9 prioritization criteria, as shown in Table 7-1.

The FDOT is decentralized in 7 districts (Figure 7-4). District 2 is located in Northeast Florida and includes the following 18 counties: Alachua, Baker, Bradford, Clay, Columbia, Dixie, Duval, Gilchrist, Hamilton, Lafayette, Levy, Madison, Nassau, Putnam, St. Johns, Suwannee, Taylor, and Union. As of now, this district has 2,556 centerline miles and 8,197 lane miles on the State Highway System, with more than 43.2 million miles daily travel[8].

Data Sources

Nationally, the USDOT Bureau of Transportation Statistics developed the National Transportation Atlas Database (NTAD), a database of transportation network data in the United States. Evaluation of conditions of bridges and highways can be collected from the National Bridge Inventory (NBI) and the Highway Performance Monitoring System (HPMS), respectively. In additional, a number of states have established their own pavement management systems and safety reporting systems. Also nationally, the Fatality Analysis Reporting System (FARS) documents all country-wide fatal crashes. Table 7-2 lists major national data sources.

FDOT and some other Florida agencies maintain a number of data base. Data used in this dissertation research were obtained from the following sources.

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[8] See http://www.dot.state.fl.us/publicinformationoffice/moreDOT/districts/dist2.shtm for details.

Project environmental impact analysis data are obtained with the Environmental Screening Tool on the Efficient Transportation Decision Making (ETDM) Web site:

https://etdmpub.fla-etat.org/est/

ETDM published on the website information about proposed transportation projects, information including environmental data and discussion, sociocultural data, and agency environmental comments, etc.

The Florida Traffic Safety Portal, developed by the State Safety Office of the FDOT, makes information available about tools, data, and ideas about traffic safety in Florida. Safety information and data (e.g., crash statistics) can then be obtained from this Portal:

https://fdotewp1.dot.state.fl.us/TrafficSafetyWebPortal/

Updated project information can be checked through the Office of Work Program and Budget of FDOT. Projects in the Five Year Work Program are displayed there, information including project description, type of work, item number, length, scheduled activities, fiscal year budgets, and map of item.

http://www2.dot.state.fl.us/fmsupportapps/workprogram/WorkProgram.aspx

Among them the map of item is made available through the interactive FDOT WPA / PSM online tool.

https://wpagis.fla-etat.org/viewer.htm

Brief Description of Selected Projects

Figure 7-5 shows the major highway projects being planned in FDOT District 2. They are at different project planning phases. Nine out of those projects were randomly selected for prioritization analysis using the methodology proposed in the dissertation. Travel demand in District 2 was first analyzed. Prioritization criteria were chosen from the discussion in Chapter 5. Weights of each criterion were calculated using the suggested AHP-Entropy method as well as the Fuzzy AHP method. The weights were then inputted in the TOPSIS spreadsheet. Based on the TOPSIS result, a prioritization list of the 9 projects was suggested.

Demand Analysis: Trip Generation

Regional Travel Demand Model: Descriptive Statistics

Samples for District 2 are first extracted out from the overall data file (i.e., the Florida samples from the 2009 National Household Travel Survey). Cases are then sorted by district. This results in 1879 cases in total for District 2.

Before cleaning the data, we may want to review the data so that we can later clean the data and create the explanatory variables reasonably. An overview of the original data from those households in District 2 is described in detail in Appendix A. Some of the observations are listed as follows.

Count of Household Members: Two-member households are common in District 2. Almost half of the households are comprised of two members (49.3% in District 2). Few households (less than 2% of total households) in the district have more than five members in them.

Count of Adult Household Members at Least 18 Years Old: Two-adult households are typical (64.8% in District 2). Followed are one-adult households (23.8% in District 2). Around 10% of the households have more than two adults.

Number of workers in HH: 43.3% of the households in District 2 have no workers in them. More than half of the households in District 2 have one (34.4%) or two (19.5%) members employed.

Life Cycle for the HH: The life cycle for the households is indicated in the frequency table. As we may see, households with two or more retired adults but without children are very common in District 2 (32.9%).

Number of Drivers in Household: Two-driver households are common (57.3% in District 2). This is consistent with the observation in count of adult household members. Similarly, followed are one-driver households (27.9% in District 2).

Count of Household Vehicles: Two-vehicle households are common in District 2 (42.4%). Few households have more than 5 vehicles in this district.

Derived Total Household Income: Assume low-income households are those with derived total income less than $30,000, med-income $30,000~$79,999, and high-income more than $80,000. There are 23.6% high-income households in District 2 36.6% low-income households in District 2.

Housing Unit Owned or Rented: Most households in District 2 (more than 90%) own their houses, and detached single houses are typical (around 70%).

Other Observations: Most of the households in District 2 are white (accounting for around 90%). More than half (52.3%) of the households in District 2 report that their home addresses are located not in an urbanized area. It seems that households in District 2 generate more trips on Mondays than other weekdays or weekends. Most of the households in District 2 are permanent residents, namely, they lives more than 6 months a year in Florida. Seasonal travelers are less than 2% in both districts.

Count of Household Vehicles by Count of Household Members Crosstabulation: Crosstabs for HHVEHCNT by HHSIZE are also run for analysis. Observations for both districts are similar: Households that have only 1 adult typically own only 1 car. Households that have 2 or more adults typically own 2 cars; in such cases, increase in number of adults in a household does not lead to significant increase in number of cars.

New Variables Creation: Other than the existing variables that have been defined in the original data, the following new variables are created based on the observations from the descriptive statistics.

- Variables for household life cycle are created, broken down by retired households, working households without children, and working households with children.
- A binary variable for seasonal residents and permanent residents is created. A household is considered seasonal if they live in Florida more than one month but less than six months a year.
- Market segmentation variables are created for increment of cars, from zero to 3 or more (3+).
- The number of children variable was created by subtracting the number of adults from the household size.
- New variables for income are created, broken down by low, medium, and high. Low income households earn less than $30,000. Medium income households earn incomes ranging from $30,000 to $80,000. High income households earn greater than $80,000.
- Binary choice variables are created for both the small city and big city variables. A small city has a population under 500,000, where a large city is any population greater than this.
- Binary choice variables are created for trips made on a weekday versus a weekend, as well as for trips made on Monday versus other days.
- Binary choice variables are also created for households owning a housing unit versus renting a housing unit.

These variables are listed in Table 7-3.

Considering possible connections between household income and number of vehicles and between household income and number of adult household members, the following interaction variables are further created.

One set of interaction variables are created by multiplying the three income levels by the number of vehicles in the household. Another set of interaction variables are created by multiplying the income levels by the number of adult members in the household. See the following table.

Data Cleaning: The possible explanatory variables, including the existing variables and the newly created variables, make the following data cleaning process necessary.

- FL1: Remove invalid cases based on number of months that the household lives in FL. Cases with negative values are removed.
- HHFAMINC: Remove invalid cases based on derived total household income. Cases that included the values -9, -8, or -7 are removed.
- URBANSIZE: Remove invalid cases based on size of urban area. Cases with a value of -1 are removed.

After data cleaning, we have a total of 1734 valid cases in District 2.

Cleaned Data Splitting: Split the cleaned data from each district into an "estimation" sample and a "validation" sample. The estimation sample should be about 80% (drawn randomly) of all the data for the district. The validation sample comprises the remaining 20% of the data for each district.

The cleaned data from District 2 are split into an estimation sample with 1418 cases and a validation sample with 316 cases.

Discussion of the Empirical Model Results

The model is presented in this section. Interpretation and discussion follow.

District 2 Model: The best District 2 model is presented in Table 7-5.

District 2 Model Interpretation: In the specification, the base categories used are high income households and weekdays. In other words, this model is based on a high-income household that takes trips on weekdays.

Generally, those explanatory variables are meaningful with regard to household trips. Those parameters, as well as their signs, are intuitively correct. For example, we can reasonably expect more household trips if the number of adults, children, or drivers in a household increase. There are also some other interesting points demonstrated as follows.

- Presence of children in households has larger impact than presence of adults. While increase in one adult in a household will increase 0.948 household trips per day, increase in one child (less than 18 years old) in a household will increase 1.999 household trips per day.
- Presence of drivers in a household has positive impacts on household daily trips. On average, one more driver makes 1.269 more trips.
- Household income has positive impact on trips in general. The richer the household is, the more trips they will make. On a daily average, a low-income household makes 2.473 less trips than a high-income household, and a medium-income household makes 1.586 less trips than a high-income household.
- Households make fewer trips on weekends than on weekdays. The average difference is 0.817 trips.

According to the results of linear regression, count of household vehicles and size of urban areas are statistically insignificant with regard to household trip making. Possible interpretation might be that it is the household member who makes trips, regardless of how many vehicles he/she owns or where he/she lives. Besides, at the significance level of 0.1, households do not make more trips on Monday. There is also no evidence showing difference between seasonal and permanent households.

The model shows the impact of household child members, income levels, and travel days on the household daily trips. Generally, a household with more adult members, with a higher income level, and who travels on weekdays is expected to make more trips. The model also indicates positive impacts of household children and drivers on daily trips. Another interesting point is that the interaction variables that are created do not show statistical significance in the model.

Predictive Assessments

In this section, the predictive performance of the locally-estimated models against that of the transferred models is compared. For validation samples from each district and for each case (household) in the validation sample we have (1) the true trip generation rates, (2) the predicted rate from the locally-estimated model, and (3) the predicted rate from the transferred model.

Prediction Expression: The District 2 model generates the following prediction expression:

Pred_trip = 1.999*NCHILD – 2.473*LowInc -1.586*MedInc -0.817*WKEND + 0.948*NUMADLT + 1.269*DRVRCNT + 3.657

Model Validation: The regression models generated from the estimation samples in District 2 are validated based on their validation samples, respectively. Mean Absolute Deviation (MAD), Root Mean Square Error (RMSE), and Mean Absolute Percent Error (MAPE) are calculated (see the following formula) for measures of overall prediction accuracy of each model.

$$MAD = \frac{\sum_{i=1}^{n} |F_i - y_i|}{n} \qquad RMSE = \sqrt{\frac{\sum_{i=1}^{n} (F_i - y_i)^2}{n}} \qquad MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{F_i}{y_i} - 1\right|$$

Where: F_i – Predicted trip rates; y_i – True trip rates; and n – Sample number.

Generally, the MAD (Mean Absolute Deviation) measures the size of the error in units, the RMSE (Root Mean Square Error) represents the sample standard deviation of the differences between predicted values and observed values, and the MAPE (Mean Absolute Percent Error) measures the size of the error in percentage terms. Results are shown in the following tables.

Discussion

The mean absolute percent errors for model validations are all above 50%, indicating lack of accuracy in the model prediction abilities. However, the results are consistent with the small R square values for both models.

The model for District 2 shows the impact of household child members, income levels, and travel days on the household daily trips. Generally, a household with more adult members, with a higher income level, and who travels on weekdays is expected to make more trips.

The District 2 model also indicates positive impacts of household children and drivers on daily trips.

Another interesting point is that the interaction variables that are created do not show statistical significance in both models.

Since the errors are high (e.g., with the mean absolute percent errors above 50%) when applying both models for prediction, the transferability of the trip generation models does not make much sense.

In the future, variables should be created and selected in a more reasonable effort based on existing theories and current research findings.

Determination of Criteria Weights

For those nine selected projects, eight evaluation criteria were created, and raw data from the measures of each criterion were collected. Those data can be either directly obtained or inferred from the data sources listed above. Criteria were determined based on the data that were readily available or reasonably projected. Those eight evaluation criteria are listed as follows:

1. Facility Type
2. Area Type
3. Average Crashes per Mile per Year
4. Existing Level of Service
5. v/c Ratio

6. Two-Way AADT per Mile
7. Present Value of Available Project Funds per Mile
8. Environmental Impact

For facility type, the numerical values were assigned in Table 7-7.

For area type, the numerical values were assigned in Table 7-8.

For level of service, the numerical values were determined in Table 7-9.

Note that some of these data should be positively correlated with the development priority. For example, the bigger the ratio of traffic volume over capacity, the more urgent the need for improvement of the highway. Two of these data, present value of project funds per mile and environmental impact, are negatively correlated with the development priority.

In the AHP analysis, linguistic terms were assigned values as listed in Table 7-10. Both fuzzy and non-fuzzy methods were used for calculation and then results compared. Pairwise comparison results were assumed as in Table 7-11. After processing of the raw data in Table 7-12, numerical values were obtained for critical project information, as listed in Table 7-13. The tables that follow show the calculation process of AHP. Among them Table 7-14 simply gives results of the original, non-fuzzy AHP, while results in Tables 7-15~19 are from the fuzzy AHP calculation. Tables 7-20~25 show the calculation process for entropy weights. The final criteria weights are results that integrate the fuzzy AHP weights with the entropy weights (Table 7-26).

Finally, we obtained the weight for each criterion as follows:

$$W = [0.027, 0.095, 0.120, 0.155, 0.143, 0.045, 0.150, 0.265]^T$$

Prioritization Based on TOPSIS

The criteria weights obtained from the above AHP-Entropy calculation were then inputted in the TOPSIS model developed with MS Excel. Tables 7-27~29 that follow display the calculation process for the TOPSIS. The final ranking for the potential projects is listed in Table 7-30 based on the calculated distance.

Summary

This chapter presented a case study using the proposed model in Chapter 5 to prioritize potential SIS highway projects in FDOT District 2. Trip generation was first analyzed in order to forecast the future travel demand. After selection of criteria based on data availability, the criteria weights were determined by the proposed fuzzy AHP-Entropy method. Criterial weights were further inputted in the proposed TOPSIS model. The TOPSIS calculation results in final project prioritization. The proposed methodology proved to be effective.

Table 7-1. NCDOT Project Prioritization Criteria

Measure	Maximum Score
Volume to Capacity	15
Crash Incidence	15
Upgrade Existing Facility	15
CTP or Thoroughfare Plan Consistency	10
Project Status	10
Connectivity	5
Access to Community Facilities	5
Truck Traffic	5
Local Priority Project	20

Table 7-2. National Highway and Transportation Data Sources

Database	Developed by	Contents
National Transportation Atlas Database (NTAD)	USDOT Bureau of Transportation Statistics (BTS)	National transportation network data
United States Geological Survey	USGS	Topographic maps, land use, and land cover maps, including information about ownership and political boundaries, transportation, and hydrography
Topologically Integrated Geographic Encoding and Referencing (TIGER)	U.S. Census Bureau	Socioeconomic and demographic data, census tract boundary files and street centerline networks

Table 7-3. List of New Variables for Travel Demand Analysis

Name	Label
RetiredHH	Hourseholds that include at least one retired household member and no full-time employed members
WorkHH_NC	Households, other than retired households, with no household members under the age of 16
WorkHH_C	Households, other than retired households, with at least one household members under the age of 16
SeasonalHH	Households whose residents live in the region more than one month, but less than six months per year
Car0	Households that have 0 cars
Car1	Households that have 1 car
Car2	Households that have 2 cars
Car3	Households that have 3 or more cars
NCHILD	Count of HHMs less than 18 years old
LowInc	Low income households less than $30,000
MedInc	Med income households $30,000 through $80,000
HighInc	High income households more than $80,000
SCity	Small cities with a population under 500,000
LCity	Large cities with a population above 500,000
MON	Monday
WKEND	Weekend
OwnHouse	Housing unit owned
RentHouse	Housing unit rented

Table 7-4. List of Interaction Variables

Name	Label
Low_veh	Number of vehicles if the household has low income
Med_veh	Number of vehicles if the household has med income
High_veh	Number of vehicles if the household has high income
Low_adlt	Number of adults if the household has low income
Med_adlt	Number of adults if the household has med income
High_adlt	Number of adults if the household has high income

Table 7-5: District 2 Model

Explanatory Variable	Parameter	*t* Statistic
Count of HHMs less than 18 years old	1.999	13.375
Low income households less than $30,000	-2.473	-6.865
Med income households $30,000 through $80,000	-1.586	-5.073
Weekend	-.817	-2.965
Count of adult HHMs at least 18 years old	.948	3.237
Number of drivers in Household	1.269	4.499
Constant	3.657	7.344
R^2	.306	
Adjusted R^2	.303	

Table 7-6. District 2 Validation Sample (316 Cases)

	Prediction from local model	Prediction from transferred model
MAD	3.52	3.63
RMSE	4.89	4.89
MAPE	50.80%	55.72%

Table 7-7. Values Assigned for Facility Type

Facility	Freeway	Highway	Arterials
Value Assigned	1.5	1.0	1.0

Table 7-8. Values Assigned for Area Type

Area Type	Urbanized Areas over 500,000	Urbanized Areas under 500,000	Transitioning	Urban	Community	Rural
Value Assigned	6	5	4	3	2	1

Table 7-9. Values Assigned for Level of Service

LOS	A	B	C	D	E	F
Value Assigned	5	4	3	2	1	0

Table 7-10. Values Assigned for Linguistic Terms

Linguistic Terms	Abbreviation	Value (Non-Fuzzy)	Fuzzy Score (TFN)		
			l	m	u
Absolutely Strong	AS	9	8.000	9.000	10.000
Very Strong	VS	7	6.000	7.000	8.000
Fairly Strong	FS	5	4.000	5.000	6.000
Slightly Strong	SS	3	2.000	3.000	4.000
Equal	EQ	1	1.000	1.000	1.000
Slightly Weak	SW	1/3	0.250	0.333	0.500
Fairly Weak	FW	1/5	0.167	0.200	0.250
Very Week	VW	1/7	0.125	0.143	0.167
Absolutely Weak	AW	1/9	0.100	0.111	0.125
	Intermediate Values	2,4,6,8			

Table 7-11. Pairwise Comparison Assumed

		Facility Type	Area Type	Average Crashes per Mile per Year	Existing Level of Service	v/c Ratio	Tow-Way AADT per Mile	PV of Project Funds per Mile	Environmental Impact
		C1	C2	C3	C4	C5	C6	C7	C8
Facility Type	C1	EQ	EQ	SW	SW	FW	SW	AW	AW
Area Type	C2		EQ	SW	SW	FW	EQ	VW	AW
Average Crashes per Mile per Year	C3			EQ	SS	EQ	FS	SW	SW
Existing Level of Service	C4				EQ	SS	VS	EQ	EQ
v/c Ratio	C5					EQ	VS	EQ	EQ
Tow-Way AADT per Mile	C6						EQ	FW	FW
PV of Project Funds per Mile	C7							EQ	EQ
Environmental Impact	C8								EQ

Table 7-12. Raw Data about Project Information

Project	Project 1	Project 2	Project 3	Project 4	Project 5	Project 6	Project 7	Project 8	Project 9
FDOT Financial Project ID	208001-1	209301-3	209537-4	209658-4	209659-3	210711-2	213323-1	213345-7	428865-1
Transportation System	Intrastate State Highway	Intrastate Interstate	Intrastate State Highway	Intrastate Interstate	Intrastate Interstate	Intrastate State Highway	Intrastate Interstate	Intrastate Interstate	Intrastate Interstate
Type of Work	Preliminary engineering	Add lanes and reconstruct	New Road Constructio n	Add Lanes and Reconstruct	Interchange Improvement	Add Lanes and Reconstruct	New Interchange Ramp	Add Lanes and Reconstruct	Interchange Improvemen t
Length (miles)	2.985	4.212	7.335	6.075	3.224	2.167	7.885	4.299	1.99
County	Bradford	Duval	Duval	Duval	Duval	Nassau	Duval	Duval	Duval
SIS	Y	Y	Y	Y	Y	Y	Y	Y	Y
PV of Project Funds	2,000	50,835,049	67,501,750	7,204,134	1,624,671	45,362,268	188,586,867	13,106,618	91,028,935
Facility	Highway	Freeway	Arterial	Freeway	Freeway	Highway	Freeway	Freeway	Freeway
Area Type	Transition	Urbanized	Urbanized	Urbanized	Urbanized	Transition	Urbanized	Urbanized	Urbanized
Speed (mph)	55	65	45	65	70	55	70	65	70
2013 Traffic	1566	8595	702	4500	4005	1729	9585	10080	4005
Max Service Volume	4460	10060	3580	6700	10060	4460	13390	10060	6700
LOS/STD	C/C	D/D	D/D	D/D	D/D	C/C	D/D	D/D	D/D
LOS	B	D	C	C	B	B	C	E	B
2035 Traffic	1674	12348	846	6939	4806	2133	12465	12888	4806
LOS in 2035	B	F	C	E	B	B	D	F	C
Two-Way AADT	18500	99000	5600	59500	4600	11400	20500	117500	9700
2011~2013 Total Crashes	126	235	7	263	69	76	62	523	75
Mile Post Distance (miles)	3	4	2	6	2	3	3	4.5	2
Average Crashes per Mile per Year	14.0	19.6	1.2	14.6	11.5	8.4	6.9	38.7	12.5

Table 7-13. Numerical Values for Critical Project Information

	Project ID	208001-1	209301-3	209537-4	209658-4	209659-3	210711-2	213323-1	213345-7	428865-1
	Project #	P1	P2	P3	P4	P5	P6	P7	P8	P9
Facility Type	C1	1	1.5	1	1.5	1.5	1	1.5	1.5	1.5
Area Type	C2	4	6	6	6	6	6	6	6	6
Average Crashes per Mile per Year	C3	14.0	19.6	1.2	14.6	11.5	8.4	6.9	38.7	12.5
Existing Level of Service	C4	1.33	1.00	1.50	1.50	2.00	1.33	1.50	0.50	2.00
v/c Ratio	C5	0.351	0.854	0.196	0.672	0.398	0.388	0.716	1.002	0.598
Tow-Way AADT per Mile	C6	6198	23504	763	9794	1427	5261	2600	27332	4874
PV of Project Funds per Mile	C7	23,013,889	12,069,100	9,202,693	1,185,866	503,930	20,933,211	23,917,168	3,048,760	45,743,184
Environmental Impact	C8	44	30	40	32	45	34	32	36	44

Table 7-14. Original AHP Calculation

		Facility Type	Area Type	Average Crashes per Mile per Year	Existing Level of Service	v/c Ratio	Tow-Way AADT per Mile	PV of Project Funds per Mile	Environmental Impact					
		C1	C2	C3	C4	C5	C6	C7	C8	$\bar{w}_i$	normalization	A_w	$n \times \bar{w}_i$	
Facility Type	C1	1.00	1.00	0.50	0.50	0.33	0.50	0.13	0.13	0.40	0.04	0.35	0.32	1.10
Area Type	C2	1.00	1.00	0.33	0.50	0.25	1.00	0.11	0.13	0.39	0.04	0.33	0.31	1.05
Average Crashes per Mile per Year	C3	2.00	3.00	1.00	2.00	1.00	5.00	0.50	0.50	1.40	0.14	1.20	1.11	1.08
Existing Level of Service	C4	2.00	2.00	0.50	1.00	2.00	6.00	1.00	1.00	1.49	0.15	1.36	1.18	1.15
v/c Ratio	C5	3.00	4.00	1.00	0.50	1.00	7.00	1.00	1.00	1.60	0.16	1.35	1.26	1.07
Tow-Way AADT per Mile	C6	2.00	1.00	0.20	0.17	0.14	1.00	0.25	0.20	0.38	0.04	0.33	0.30	1.08
PV of Project Funds per Mile	C7	8.00	9.00	2.00	1.00	1.00	4.00	1.00	1.00	2.21	0.22	1.84	1.75	1.05
Environmental Impact	C8	8.00	8.00	2.00	1.00	1.00	5.00	1.00	1.00	2.24	0.22	1.84	1.77	1.04
										10.12	1.00		λ	8.63
													CI	0.09
													RCI	1.41
													CR	0.06

Table 7-15. Fuzzy AHP Calculation I

Middle		Facility Type	Area Type	Average Crashes per Mile per Year	Existing Level of Service	v/c Ratio	Tow-Way AADT per Mile	PV of Project Funds per Mile	Environmental Impact					
		C1	C2	C3	C4	C5	C6	C7	C8	$\bar{w}_i$	normalization	A_w	$n \times \bar{w}_i$	
Facility Type	C1	1.00	1.00	0.33	0.33	0.20	0.33	0.11	0.11	0.31	0.03	0.26	0.24	1.08
Area Type	C2	1.00	1.00	0.33	0.33	0.20	1.00	0.14	0.11	0.37	0.03	0.29	0.28	1.02
Average Crashes per Mile per Year	C3	3.00	3.00	1.00	3.00	1.00	5.00	0.33	0.33	1.40	0.13	1.29	1.06	1.22
Existing Level of Service	C4	3.00	3.00	0.33	1.00	3.00	7.00	1.00	1.00	1.68	0.16	1.57	1.27	1.24
v/c Ratio	C5	5.00	5.00	1.00	0.33	1.00	7.00	1.00	1.00	1.66	0.16	1.37	1.26	1.09
Tow-Way AADT per Mile	C6	3.00	1.00	0.20	0.14	0.14	1.00	0.20	0.20	0.39	0.04	0.32	0.29	1.10
PV of Project Funds per Mile	C7	9.00	7.00	3.00	1.00	1.00	5.00	1.00	1.00	2.35	0.22	1.86	1.78	1.04
Environmental Impact	C8	9.00	9.00	3.00	1.00	1.00	5.00	1.00	1.00	2.43	0.23	1.93	1.83	1.05
										10.60	1.00		λ	8.86
													CI	0.12
													RCI	1.41
													CR	0.09

Table 7-16. Fuzzy AHP Calculation II

Lower	Facility Type	Area Type	Average Crashes per Mile per Year	Existing Level of Service	v/c Ratio	Tow-Way AADT per Mile	PV of Project Funds per Mile	Environmental Impact					
	C1	C2	C3	C4	C5	C6	C7	C8	$\bar{w}_i$	normalization	A_w	$n \times \bar{w}_i$	
Facility Type C1	1.00	1.00	0.25	0.25	0.17	0.25	0.10	0.10	0.27	0.02	0.21	0.19	1.09
Area Type C2	1.00	1.00	0.25	0.25	0.17	1.00	0.13	0.10	0.33	0.03	0.24	0.23	1.02
Average Crashes per Mile per Year C3	4.00	4.00	1.00	4.00	1.00	6.00	0.25	0.25	1.49	0.13	1.46	1.06	1.38
Existing Level of Service C4	4.00	4.00	0.25	1.00	4.00	8.00	1.00	1.00	1.83	0.16	1.74	1.31	1.33
v/c Ratio C5	6.00	6.00	1.00	0.25	1.00	8.00	1.00	1.00	1.71	0.15	1.37	1.22	1.12
Tow-Way AADT per Mile C6	4.00	1.00	0.17	0.13	0.13	1.00	0.17	0.17	0.36	0.03	0.30	0.26	1.15
PV of Project Funds per Mile C7	10.00	8.00	4.00	1.00	1.00	6.00	1.00	1.00	2.57	0.23	1.98	1.84	1.08
Environmental Impact C8	10.00	10.00	4.00	1.00	1.00	6.00	1.00	1.00	2.65	0.24	2.04	1.89	1.08
									11.20	1.00		λ	9.23
												CI	0.18
												RCI	1.41
												CR	0.12

Table 7-17. Fuzzy AHP Calculation III

Upper	Facility Type	Area Type	Average Crashes per Mile per Year	Existing Level of Service	v/c Ratio	Tow-Way AADT per Mile	PV of Project Funds per Mile	Environmental Impact					
	C1	C2	C3	C4	C5	C6	C7	C8	$\bar{w}_i$	normalization	A_w	$n \times \bar{w}_i$	
Facility Type C1	1.00	1.00	0.50	0.50	0.25	0.50	0.13	0.13	0.39	0.04	0.34	0.31	1.09
Area Type C2	1.00	1.00	0.50	0.50	0.25	1.00	0.17	0.13	0.44	0.04	0.37	0.35	1.05
Average Crashes per Mile per Year C3	2.00	2.00	1.00	2.00	1.00	4.00	0.50	0.50	1.30	0.13	1.14	1.05	1.09
Existing Level of Service C4	2.00	2.00	0.50	1.00	2.00	6.00	1.00	1.00	1.49	0.15	1.39	1.20	1.16
v/c Ratio C5	4.00	4.00	1.00	0.50	1.00	6.00	1.00	1.00	1.62	0.16	1.38	1.31	1.06
Tow-Way AADT per Mile C6	2.00	1.00	0.25	0.17	0.17	1.00	0.25	0.25	0.41	0.04	0.36	0.33	1.07
PV of Project Funds per Mile C7	8.00	6.00	2.00	1.00	1.00	4.00	1.00	1.00	2.10	0.21	1.75	1.70	1.03
Environmental Impact C8	8.00	8.00	2.00	1.00	1.00	4.00	1.00	1.00	2.18	0.22	1.83	1.76	1.04
									9.93	1.00		λ	8.59
												CI	0.08
												RCI	1.41
												CR	0.06

Table 7-18. Normalization of Fuzzy AHP Weights

	l	m	n
Facility Type R1	0.267	0.313	0.386
Area Type R2	0.327	0.370	0.436
Average Crashes per Mile per Year R3	1.488	1.403	1.297
Existing Level of Service R4	1.834	1.678	1.488
v/c Ratio R5	1.707	1.662	1.622
Tow-Way AADT per Mile R6	0.361	0.386	0.414
PV of Project Funds per Mile R7	2.573	2.355	2.104
Environmental Impact R8	2.646	2.430	2.181
Sum	11.202	10.597	9.928

Table 7-19. Final Weight from AHP Calculations

			BNP		Normalized	AHP
w1	0.027	0.030	0.034	0.030	0.030	0.039
w2	0.033	0.035	0.039	0.036	0.035	0.039
w3	0.116	0.132	0.150	0.133	0.132	0.139
w4	0.133	0.158	0.185	0.159	0.158	0.147
w5	0.145	0.157	0.172	0.158	0.157	0.158
w6	0.036	0.036	0.037	0.037	0.036	0.038
w7	0.188	0.222	0.259	0.223	0.222	0.219
w8	0.195	0.229	0.266	0.230	0.229	0.222
				1.005	1.000	

Table 7-20. Data Used for Entropy Weights Calculation

		208001-1 A1	209301-3 A2	209537-4 A3	209658-4 A4	209659-3 A5	210711-2 A6	213323-1 A7	213345-7 A8	428865-1 A9	
Facility Type	C1	1	1.5	1	1.5	1.5	1	1.5	1.5	1.5	x/max(x)
Area Type	C2	4	6	6	6	6	6	6	6	6	x/max(x)
Average Crashes per Mile per Year	C3	14.0	19.6	1.2	14.6	11.5	8.4	6.9	38.7	12.5	x/max(x)
Existing Level of Service	C4	1.33	1.00	1.50	1.50	2.00	1.33	1.50	0.50	2.00	x/max(x)
v/c Ratio	C5	0.351	0.854	0.196	0.672	0.398	0.388	0.716	1.002	0.598	x/max(x)
Tow-Way AADT per Mile	C6	6198	23504	763	9794	1427	5261	2600	27332	4874	x/max(x)
PV of Project Funds per Mile	C7	23,013,889	12,069,100	9,202,693	1,185,866	503,930	20,933,211	23,917,168	3,048,760	45,743,184	min(x)/x
Environmental Impact	C8	44	30	40	32	45	34	32	36	44	min(x)/x

Table 7-21. Entropy Weights Calculation I

Normalization

	A1	A2	A3	A4	A5	A6	A7	A8	A9
C1	0.667	1.000	0.667	1.000	1.000	0.667	1.000	1.000	1.000
C2	0.667	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
C3	0.362	0.506	0.031	0.377	0.297	0.217	0.178	1.000	0.323
C4	0.667	0.500	0.750	0.750	1.000	0.667	0.750	0.250	1.000
C5	0.350	0.853	0.196	0.670	0.397	0.387	0.714	1.000	0.597
C6	0.227	0.860	0.028	0.358	0.052	0.192	0.095	1.000	0.178
C7	0.022	0.042	0.055	0.425	1.000	0.024	0.021	0.165	0.011
C8	0.682	1.000	0.750	0.938	0.667	0.882	0.938	0.833	0.682

Table 7-22. Entropy Weights Calculation II

R(delta)

	A1	A2	A3	A4	A5	A6	A7	A8	A9	Sum
C1	0.111	0.000	0.111	0.000	0.000	0.111	0.000	0.000	0.000	0.333
C2	0.111	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.111
C3	0.407	0.244	0.939	0.388	0.494	0.613	0.675	0.000	0.458	4.218
C4	0.111	0.250	0.063	0.063	0.000	0.111	0.063	0.563	0.000	1.222
C5	0.422	0.022	0.647	0.109	0.363	0.376	0.082	0.000	0.163	2.183
C6	0.598	0.020	0.945	0.412	0.898	0.652	0.819	0.000	0.675	5.019
C7	0.957	0.918	0.893	0.331	0.000	0.952	0.958	0.697	0.978	6.685
C8	0.101	0.000	0.063	0.004	0.111	0.014	0.004	0.028	0.101	0.426

Table 7-23. Entropy Weights Calculation III

f(ij)

	A1	A2	A3	A4	A5	A6	A7	A8	A9
C1	0.333	0.000	0.333	0.000	0.000	0.333	0.000	0.000	0.000
C2	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
C3	0.097	0.058	0.223	0.092	0.117	0.145	0.160	0.000	0.109
C4	0.091	0.205	0.051	0.051	0.000	0.091	0.051	0.460	0.000
C5	0.193	0.010	0.296	0.050	0.166	0.172	0.037	0.000	0.075
C6	0.119	0.004	0.188	0.082	0.179	0.130	0.163	0.000	0.135
C7	0.143	0.137	0.134	0.049	0.000	0.142	0.143	0.104	0.146
C8	0.238	0.000	0.147	0.009	0.261	0.033	0.009	0.065	0.238

Table 7-24. Entropy Weights Calculation IV

lnf(ij)

	A1	A2	A3	A4	A5	A6	A7	A8	A9
C1	-1.099	0.000	-1.099	0.000	0.000	-1.099	0.000	0.000	0.000
C2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
C3	-2.337	-2.852	-1.502	-2.387	-2.145	-1.929	-1.832	0.000	-2.220
C4	-2.398	-1.587	-2.973	-2.973	0.000	-2.398	-2.973	-0.776	0.000
C5	-1.643	-4.611	-1.216	-3.000	-1.793	-1.759	-3.287	0.000	-2.596
C6	-2.127	-5.545	-1.670	-2.501	-1.720	-2.041	-1.813	0.000	-2.006
C7	-1.944	-1.985	-2.012	-3.006	0.000	-1.949	-1.942	-2.261	-1.922
C8	-1.436	0.000	-1.918	-4.691	-1.343	-3.426	-4.691	-2.729	-1.436

Table 7-25. Entropy Weights Calculation V

f(ij)lnf(ij)

	A1	A2	A3	A4	A5	A6	A7	A8	A9	Sum	Hi	w'
C1	-0.366	0.000	-0.366	0.000	0.000	-0.366	0.000	0.000	0.000	-0.732	0.667	0.094
C2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.283
C3	-0.226	-0.165	-0.334	-0.219	-0.251	-0.280	-0.293	0.000	-0.241	-0.725	0.660	0.096
C4	-0.218	-0.325	-0.152	-0.152	0.000	-0.218	-0.152	-0.357	0.000	-0.695	0.632	0.104
C5	-0.318	-0.046	-0.360	-0.149	-0.298	-0.303	-0.123	0.000	-0.194	-0.724	0.659	0.097
C6	-0.253	-0.022	-0.314	-0.205	-0.308	-0.265	-0.296	0.000	-0.270	-0.590	0.537	0.131
C7	-0.278	-0.273	-0.269	-0.149	0.000	-0.278	-0.278	-0.236	-0.281	-0.820	0.746	0.072
C8	-0.342	0.000	-0.282	-0.043	-0.351	-0.111	-0.043	-0.178	-0.342	-0.623	0.567	0.122
											4.468	

Table 7-26. Determination of Final Weights

		Fuzzy AHP	Entropy	Product	Final Weight
Facility Type	C1	0.030	0.094	0.003	0.027
Area Type	C2	0.035	0.283	0.010	0.095
Average Crashes per Mile per Year	C3	0.132	0.096	0.013	0.120
Existing Level of Service	C4	0.158	0.104	0.016	0.155
v/c Ratio	C5	0.157	0.097	0.015	0.143
Tow-Way AADT per Mile	C6	0.036	0.131	0.005	0.045
PV of Project Funds per Mile	C7	0.222	0.072	0.016	0.150
Environmental Impact	C8	0.229	0.122	0.028	0.265
		1.000	1.000	0.106	1.000

Table 7-27. TOPSIS Input Data

		Project ID	208001-1	209301-3	209537-4	209658-4	209659-3	210711-2	213323-1	213345-7	428865-1	Criteria
		Project #	P1	P2	P3	P4	P5	P6	P7	P8	P9	Weights
Criteria	Criterion #	Optimum										
Facility Type	C1	Max	1	1.5	1	1.5	1.5	1	1.5	1.5	1.5	0.027
Area Type	C2	Max	4	6	6	6	6	6	6	6	6	0.095
Average Crashes per Mile per Year	C3	Max	14	19.6	1.2	14.6	11.5	8.4	6.9	38.7	12.5	0.120
Existing Level of Service	C4	Max	1.3	1.0	1.5	1.5	2.0	1.3	1.5	0.5	2.0	0.155
v/c Ratio	C5	Max	0.351	0.854	0.196	0.672	0.398	0.388	0.716	1.002	0.598	0.143
Two-Way AADT per Mile	C6	Max	6,198	23,504	763	9,794	1,427	5,261	2,600	27,332	4,874	0.045
PV of Project Funds per Mile ($)	C7	Min	23,013,889	12,069,100	9,202,693	1,185,866	503,930	20,933,211	23,917,168	3,048,760	45,743,184	0.150
Environmental Impact Score	C8	Min	44	30	40	32	45	34	32	36	44	0.265

Table 7-28. TOPSIS Normalized Criterion Matrix

		Project ID	208001-1	209301-3	209537-4	209658-4	209659-3	210711-2	213323-1	213345-7	428865-1	Criteria
		Project #	P1	P2	P3	P4	P5	P6	P7	P8	P9	Weights
Criteria	Criterion #	Optimum										
Facility Type	C1	Max	0.246	0.369	0.246	0.369	0.369	0.246	0.369	0.369	0.369	0.027
Area Type	C2	Max	0.229	0.344	0.344	0.344	0.344	0.344	0.344	0.344	0.344	0.095
Average Crashes per Mile per Year	C3	Max	0.269	0.377	0.023	0.281	0.221	0.162	0.133	0.745	0.241	0.120
Existing Level of Service	C4	Max	0.301	0.226	0.339	0.339	0.452	0.301	0.339	0.113	0.452	0.155
v/c Ratio	C5	Max	0.187	0.455	0.104	0.358	0.212	0.207	0.381	0.534	0.318	0.143
Two-Way AADT per Mile	C6	Max	0.160	0.608	0.020	0.253	0.037	0.136	0.067	0.707	0.126	0.045
PV of Project Funds per Mile ($)	C7	Min	0.370	0.194	0.148	0.019	0.008	0.336	0.384	0.049	0.735	0.150
Environmental Impact Score	C8	Min	0.387	0.264	0.352	0.282	0.396	0.299	0.282	0.317	0.387	0.265

Table 7-29. Weighted Criterion Matrix

			Project ID	See Tables 7-27 and 7-28.									Criteria	Max	Min
			Project #	P1	P2	P3	P4	P5	P6	P7	P8	P9	Weights	Weight	Weight
Criteria	Criterion #	Optimum													
Facility Type	C1	Max		0.007	0.010	0.007	0.010	0.010	0.007	0.010	0.010	0.010	0.027	0.010	0.007
Area Type	C2	Max		0.022	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.095	0.033	0.022
Average Crashes per Mile per Year	C3	Max		0.032	0.045	0.003	0.034	0.027	0.019	0.016	0.089	0.029	0.120	0.089	0.003
Existing Level of Service	C4	Max		0.047	0.035	0.053	0.053	0.070	0.047	0.053	0.018	0.070	0.155	0.070	0.018
v/c Ratio	C5	Max		0.027	0.065	0.015	0.051	0.030	0.030	0.055	0.076	0.046	0.143	0.076	0.015
Two-Way AADT per Mile	C6	Max		0.007	0.027	0.001	0.011	0.002	0.006	0.003	0.032	0.006	0.045	0.032	0.001
PV of Project Funds per Mile ($)	C7	Min		0.056	0.029	0.022	0.003	0.001	0.051	0.058	0.007	0.111	0.150	0.111	0.001
Environmental Impact Score	C8	Min		0.103	0.070	0.093	0.075	0.105	0.079	0.075	0.084	0.103	0.265	0.105	0.070
Distance to the Positive Ideal Solution				0.105	0.064	0.116	0.067	0.091	0.104	0.101	0.055	0.135			
Distance to the Negative Ideal Solution				0.070	0.115	0.096	0.128	0.125	0.076	0.083	0.153	0.067			
Relative Closeness to Ideal Solutions				0.401	0.643	0.453	0.656	0.580	0.421	0.449	0.736	0.333			

Table 7-30. Final Ranking from TOPSIS

Ranking	Project #	Project ID	Relative Closeness to Ideal Solutions
1	P8	213345-7	0.736
2	P4	209658-4	0.656
3	P2	209301-3	0.643
4	P5	209659-3	0.580
5	P3	209537-4	0.453
6	P7	213323-1	0.449
7	P6	210711-2	0.421
8	P1	208001-1	0.401
9	P9	428865-1	0.333

Item Segment: 2078502 **District 2**

Facility: SR 26 CORRIDOR

Project Limits: FROM GILCHRIST C/L TO CR 26A E OF NEWB

Highway

Improvement: New Road

Description:

The project consists of the addition of 2 lanes on SR 26 from Gilchrist County line to CR 26A east of Newberry. The improvements are anticipated to relieve congestion by providing additional capacity for future growth.

Phasing Costs:

Phase	Cost	Year
PD&E	$6	2015
Preliminary Engineering	$100	2019
Right of Way	$0	
Construction	$0	
Grant	$0	

All costs include support and are in thousands of as-programmed dollars

Strategic Investment Tool (SIT) Scores (Highway Projects Only):

Florida Transportation Plan Goals	Unweighted Points
Safety & Security	1.00
Maintenance & Operations	6.00
Mobility & Connectivity	5.00
Economic Competitiveness	6.40
Livable Communities	7.70
Environmental Stewardship	13.50
Total	**39.60**

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Figure 7-1. An Example of a FDOT-SIS Project Listed in the 1st Five-Year Plan

SIS Objective	Measure	Maximum Score
Safety & Security (5 Measures)	Crash Ratio	10
	Fatal Crash Ratio	4
	Bridge Appraisal Rating	2
	Link to Military Base	2
	Emergency Evacuation	2
	Possible Subtotal	***20 points***
Maintenance & Operations (4 Measures)	Travel Time Reliability	8
	Truck Volume (AADTT)	8
	Adaptation Measure	2
	Bridge Condition Rating	2
	Possible Subtotal	***20 points***
Mobility & Connectivity (8 Measures)	Connector Location	1
	Volume / Capacity (v/c) Ratio	4
	Truck Percentage	2
	Vehicular Volume (AADT)	2
	System Gap	2
	Change in v/c (Mainline) or Interchange Ops (Interchanges)	3
	Bottlenecks	2
	Delay	4
	Possible Subtotal	***20 points***
Economic Competitiveness (14 Measures)	Rural Areas of Critical Economic Concern	2
	Workforce Size	1
	Educational Attainment Level	1
	Population Growth Rate	1
	Per Capita Income	1
	Freight Employment Intensity	1
	Property Taxes	1
	Freight Transportation Infrastructure	2
	Military Bases Employment	1
	Per Capita Sales Tax	2
	Number of Visitors	2
	Institutions of Higher Education	2
	Medical Centers	1
	Tech Centers	2
	Possible Subtotal	***20 points***
Livable Communities (7 Measures)	Residential and Community Impacts	4
	Population Density	2
	Transit Connectivity	3
	Bicycle / Pedestrian Access	4
	Managed Lanes / Special Use	2
	Social Investment / Justice	2
	Personal Safety	3
	Possible Subtotal	***20 points***
Environmental Stewardship (13 Measures)	Farmlands	1
	Geology	1
	Archeological / Historical Sites	2
	Contamination	1
	Conservation and Preservation	2
	Wildlife and Habitat	2
	Flood Plains / Flood Control	1
	Coastal / Marine	1
	Special Designations	2
	Water Quality	1
	Wetlands	2
	Air Quality	2
	Energy and Sustainability	2
	Possible Subtotal	***20 points***
	Total Maximum Score	**120 points**

Figure 7-2. FDOT Strategic Investment Tool Highway and Connector Measures

Source: Strategic Investment Tool Highway Component. (2015). FDOT Systems Planning Office

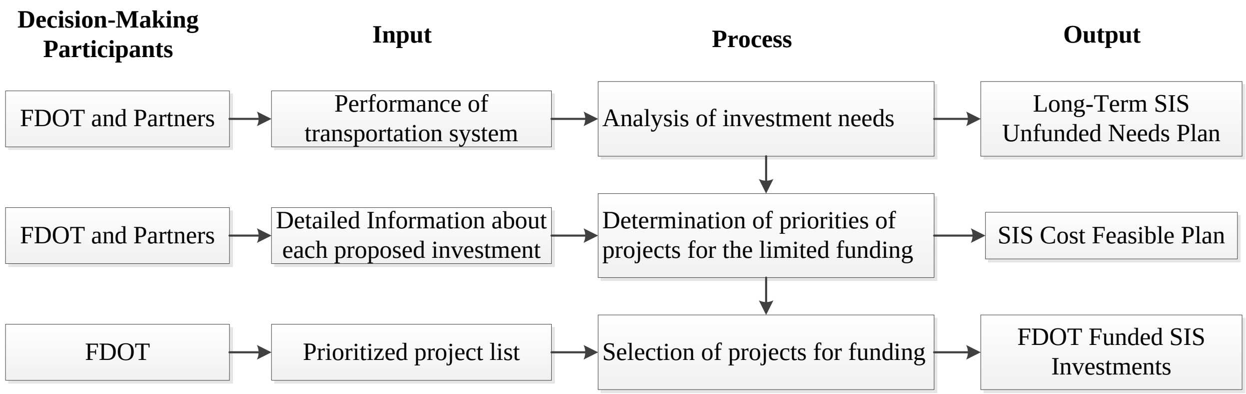


Figure 7-3. Decision-Making process of FDOT for funding SIS investments

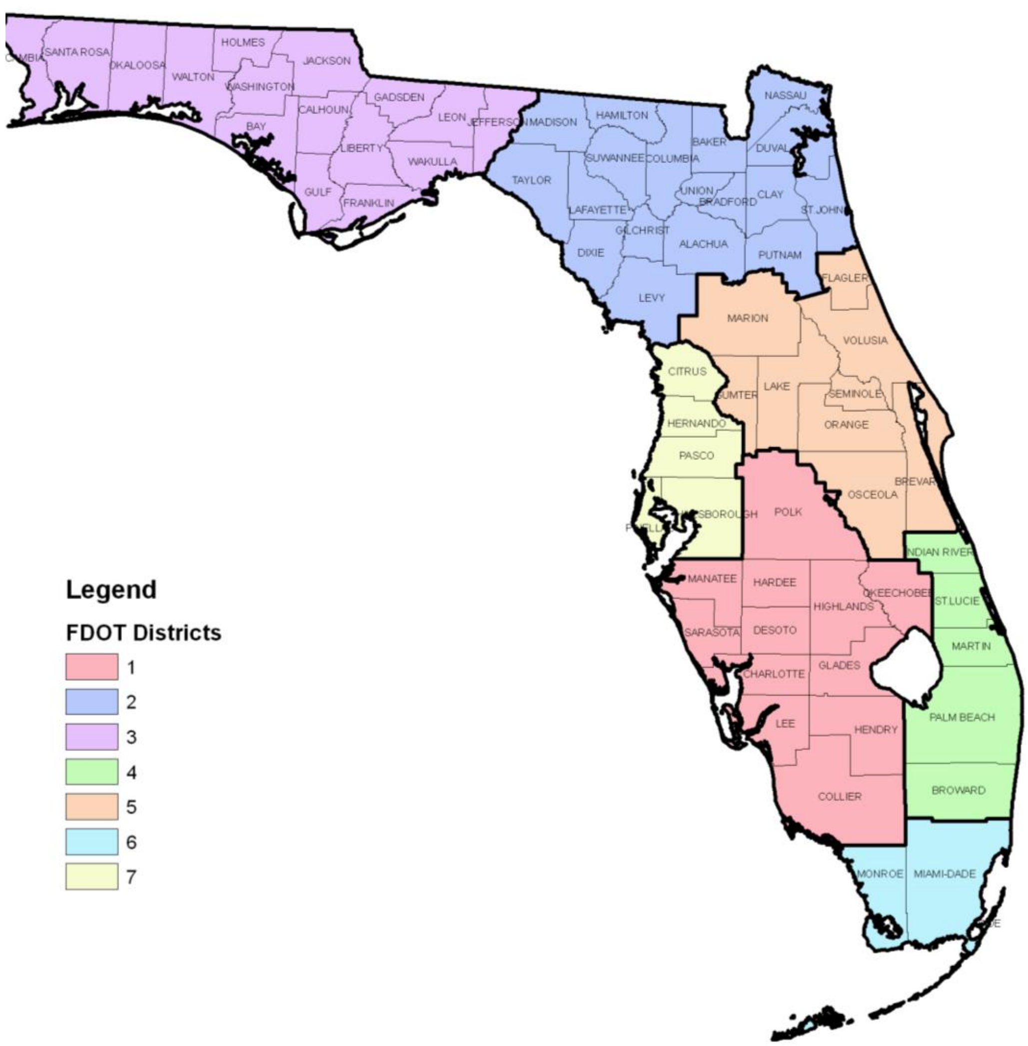


Figure 7-4. Map of FDOT Districts

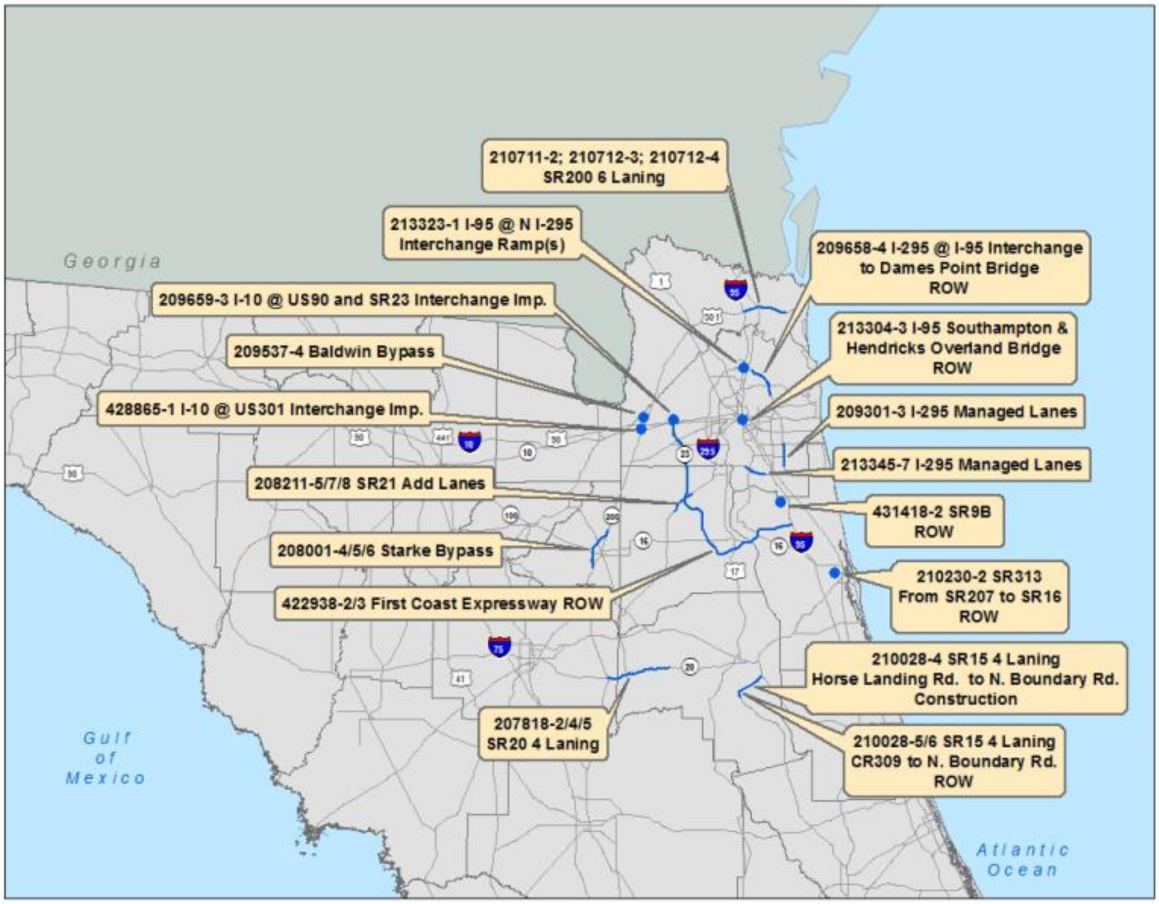


Figure 7-5. Map of Major Projects Being Planned in District 2

CHAPTER 8
CASE STUDY II: MULTI-OBJECTIVE OPTIMIZATION FOR PROJECT DEVELOPMENT

Case Description and Inputs

In recent decades, transportation infrastructure in the United States has been thought to be deteriorated due to unbalanced transportation supply and demand, underfunding, and lack of financial resources (Kim, 1998, p.4). After a specific project is selected through the prioritization process discussed in Chapters 5 and 7, the project sponsor and the project manager must further optimize the trade-off among project time, cost, and quality within the financial constraints. The MODM techniques discussed in Chapter 6 can now be applied to a case study.

Consider a simple project with 18 activities as shown in Table 8-1 and Figure 8-1 with pre-defined activity predecessors, normal duration, normal cost per day, and normal quality index. Threshold quality index and maximum days that can be crashed for each activity are also determined. These variables are shaded in Table 8-1 as original inputs.

Baseline Calculation

The project baseline sets the normal project schedule. In Table 8-2 the normal project time is calculated. These include the early start (ES), early finish (EF), late start (LS), late finish (LF), total float (TF), and free float (FF) of each activity. The bolded activities in Table 8-2 indicate those activities on the critical path based on the calculation results (i.e., $TF = 0$). Prior to optimization (see Table 8-3 as well), the project can be completed within 424 days with a total construction cost of $17,808,000. The normal activity quality index (0.9) has been set generally above the threshold quality index (0.6).

Optimization Assumptions

Optimization of the suggested model aims to: (1) minimize the total cost, (2) reduce the project duration, and (3) still meet the project quality requirements.

The key conditions for this case project include (see Table 8-3):

- Maximum days that can be crashed for each activity has been determined.
- Time constraint: The project duration should be less than 365 days.
- Cost constraint: Crash cost per day for each activity is 20% higher than normal cost.
- Quality constraint: Each quality index should be above the threshold quality index.
- Quality assumption: The activity quality shows linear relationship with the activity duration.

Optimization Results

The optimization, based on the suggested model in this dissertation, results in a total cost reduction from $17,808,000 to $14,955,000, a 16% saving in total cost. Meanwhile, the total project time has been reduced from 424 days to 300 days, a decrease of 29% from normal project time. The quality indexes for some activities have to be sacrificed in order to achieve both cost savings and time reduction, but they are still well above the threshold index. See Table 8-3 for details. The optimization results have validated the effectiveness and efficiency of the proposed model.

Construction Financing and Project Development Budget

From the above calculation, the total construction costs have been reduced to $14,955,000 and the project duration has been decreased to 300 days, or 10 months. Usually, the project sponsor or the project manager then needs to seek construction financing, either by getting construction loans from lenders or by issuing project bonds. Therefore, the financing costs must be calculated and included in the project development budget.

There are two specifically important challenges, among many other challenges, when a project development budget is modeled:

1. Construction costs distribution: Construction costs can be easily forecasted using a straight-line distribution, in which the construction costs are evenly assigned to each month. In the real world, however, this is often not the case. Instead, cumulative construction costs tend to show an S-curve distribution. Specifically, construction costs

are usually lower both at the beginning and at the end of a project, but are higher in the middle when the project goes on.

2. Financing costs minimization: In each month, the financing costs rely on the beginning balance of the construction loan in the same month, while the beginning balance is the sum of the ending balance in the previous month and the financing advances drawn in the same month, which partially depends on the total development costs in the same month, including the financing costs. This causes iterative calculation problems.

An innovative mechanism has been designed in the proposed model in this dissertation to solve the two problems discussed above. Assumptions on construction contingency, interest-only construction loan costs, and project sponsor equity contributions are made as follows:

- Contingency: 5.0% of construction costs
- Interest-Only rate for construction financing: 4.0%
- Sponsor equity: 35% of total funds

Calculation of construction financing costs is shown in Table 8-4, which also encloses a comprehensive project development budget. Figures 8-2~8-4 illustrate the construction costs S-curve distribution and the funds draw schedule, respectively. The financing cost optimization process results in total project development expenditures of $15,818,383, including financing costs of $115,633. Using the sponsor equity as 35% of total funds needed, this requires sponsor equity contribution of $5,536,434 and a total of $10,281,949 in construction loans or project bonds.

Summary

This chapter presented another case study using the multi-objective decision-making optimization model proposed in Chapter 6. The case study aims to find the best solution to the trade-off of major project objectives, along with the consideration of construction financing costs optimization. The calculation results indicated that the proposed model is effective and provides a quick solution to project optimization.

Table 8-1. Example Project

Activity #	Activity	Predecessor	Normal Duration	Normal Cost per Day ($1,000)	Normal Quality Index	Threshold Quality Index	Max Days Crashed
1	A		4	$30.00	0.9	0.6	1
2	B	1	48	$25.00	0.9	0.6	7
3	C	2	24	$35.00	0.9	0.6	4
4	D	3	72	$38.00	0.9	0.6	28
5	E	4	62	$40.00	0.9	0.6	21
6	F	5	102	$43.00	0.9	0.6	34
7	G	6	4	$40.00	0.9	0.6	1
8	H	7	4	$39.00	0.9	0.6	1
9	I	6	34	$45.00	0.9	0.6	14
10	J	9	17	$38.00	0.9	0.6	11
11	K	6	24	$42.00	0.9	0.6	7
12	L	10,11	17	$35.00	0.9	0.6	4
13	M	8,12	7	$50.00	0.9	0.6	2
14	N	13	14	$55.00	0.9	0.6	4
15	O	14	4	$40.00	0.9	0.6	1
16	P	15	11	$37.00	0.9	0.6	4
17	Q	16	4	$36.00	0.9	0.6	1
18	R	17	4	$30.00	0.9	0.6	1

Table 8-2. Project Schedule

Activity #	Activity	Predecessor	Normal Duration	Early Start (ES)	Early Finish (EF)	Late Start (LS)	Late Finish (LF)	Total Float (TF)	Free Float (FF)
1	**A**		4	0	4	0	4	0	0
2	**B**	1	48	4	52	4	52	0	0
3	**C**	2	24	52	76	52	76	0	0
4	**D**	3	72	76	148	76	148	0	0
5	**E**	4	62	148	210	148	210	0	0
6	**F**	5	102	210	312	210	312	0	0
7	G	6	4	312	316	372	376	60	0
8	H	7	4	316	320	376	380	60	60
9	**I**	6	34	312	346	312	346	0	0
10	**J**	9	17	346	363	346	363	0	0
11	K	6	24	312	336	339	363	27	27
12	**L**	10,11	17	363	380	363	380	0	0
13	**M**	8,12	7	380	387	380	387	0	0
14	**N**	13	14	387	401	387	401	0	0
15	**O**	14	4	401	405	401	405	0	0
16	**P**	15	11	405	416	405	416	0	0
17	**Q**	16	4	416	420	416	420	0	0
18	**R**	17	4	420	424	420	424	0	0

Table 8-3. Project Optimization

	Duration					Time			Quality			Cost			
Activity	Normal Duration	Max Days Crashed	Days Crashed	Crash Duration	Normal ES	Crashed ES	Original EF	Crashed EF	Normal Quality Index	Threshold Quality Index	Crash Quality	Normal Cost per Day ($1,000)	Total Normal Cost ($1,000)	Crash Cost per Day ($1,000)	Total Crash Cost ($1,000)
A	4	1	1	3			4	3	0.9	0.6	0.68	$30.00	$120	$36.00	$108
B	48	7	7	41	4	3	52	44	0.9	0.6	0.77	$25.00	$1,200	$30.00	$1,230
C	24	4	4	20	52	44	76	64	0.9	0.6	0.75	$35.00	$840	$42.00	$840
D	72	28	24	48	76	64	148	112	0.9	0.6	0.60	$38.00	$2,736	$45.60	$2,189
E	62	21	21	41	148	112	210	153	0.9	0.6	0.60	$40.00	$2,480	$48.00	$1,984
F	102	34	34	68	210	153	312	221	0.9	0.6	0.60	$43.00	$4,386	$51.60	$3,509
G	4	1	1	3	312	221	316	224	0.9	0.6	0.68	$40.00	$160	$48.00	$144
H	4	1	1	3	316	224	320	227	0.9	0.6	0.68	$39.00	$156	$46.80	$140
I	34	14	11	23	312	221	346	244	0.9	0.6	0.60	$45.00	$1,530	$54.00	$1,224
J	17	11	6	11	346	244	363	255	0.9	0.6	0.60	$38.00	$646	$45.60	$517
K	24	7	7	17	312	221	336	238	0.9	0.6	0.64	$42.00	$1,008	$50.40	$857
L	17	4	4	13	363	255	380	268	0.9	0.6	0.69	$35.00	$595	$42.00	$546
M	7	2	2	5	380	268	387	273	0.9	0.6	0.64	$50.00	$350	$60.00	$300
N	14	4	4	10	387	273	401	283	0.9	0.6	0.64	$55.00	$770	$66.00	$660
O	4	1	1	3	401	283	405	286	0.9	0.6	0.68	$40.00	$160	$48.00	$144
P	11	4	4	7	405	286	416	294	0.9	0.6	0.60	$37.00	$407	$44.40	$326
Q	4	1	1	3	416	294	420	297	0.9	0.6	0.68	$36.00	$144	$43.20	$130
R	4	1	1	3	420	297	424	300	0.9	0.6	0.68	$30.00	$120	$36.00	$108
						Project Time	424	300				Total Cost	$17,808		$14,955
	TCQT Optimization Summary					Days Saved		124		Satisfied: Crash quality not less than threshold		Cost Savings			$2,853
						Days Saved (%)		29.2%				Cost Savings (%)			16.0%

Table 8-4. Project Development Budget

		Month										
	Total	0	1	2	3	4	5	6	7	8	9	10
Expenditures:												
Financing Costs	$115,633	$-	$-	$-	$-	$-	$-	$7,716	$17,890	$25,893	$30,848	$33,286
Construction	$14,955,000	$-	$250,473	$667,159	$1,390,861	$2,269,677	$2,899,329	$2,899,329	$2,269,677	$1,390,861	$667,159	$250,473
Contingency	$747,750	$-	$12,524	$33,358	$69,543	$113,484	$144,966	$144,966	$113,484	$69,543	$33,358	$12,524
Total	$15,818,383	$-	$262,997	$700,517	$1,460,404	$2,383,161	$3,044,295	$3,052,012	$2,401,051	$1,486,298	$731,365	$296,283
Construction Loan Beginning Balance		$-	$-	$-	$-	$-	$-	$2,314,941	$5,366,953	$7,768,004	$9,254,301	$9,985,666
Cash Flows:												
Sponsor Equity	$5,536,434	$-	$262,997	$700,517	$1,460,404	$2,383,161	$729,354	$-	$-	$-	$-	$-
Financing Advances	$10,281,949	$-	$-	$-	$-	$-	$2,314,941	$3,052,012	$2,401,051	$1,486,298	$731,365	$296,283
Total Sources	$15,818,383	$-	$262,997	$700,517	$1,460,404	$2,383,161	$3,044,295	$3,052,012	$2,401,051	$1,486,298	$731,365	$296,283
Net Cash Flow		$-	$-	$-	$-	$-	$-	$-	$-	$-	$-	$-
Cash Balance		$-	$-	$-	$-	$-	$-	$-	$-	$-	$-	$-
Total Project Cost		$-	$262,997	$963,514	$2,423,918	$4,807,080	$7,851,375	$10,903,387	$13,304,438	$14,790,736	$15,522,100	$15,818,383
Construction Loan Ending Balance		$-	$-	$-	$-	$-	$2,314,941	$5,366,953	$7,768,004	$9,254,301	$9,985,666	$10,281,949
Loan to Cost		NA	0%	0%	0%	0%	29%	49%	58%	63%	64%	65%

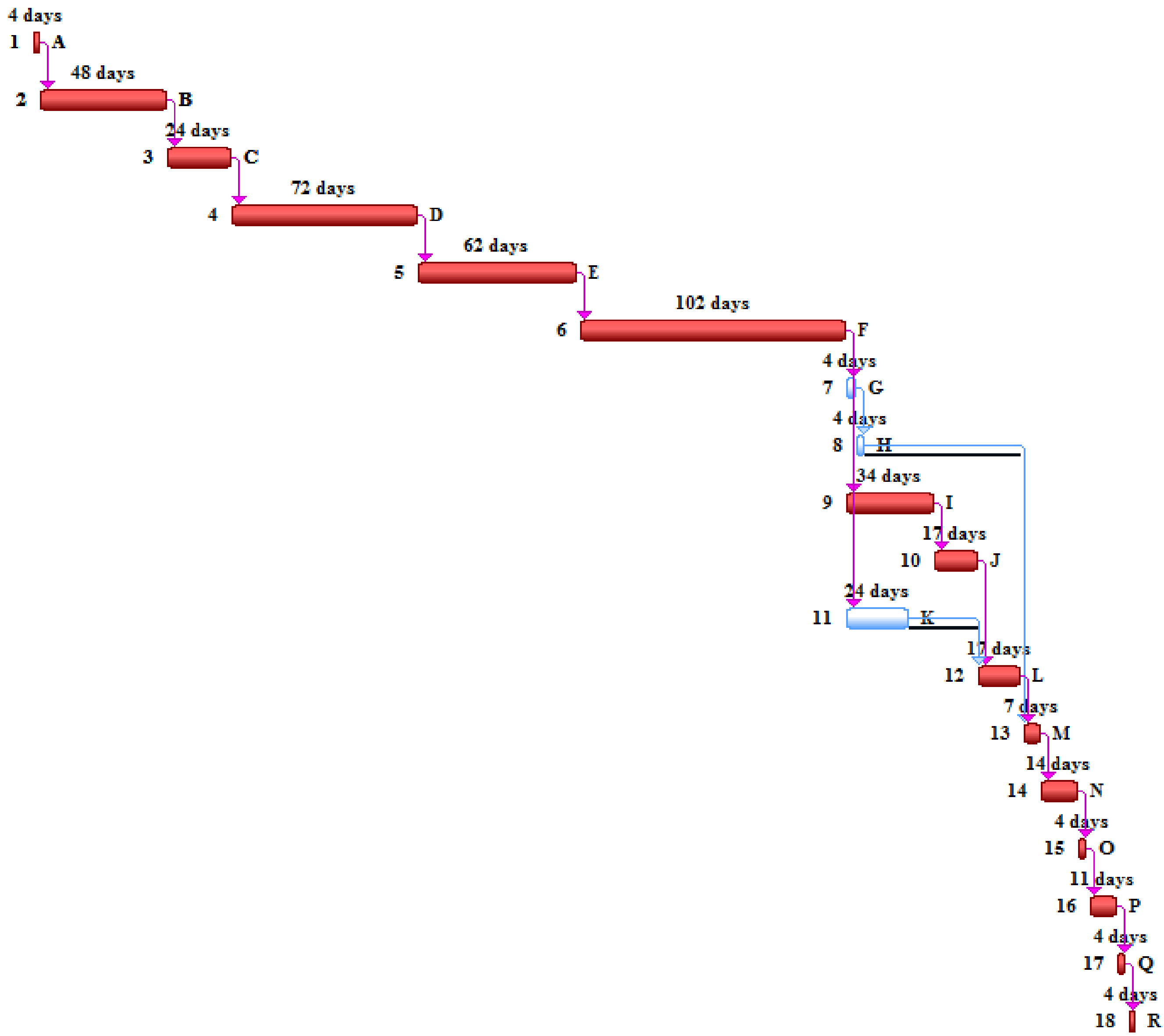


Figure 8-1. Project Schedule

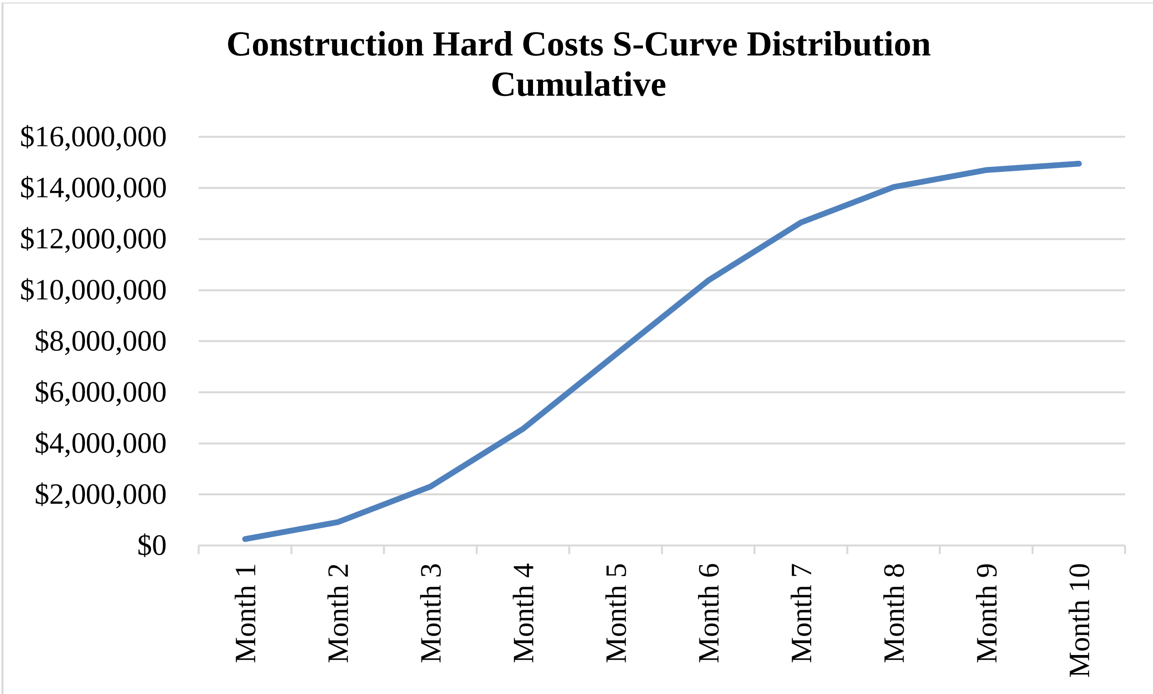


Figure 8-2. Construction Costs S-Curve Distribution (Cumulative)

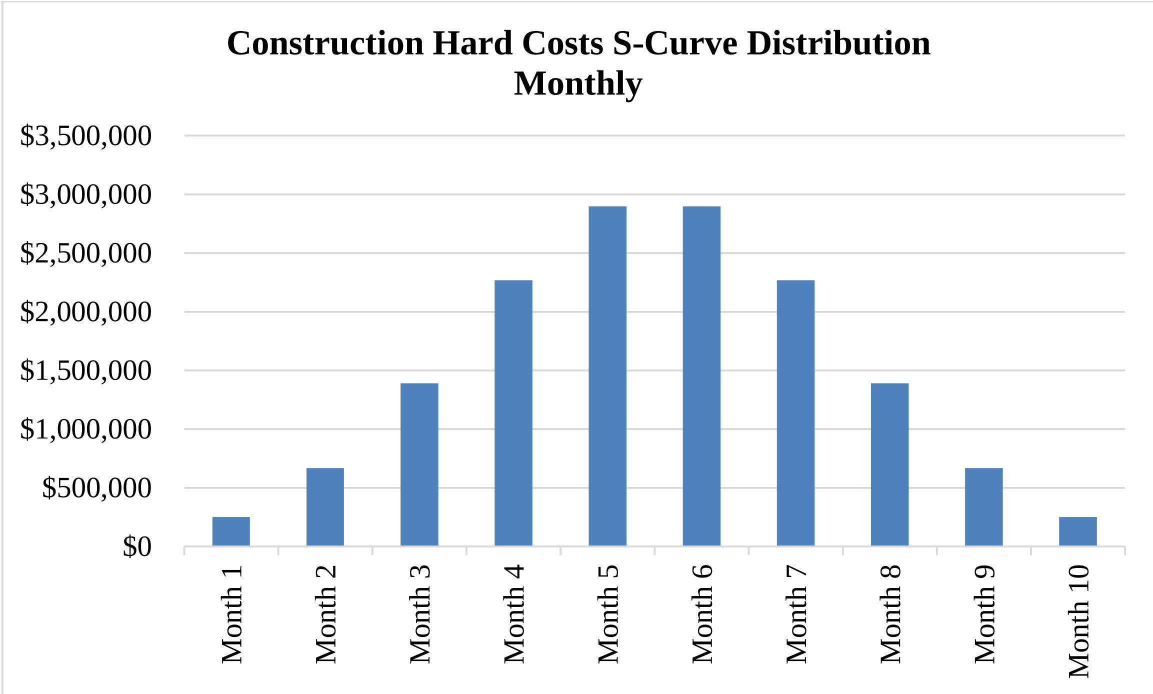


Figure 8-3. Construction Costs S-Curve Distribution (Monthly)

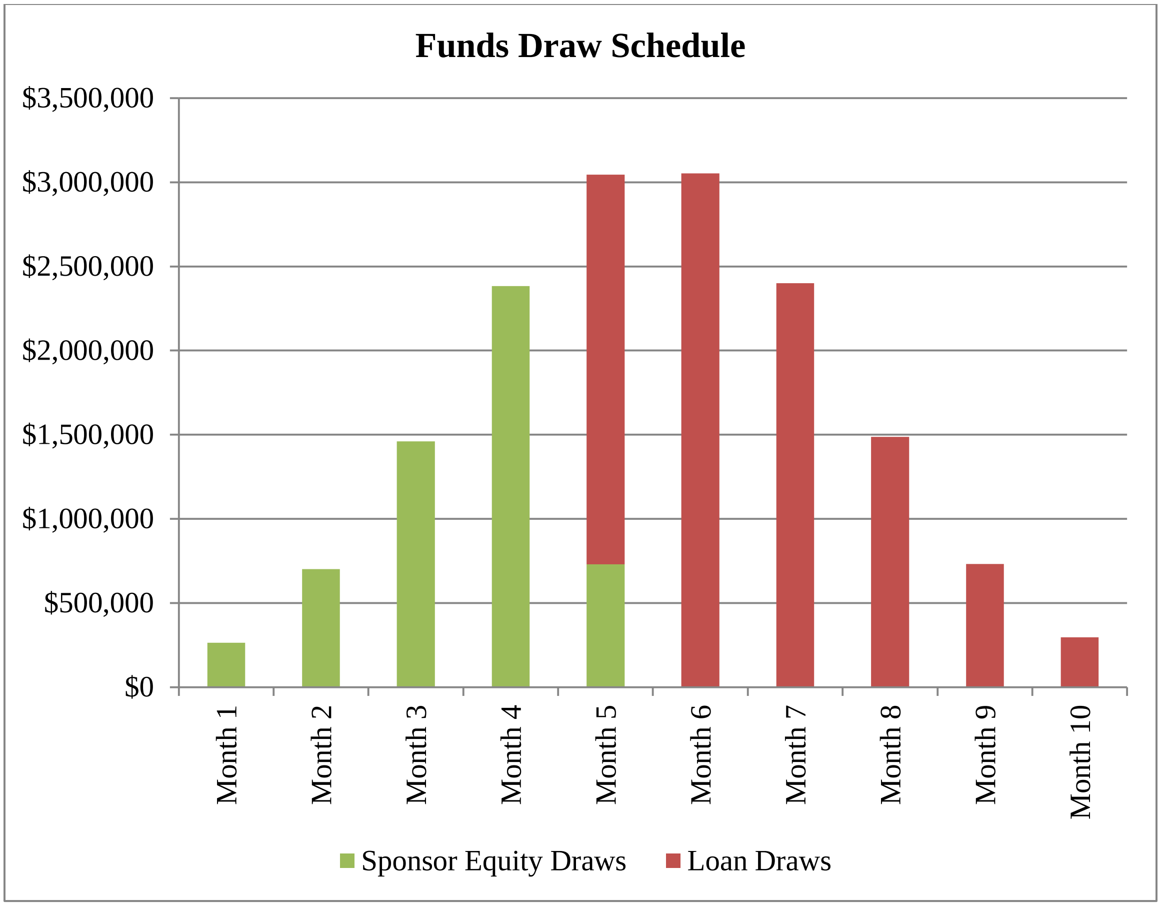


Figure 8-4. Funds Draw Schedule

CHAPTER 9
CONCLUSIONS

Concluding Remarks

State highway agencies struggle to provide the public with timely, qualified, and environment-friendly construction of highways with high safety requirements and with limited budgets. Construction delays, cost overrun, and poor project quality may cause significant inconveniences to the public and should be avoided through proper planning practices (e.g., proper project prioritization processes) and through project time-cost-quality optimization processes.

Development of global construction, alongside with advancement of construction engineering and management, facilitates the needs for trade-off optimization among multiple objectives such as project time, cost, quality and other indicators. Most of previous studies have followed the steps below:

1. Quantify one single objective or define the boundaries, both qualitatively and quantitatively, between two different objectives
2. Set up models based on Step 1
3. Solve models using common mathematical tools and techniques.

Such models usually have to make assumptions that are not practical in real engineering and have to ignore the integration of different objectives that are "connectively" constrained. Besides, traditional mathematical tools have also been proven complicated, unproductive, inaccuracy, and uni-versatile. This dissertation aimed to improve such decision-making procedures in the development of infrastructure engineering projects.

Specifically, this dissertation centered upon the study of methodology in decision making of infrastructure engineering development and management. It further proposed comprehensive finance-based time-cost-quality trade-off optimization models to help infrastructure engineering decision makers enhance their integrated decision-making procedures. After a literature review on the theory and methods of multi-criteria decision making (MCDM), two types of applications were discussed: (1) multi-attribute decision-making (MADM) optimization, and (2) multi-objective decision-making (MODM) optimization. The MADM method was proposed to be applied in the prioritization process of highway projects by constructing an index system through analysis of economic attributes, technological attributes, and environmental attributes of potential projects. The MODM method was proposed to be applied in the optimization of multiple objectives trade-off for a selected project through identification and modification of relationships among multiple objectives and through advanced optimization techniques. The former was then applied in Case Study I which aims to prioritize the Strategic Intermodal System highway projects in Florida Department of Transportation District 2, and the latter was then applied in Case Study II which provides the project sponsor with a finance-based multi-objective trade-off optimization model. An integration of analytic hierarchy process, entropy weight, and technique for order of preference by similarity to ideal solution was modeled to solve the MADM problem, while the genetic algorithm was suggested to solve the proposed MODM optimization model.

In addition, some critical success factors and key performance indicators for successful projects and successful project management were identified and incorporated in the proposed models with consideration of financial constraints over the project life cycle. Uncertainties and imprecisions that have often been encountered in the infrastructure engineering decision-making practice were modeled through the application of fuzzy sets theory. The two case studies testified the effectiveness and the efficiency of the proposed models. Generally, this dissertation research has provided infrastructure engineering decision makers (e.g., project sponsors and project managers) with a look into the existing methods and their applications to MCDM problems.

Table 9-1 summarizes the gap between this dissertation and the existing body of knowledge in the research on general time-cost-quality trade-off problems.

Suggestions

The project prioritization procedure proposed in the dissertation can be improved by filtering and including more, appropriate variables and parameters that best indicate the features and performance of potential projects. Other than fuzzy sets techniques, probabilistic models may also show advantages over the proposed model. In addition, the effectiveness of the proposed model should be further tested if more available data are obtained.

Most of the existing TCQT models have been developed as if the contractor performs all the project activities on its own. In other words, the management of subcontractor work is seldom enclosed in the TCQT analysis. In practice, however, the general contractor often trades time with subcontractors in sequential projects, and accordingly management of the subcontractor's efficiency becomes a challenge in project scheduling. The time, cost, and quality objectives cannot be met without the project manager's effort to effectively control subcontractors' performances. The interaction between the project manager from the general contractor and the subcontractor makes room for the application of cooperative game theory (Asgari and Afshar, 2008; Sacks and Harel, 2006).

For example, the numerical calculation of the expected utilities, developed by Sacks and Harel (2006), yields to a payoff matrix to evaluate the subcontractor's resource allocation behavior, given neither the project manager nor the subcontractor has any knowledge of the probability distribution of the work load. In this case, a perfect equilibrium exists that the project manager demands more work while the subcontractor allocates fewer resources. Similar analyses should be incorporated in the TCQT problem to get a more comprehensive optimization solution.

A finance-based fuzzy time-cost-quality trade-off optimization model over the project life cycle has been proposed in this research. This model can be used as a tool to enhance the integrated decision-making procedure of project owners/sponsors as well as of architecture, engineering, and construction firms in the infrastructure engineering field. Discussion of critical success factors and key performance indicators of successful infrastructure engineering projects adds more fuel to the proposed model. A methodology to integrate potential indicators with project time-cost-quality trade-off analysis has also been developed. A framework has been created that facilitates the positive feedback from project success through project management practice to corporate's competitiveness. The next step in the future may start with modeling project quality in a more realistic and effective way, either through the proposed AHP-Entropy-TOPSIS integration process or through creation of advanced mathematical functions.

In addition, an integrated approach should be further studied that connects the MADM optimization with the MODM optimization over the project life cycle. Such an approach should be able to offer project decision makers more values as a whole.

Table 9-1. Knowledge Gap between the Existing Research and the Proposed Research

	Existing Research	Proposed Research
Project Prioritization	Focused on development of weighted criteria according to expert opinions.	Integrates AHP and entropy weights to assign criteria weights and then apply them to TOPSIS for final ranking.
System Approach	No; conducted research separately on different project management issues.	Yes; proposes a system view on project management decision-making procedures.
Identification of CSFs	Focused on a variety of project types, on a specific country, or on different project phases.	Conducts meta-analysis to statistically synthesize results from existing studies; focuses at and above the project level.
Sustainability	Identified sustainable performance criteria mainly in building construction; no suggestions on incorporation of those criteria in the trade-off analysis.	Identifies sustainability indicators in infrastructure engineering; integrates indicators in the trade-off analysis by customizing LCA and LCC procedures.
TCQT Analysis	Developed common procedures; focused on the trade-off in a relatively limited scope, only among time, cost, and quality in the project construction phase; neglected other critical factors and financial constraints over the project life cycle.	Incorporates other critical factors; integrates project life cycle performance and financing needs; analyzes the TCQT problem in a wider and more general view of project life cycle as well as of corporate's financial constraints.
Finance-based Model	Focused on financing needs and cash flow management of contractors; missed general strategies about the trade-off between financing and other project objectives.	Seeks for integration between the functions of scheduling and financing; develops new approaches to model, analyze, and optimize financial constraints and cash flows in infrastructure engineering project management.
Optimization	Focused on local optimization within a specific project phase.	Focuses on global optimization over the whole project life cycle.

APPENDIX A
TRAVEL DEMAND DATA ANALYSIS

The travel demand data analysis was conducted using SPSS Statistics, a software package used for statistical analysis.

Descriptive Statistics Details

District 2 Frequency Tables

Count of HH members[a]

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1	418	22.2	22.2	22.2
	2	926	49.3	49.3	71.5
	3	245	13.0	13.0	84.6
	4	201	10.7	10.7	95.3
	5	63	3.4	3.4	98.6
	6	17	.9	.9	99.5
	7	5	.3	.3	99.8
	8	1	.1	.1	99.8
	9	1	.1	.1	99.9
	11	1	.1	.1	99.9
	13	1	.1	.1	100.0
	Total	1879	100.0	100.0	

a. FDOT district of HH location = 2

Count of adult HHMs at least 18 years old[a]

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1	447	23.8	23.8	23.8
	2	1218	64.8	64.8	88.6
	3	160	8.5	8.5	97.1
	4	49	2.6	2.6	99.7
	5	4	.2	.2	99.9
	8	1	.1	.1	100.0
	Total	1879	100.0	100.0	

a. FDOT district of HH location = 2

Number of workers in HH[a]

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	0	813	43.3	43.3	43.3
	1	646	34.4	34.4	77.6
	2	366	19.5	19.5	97.1
	3	47	2.5	2.5	99.6
	4	7	.4	.4	100.0
	Total	1879	100.0	100.0	

a. FDOT district of HH location = 2

Life Cycle for the HH[a]

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	one adult, no children	169	9.0	9.0	9.0
	2+ adults, no children	382	20.3	20.3	29.3
	one adult, youngest child 0-5	9	.5	.5	29.8
	2+ adults, youngest child 0-5	121	6.4	6.4	36.2
	one adult, youngest child 6-15	18	1.0	1.0	37.2
	2+ adults, youngest child 6-15	205	10.9	10.9	48.1
	one adult, youngest child 16-21	20	1.1	1.1	49.2
	2+ adults, youngest child 16-21	87	4.6	4.6	53.8
	one adult, retired, no children	249	13.3	13.3	67.1
	2+ adults, retired, no children	619	32.9	32.9	100.0
	Total	1879	100.0	100.0	

a. FDOT district of HH location = 2

Number of drivers in Household[a]

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	0	56	3.0	3.0	3.0
	1	524	27.9	27.9	30.9
	2	1076	57.3	57.3	88.1
	3	172	9.2	9.2	97.3
	4	44	2.3	2.3	99.6
	5	6	.3	.3	99.9
	6	1	.1	.1	100.0
	Total	1879	100.0	100.0	

a. FDOT district of HH location = 2

Count of HH vehicles[a]

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	0	72	3.8	3.8	3.8
	1	495	26.3	26.3	30.2
	2	797	42.4	42.4	72.6
	3	338	18.0	18.0	90.6
	4	123	6.5	6.5	97.1
	5	37	2.0	2.0	99.1
	6	9	.5	.5	99.6
	7	3	.2	.2	99.7
	8	3	.2	.2	99.9
	9	1	.1	.1	99.9
	10	1	.1	.1	100.0
	Total	1879	100.0	100.0	

a. FDOT district of HH location = 2

Derived total HH income[a]

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Don't know	48	2.6	2.6	2.6
	Refused	94	5.0	5.0	7.6
	less than $5,000	27	1.4	1.4	9.0
	$5,000 - $9,999	94	5.0	5.0	14.0
	$10,000 - $14,999	99	5.3	5.3	19.3
	$15,000 - $19,999	105	5.6	5.6	24.9
	$20,000 - $24,999	94	5.0	5.0	29.9
	$25,000 - $29,999	126	6.7	6.7	36.6
	$30,000 - $34,999	76	4.0	4.0	40.6
	$35,000 - $39,999	115	6.1	6.1	46.7
	$40,000 - $44,999	55	2.9	2.9	49.7
	$45,000 - $49,999	113	6.0	6.0	55.7
	$50,000 - $54,999	51	2.7	2.7	58.4
	$55,000 - $59,999	98	5.2	5.2	63.6
	$60,000 - $64,999	39	2.1	2.1	65.7
	$65,000 - $69,999	87	4.6	4.6	70.3
	$70,000 - $74,999	42	2.2	2.2	72.5
	$75,000 - $79,999	72	3.8	3.8	76.4
	$80,000 - $99,999	147	7.8	7.8	84.2
	more than $100,000	297	15.8	15.8	100.0
	Total	1879	100.0	100.0	

a. FDOT district of HH location = 2

Housing unit owned or rented[a]

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	own	1698	90.4	90.4	90.4
	rent	181	9.6	9.6	100.0
	Total	1879	100.0	100.0	

a. FDOT district of HH location = 2

Type of housing unit[a]

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Don't know	2	.1	.1	.1
	Refused	3	.2	.2	.3
	Detached single house	1377	73.3	73.3	73.5
	Duplex	53	2.8	2.8	76.4
	Rowhouse or townhouse	130	6.9	6.9	83.3
	Apartment, condominium	311	16.6	16.6	99.8
	Mobile home or trailer	3	.2	.2	100.0
	Total	1879	100.0	100.0	

a. FDOT district of HH location = 2

Hispanic status of HH respondent[a]

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Not ascertained	1	.1	.1	.1
	Don't know	3	.2	.2	.2
	Refused	4	.2	.2	.4
	yes	48	2.6	2.6	3.0
	no	1823	97.0	97.0	100.0
	Total	1879	100.0	100.0	

a. FDOT district of HH location = 2

Race of HH respondent[a]

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Not ascertained	1	.1	.1	.1
	Don't know	1	.1	.1	.1
	Refused	8	.4	.4	.5
	White	1664	88.6	88.6	89.1
	African American, Black	127	6.8	6.8	95.8
	Asian Only	19	1.0	1.0	96.9
	American Indian, Alaskan Native	18	1.0	1.0	97.8
	Native Hawaiian, other Pacific	6	.3	.3	98.1
	Multiracial	15	.8	.8	98.9
	Other specify	5	.3	.3	99.2
	Other specify	15	.8	.8	100.0
	Total	1879	100.0	100.0	

a. FDOT district of HH location = 2

Size of urban area in which home address is located[a]

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	50,000 – 199,999	193	10.3	10.3	10.3
	500,000 – 999,999	704	37.5	37.5	47.7
	Not in an urbanized area	982	52.3	52.3	100.0
	Total	1879	100.0	100.0	

a. FDOT district of HH location = 2

Travel day - day of week[a]

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Sunday	267	14.2	14.2	14.2
	Monday	303	16.1	16.1	30.3
	Tuesday	269	14.3	14.3	44.7
	Wednesday	274	14.6	14.6	59.2
	Thursday	247	13.1	13.1	72.4
	Friday	257	13.7	13.7	86.1
	Saturday	262	13.9	13.9	100.0
	Total	1879	100.0	100.0	

a. FDOT district of HH location = 2

Number of months lives in FL[a]

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Not ascertained	1	.1	.1	.1
	Don't know	2	.1	.1	.2
	2	1	.1	.1	.2
	4	2	.1	.1	.3
	5	1	.1	.1	.4
	6	10	.5	.5	.9
	7	6	.3	.3	1.2
	8	3	.2	.2	1.4
	9	5	.3	.3	1.6
	10	5	.3	.3	1.9
	11	11	.6	.6	2.5
	12	1830	97.4	97.4	99.9
	99	2	.1	.1	100.0
	Total	1879	100.0	100.0	

a. FDOT district of HH location = 2

Summary of Crosstabs

FDOT district of HH location = 2

Case Processing Summary[a]

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Count of HH vehicles * Count of HH members	1879	100.0%	0	0.0%	1879	100.0%

a. FDOT district of HH location = 2

Count of HH vehicles * Count of HH members Crosstabulation[a]

			Count of HH members											Total
			1	2	3	4	5	6	7	8	9	11	13	
Count of HH vehicles	0	Count	50	16	3	3	0	0	0	0	0	0	0	72
		% within Count of HH members	12.0%	1.7%	1.2%	1.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	3.8%
	1	Count	298	154	27	13	2	1	0	0	0	0	0	495
		% within Count of HH members	71.3%	16.6%	11.0%	6.5%	3.2%	5.9%	0.0%	0.0%	0.0%	0.0%	0.0%	26.3%
	2	Count	50	526	95	93	20	9	4	0	0	0	0	797
		% within Count of HH members	12.0%	56.8%	38.8%	46.3%	31.7%	52.9%	80.0%	0.0%	0.0%	0.0%	0.0%	42.4%
	3	Count	12	164	88	50	21	1	1	0	0	1	0	338
		% within Count of HH members	2.9%	17.7%	35.9%	24.9%	33.3%	5.9%	20.0%	0.0%	0.0%	100.0%	0.0%	18.0%
	4	Count	8	46	21	29	14	2	0	1	1	0	1	123
		% within Count of HH members	1.9%	5.0%	8.6%	14.4%	22.2%	11.8%	0.0%	100.0%	100.0%	0.0%	100.0%	6.5%
	5	Count	0	13	10	8	2	4	0	0	0	0	0	37
		% within Count of HH members	0.0%	1.4%	4.1%	4.0%	3.2%	23.5%	0.0%	0.0%	0.0%	0.0%	0.0%	2.0%
	6	Count	0	3	0	3	3	0	0	0	0	0	0	9
		% within Count of HH members	0.0%	0.3%	0.0%	1.5%	4.8%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%
	7	Count	0	1	0	2	0	0	0	0	0	0	0	3
		% within Count of HH members	0.0%	0.1%	0.0%	1.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%
	8	Count	0	1	1	0	1	0	0	0	0	0	0	3
		% within Count of HH members	0.0%	0.1%	0.4%	0.0%	1.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%
	9	Count	0	1	0	0	0	0	0	0	0	0	0	1
		% within Count of HH members	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%
	10	Count	0	1	0	0	0	0	0	0	0	0	0	1
		% within Count of HH members	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%
Total		Count	418	926	245	201	63	17	5	1	1	1	1	1879
		% within Count of HH members	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

a. FDOT district of HH location = 2

Regression Model Details

Model 1

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	Housing unit owned or rented, Households whose residents live in the region more than one month, but less than six months per year, Count of HHMs less than 18 years old, Monday, Med income households $30,000 through $80,000, Count of adult HHMs at least 18 years old, Number of workers in HH, High income households more than $80,000, Number of drivers in Household[b]	.	Enter

a. Dependent Variable: Total number of Trips made by HH

b. All requested variables entered.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.558[a]	.311	.306	4.630

a. Predictors: (Constant), Housing unit owned or rented, Households whose residents live in the region more than one month, but less than six months per year, Count of HHMs less than 18 years old, Monday, Med income households $30,000 through $80,000, Count of adult HHMs at least 18 years old, Number of workers in HH, High income households more than $80,000, Number of drivers in Household

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	13610.083	9	1512.231	70.559	.000[b]
	Residual	30176.673	1408	21.432		
	Total	43786.756	1417			

a. Dependent Variable: Total number of Trips made by HH

b. Predictors: (Constant), Housing unit owned or rented, Households whose residents live in the region more than one month, but less than six months per year, Count of HHMs less than 18 years old, Monday, Med income households $30,000 through $80,000, Count of adult HHMs at least 18 years old, Number of workers in HH, High income households more than $80,000, Number of drivers in Household

Coefficients[a]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	1.549	.658		2.355	.019
	Count of adult HHMs at least 18 years old	.860	.295	.106	2.920	.004
	Count of HHMs less than 18 years old	1.974	.151	.309	13.099	.000
	Number of workers in HH	.697	.175	.108	3.974	.000
	Number of drivers in Household	1.012	.288	.139	3.514	.000
	Med income households $30,000 through $80,000	.624	.314	.056	1.984	.047
	High income households more than $80,000	2.052	.379	.161	5.410	.000
	Monday	-.091	.332	-.006	-.275	.783
	Households whose residents live in the region more than one month, but less than six months per year	2.030	1.294	.035	1.568	.117
	Housing unit owned or rented	-.295	.438	-.015	-.674	.500

a. Dependent Variable: Total number of Trips made by HH

Model 2

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	Derived total HH income, Count of HHMs less than 18 years old, Count of adult HHMs at least 18 years old[b]	.	Enter

a. Dependent Variable: Total number of Trips made by HH

b. All requested variables entered.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.545[a]	.297	.295	4.667

a. Predictors: Derived total HH income, Count of HHMs less than 18 years old, Count of adult HHMs at least 18 years old

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	12987.789	3	4329.263	198.759	.000[b]
	Residual	30798.967	1414	21.781		
	Total	43786.756	1417			

a. Dependent Variable: Total number of Trips made by HH

b. Predictors: (Constant), Derived total HH income, Count of HHMs less than 18 years old, Count of adult HHMs at least 18 years old

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.246	.394		.623	.533
	Count of adult HHMs at least 18 years old	1.870	.192	.230	9.740	.000
	Count of HHMs less than 18 years old	2.172	.146	.340	14.873	.000
	Derived total HH income	.210	.024	.211	8.900	.000

a. Dependent Variable: Total number of Trips made by HH

Model 3

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	Weekend, Number of drivers in Household, Med income households $30,000 through $80,000, Count of HHMs less than 18 years old, Low income households less than $30,000[b]	.	Enter

a. Dependent Variable: Total number of Trips made by HH

b. All requested variables entered.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.549[a]	.301	.299	4.655

a. Predictors: (Constant), Weekend, Number of drivers in Household, Med income households $30,000 through $80,000, Count of HHMs less than 18 years old, Low income households less than $30,000

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	13191.967	5	2638.393	121.766	.000[b]
	Residual	30594.789	1412	21.668		
	Total	43786.756	1417			

a. Dependent Variable: Total number of Trips made by HH

b. Predictors: (Constant), Weekend, Number of drivers in Household, Med income households $30,000 through $80,000, Count of HHMs less than 18 years old, Low income households less than $30,000

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	4.216	.469		8.998	.000
	Number of drivers in Household	1.963	.184	.269	10.682	.000
	Count of HHMs less than 18 years old	1.951	.149	.306	13.074	.000
	Low income households less than $30,000	-2.423	.361	-.202	-6.712	.000
	Med income households $30,000 through $80,000	-1.588	.314	-.141	-5.061	.000
	Weekend	-.836	.276	-.067	-3.025	.003

a. Dependent Variable: Total number of Trips made by HH

Model 4

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	Number of drivers in Household, Weekend, Med income households $30,000 through $80,000, Count of HHMs less than 18 years old, Low income households less than $30,000, Count of adult HHMs at least 18 years old[b]	.	Enter

a. Dependent Variable: Total number of Trips made by HH

b. All requested variables entered.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.554[a]	.306	.303	4.639

a. Predictors: (Constant), Number of drivers in Household, Weekend, Med income households $30,000 through $80,000, Count of HHMs less than 18 years old, Low income households less than $30,000, Count of adult HHMs at least 18 years old

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	13417.489	6	2236.248	103.899	.000[b]
	Residual	30369.267	1411	21.523		
	Total	43786.756	1417			

a. Dependent Variable: Total number of Trips made by HH

b. Predictors: (Constant), Number of drivers in Household, Weekend, Med income households $30,000 through $80,000, Count of HHMs less than 18 years old, Low income households less than $30,000, Count of adult HHMs at least 18 years old

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	3.657	.498		7.344	.000
	Count of HHMs less than 18 years old	1.999	.149	.313	13.375	.000
	Low income households less than $30,000	-2.473	.360	-.207	-6.865	.000
	Med income households $30,000 through $80,000	-1.586	.313	-.141	-5.073	.000
	Weekend	-.817	.275	-.066	-2.965	.003
	Count of adult HHMs at least 18 years old	.948	.293	.116	3.237	.001
	Number of drivers in Household	1.269	.282	.174	4.499	.000

a. Dependent Variable: Total number of Trips made by HH

Model Validation Details

For the purpose of simplicity, only the first 20 rows are extracted from the spreadsheet, which shows the calculation process.

True rates	Pred. rates from local model	Pred. Rates from transferred model	Absolute difference local vs. true	Abs. % diff. local vs. true	Absolute difference transfer vs. true	Abs. % diff. transfer vs. true
15	5.749	6.635	9.251	0.617	8.365	0.558
16	9.686	9.479	6.314	0.395	6.521	0.408
12	12.938	13.363	0.938	0.078	1.363	0.114
9	8.956	10.496	0.044	0.005	1.496	0.166
9	8.722	8.549	0.278	0.031	0.451	0.050
18	8.722	4.927	9.278	0.515	13.073	0.726
12	5.688	4.583	6.312	0.526	7.417	0.618
6	3.471	4.210	2.529	0.422	1.790	0.298
2	3.401	4.142	1.401	0.701	2.142	1.071
4	2.132	3.141	1.868	0.467	0.859	0.215
6	6.505	4.927	0.505	0.084	1.073	0.179
8	8.091	9.177	0.091	0.011	1.177	0.147
20	10.939	10.360	9.061	0.453	9.640	0.482
11	6.505	5.869	4.495	0.409	5.131	0.466
0	8.091	9.334	8.091		9.334	
4	4.801	3.484	0.801	0.200	0.516	0.129
8	6.822	6.654	1.178	0.147	1.346	0.168
0	5.236	5.398	5.236		5.398	
18	8.799	11.217	9.201	0.511	6.783	0.377
0	3.401	4.456	3.401		4.456	

APPENDIX B
PROJECT DATA FOR CASE STUDY I

Project # 208001-1

Project Summary

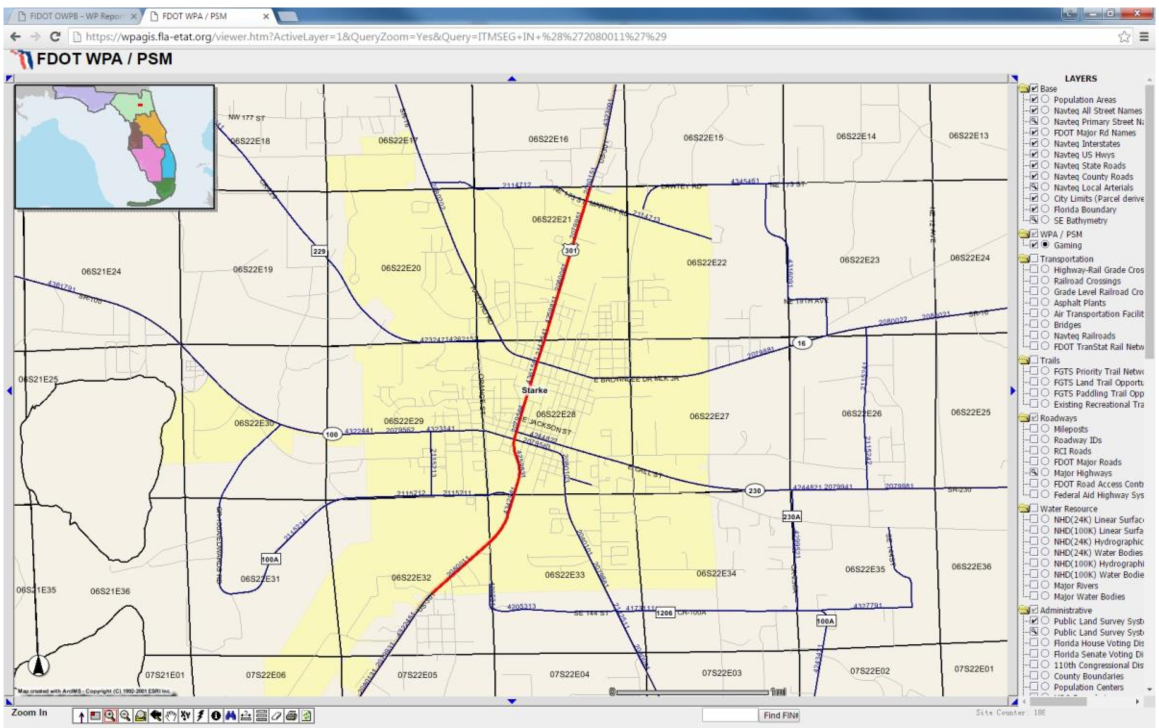
Project Summary

Transportation System: INTRASTATE STATE HIGHWAY — District 02 - Bradford County
Description: SR 200 (US 301) FROM S CITY LIMITS TO N CITY LIMITS
Type of Work: PRELIM ENG FOR FUTURE CAPACITY — View Scheduled Activities
Item Number: 208001-1 — **SIS**
Length: 2.985 — View Map of Item

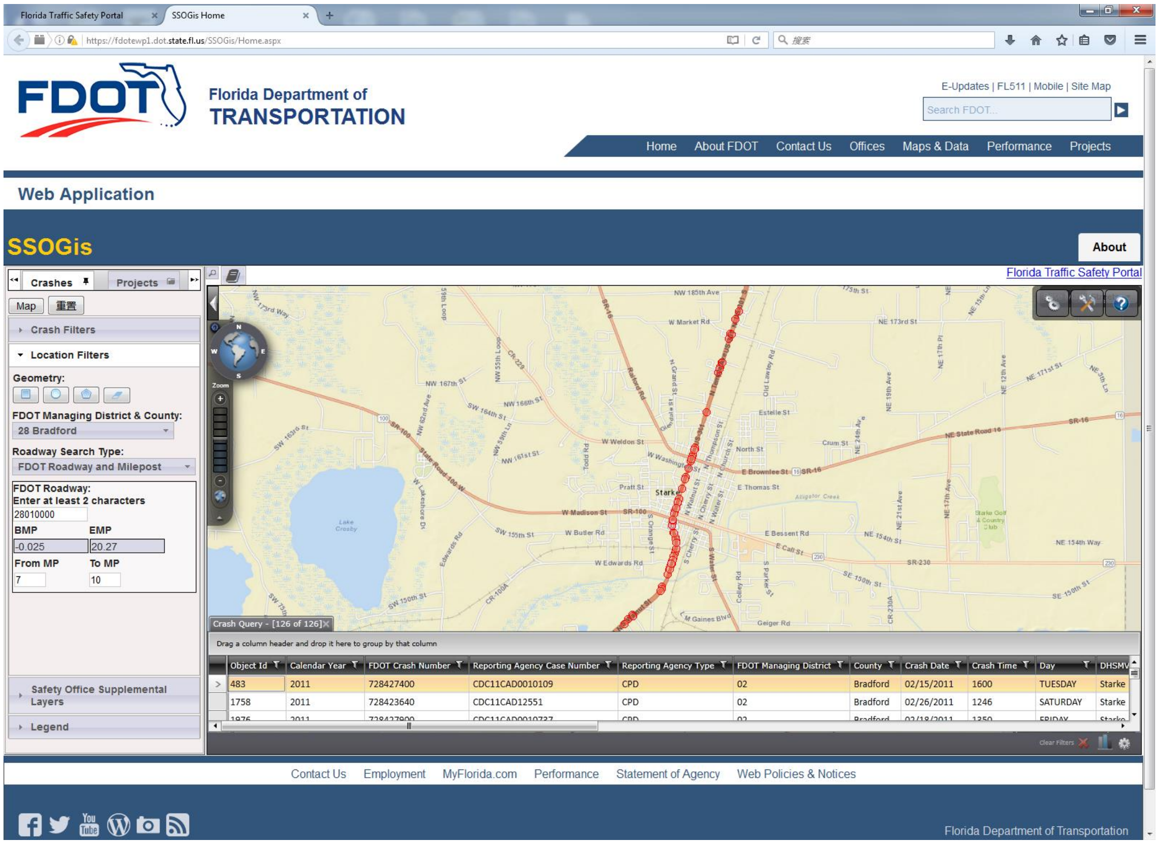
Project Detail

Fiscal Year:	2016	2017	2018	2019	2020	2021
Highways/PD & E						*(On-Going)*
Amount:	$2,000					
Highways/Preliminary Engineering						*(On-Going)*
Amount:						
Item Total:	**$2,000**					

Project Map



Crash Data



Environmental Impact

Legend

- N/A — N/A / No Involvement
- 1 — Enhanced
- 0 — None
- 2 — Minimal (after 12/5/2005)
- 3 — Moderate
- 4 — Substantial
- 5 — Dispute Resolution (Programming)

Evaluation of Direct Effects

	Natural											Cultural			Community						
	Air Quality	Coastal and Marine	Contaminated Sites	Farmlands	Floodplains	Infrastructure	Navigation	Special Designations	Water Quality and Quantity	Wetlands	Wildlife and Habitat	Historic and Archaeological Sites	Recreation Areas	Section 4(f) Potential	Aesthetics	Economic	Land Use	Mobility	Relocation	Social	Secondary and Cumulative Effects
Alternative #1 **From CR 227 To CR 233** *- Reviewed from 6/16/2006 to 7/31/2006* *- Published on 3/26/2007*	3	N/A	3	N/A	2	0	0	N/A	3	2	2	4	3	2	3	N/A	4	3	2	4	2
Alternative #2 **From CR 227 To CR 233** *- Reviewed from 6/16/2006 to 7/31/2006* *- Published on 3/26/2007*	3	N/A	2	N/A	3	N/A	0	2	3	3	3	3	3	2	2	N/A	3	3	3	3	3

Other Information

The proposed project is consistent with the 2060 Florida Transportation Plan long-range goals and objectives. Funding for this project is identified in the current District 2 SIS Plan.[9] The project is also consistent with local County and City comprehensive plans.

Capacity and Level of Service. With the No Build Alternative the level of service conditions are anticipated to be LOS F. The proposed Rural Alternative will achieve 2040 design year LOS B on the bypass route and result in a LOS B on the existing route. The Rural Alternative will meet the SIS level of service criteria. In the design year, 2040, there will be a 57 percent reduction of traffic on existing U.S. 301 between S.R. 100 and S.R. 16, a 31 percent reduction in traffic on S.R. 16 west of U.S. 301, and a 16 percent reduction of traffic on S.R.100 west of U.S. 301.[10]

This project is located on the facility of SR 200 (US 301) from CR 227 to CR 233. The improvement involves project development and environment (PD&E) study. The project is to result in the construction of a four lane limited-access bypass on a new alignment, located on the west side of the City of Starke urban area.

The project plan is consistent with Bradford County Comprehensive Plan, City of Starke Comprehensive Plan, State Transportation Program, Florida's Cost Feasible SIS Plan, and FDOT Five-Year Work Program.

[9] U.S. 301 (State Road 200) Record of Decision, February 4, 2014

[10] Draft Environmental Impact Statement Starke U.S. 301 Corridor Study

Project # 209301-3

Project Summary

Project Summary

Transportation System: INTRASTATE INTERSTATE — District 02 - Duval County

Description: I-295 (SR 9A) FROM SR 202 JTB BLVD TO SR 9B (MANAGED LANES)

Type of Work: ADD LANES & RECONSTRUCT — View Scheduled Activities

Item Number: 209301-3 — SIS

Length: 4.212 — View Map of Item

Construction Contract Information

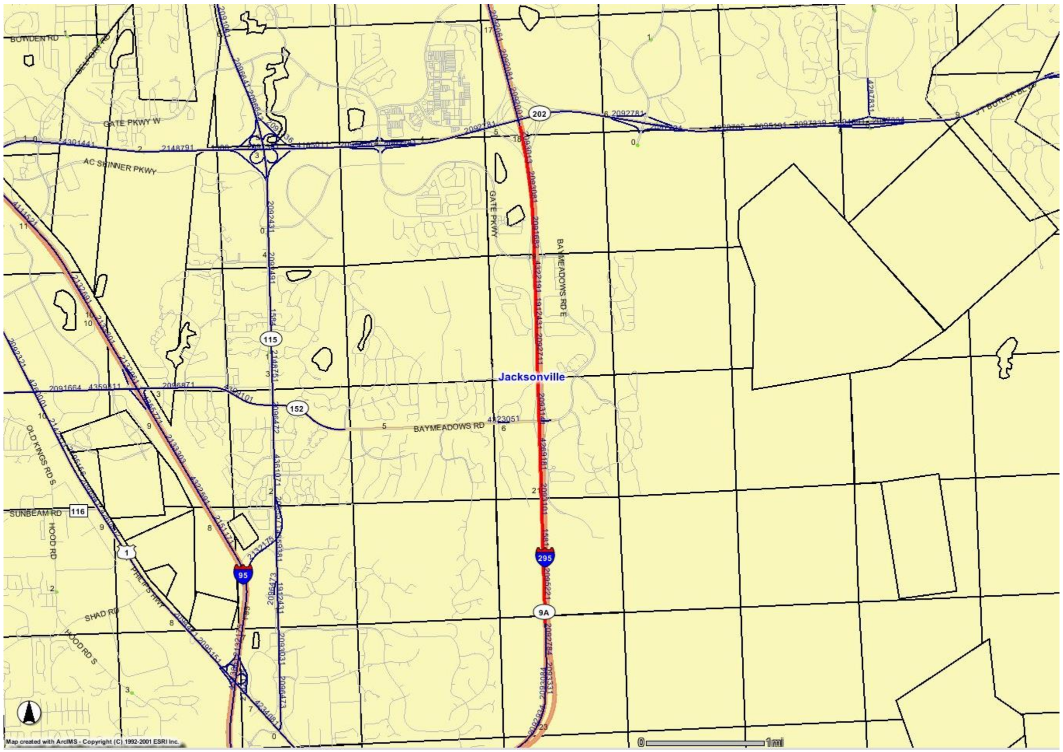
Notice to Proceed Date	Work Begun Date	Present Contract Days	Contract Days Used	Percent Days Used
02/23/2016	02/23/2016	900	27	3.00%

Vendor Name: ARCHER WESTERN CONTRACTORS LLC

Project Detail

Fiscal Year:	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Highways/PD & E						*(On-Going)*
Amount:	$600					
Highways/Preliminary Engineering						*(On-Going)*
Amount:	$32,077					
Highways/Right of Way						*(On-Going)*
Amount:	$1,836,797	$730,144				
Highways/Railroad & Utilities						*(On-Going)*
Amount:	$47,608					
Highways/Environmental						*(On-Going)*
Amount:						
Highways/Operations						
Amount:	$100,000			$300,000	$300,000	$300,000
Highways/Design Build						*(On-Going)*
Amount:	$39,066,619	$3,871,456				
Maintenance/Bridge/Roadway/Contract Maintenance						
Amount:	$10,000			$468,480	$468,480	$468,480
Item Total:	**$41,093,701**	**$4,601,600**		**$768,480**	**$768,480**	**$768,480**

Project Map



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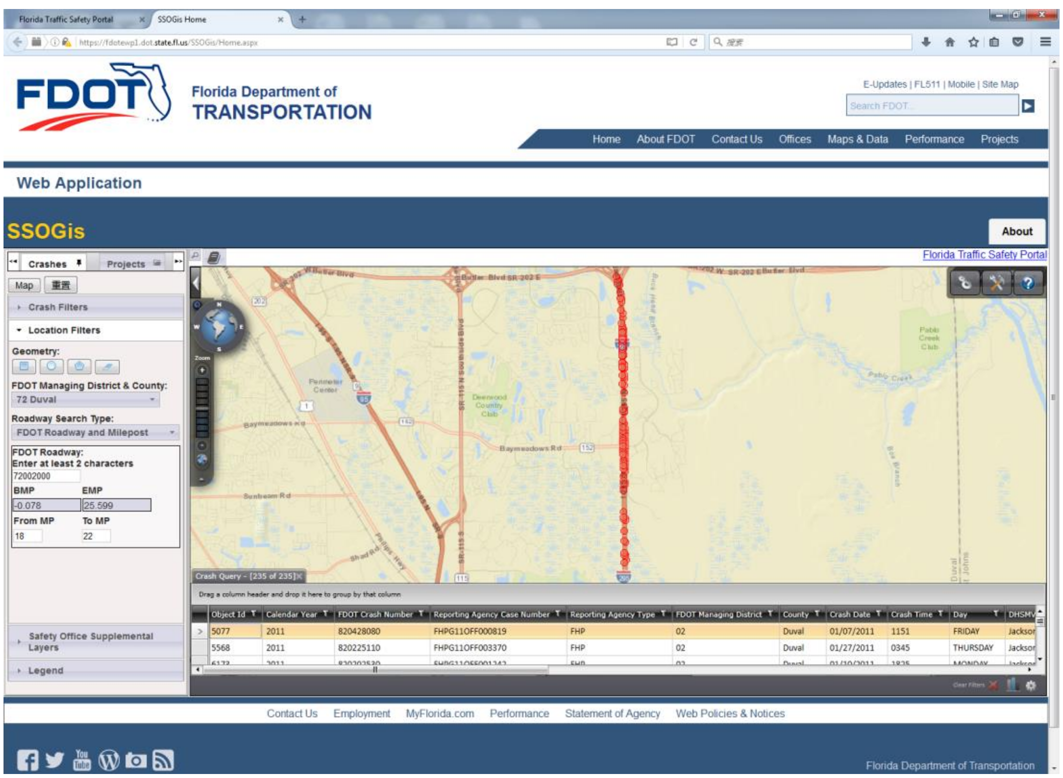


Other Information

Capacity - The segment of I-295 from SR 9B to SR 202 (JTB Blvd.) currently experiences heavy peak period congestion with speeds well below the posted speed limits due to demand that exceeds capacity. In 2013, I-295 operated at Level of Service (LOS) F from SR 9B to SR 152 (Baymeadows Road) and at LOS D from SR 152 (Baymeadows Road) to SR 202 (JTB Blvd.). By 2040, the entire segment of I-295 within the study limits will operate at LOS F.

Travel Time Reliability - Travel time reliability measures the extent of this unexpected delay and is defined as the consistency or dependability of travel times, as measured from day-to-day and/or across different times of day. The free-flow travel time along I-295 (measured as part of the I-295 Planning Feasibility Study) between US 1 and Town Center Parkway is approximately 7.4 minutes. In the existing conditions, travel times in the peak hour vary between 8.4 and 13.5 minutes in the I-295 northbound direction (a.m. peak), and between 10.6 and 19.3 minutes in the southbound direction (p.m. peak). The travel times from US 1 to Town Center Parkway vary from 14 to 160 percent above the free flow travel time during these peak hours. The variability in travel time is caused by several bottleneck locations within the study area that cause stop-and-go conditions.

Transportation Demand - The North Florida Transportation Planning Organization (NFTPO) Envision 2035 Long Range Transportation Plan (LRTP) (revised March 14, 2013) identifies the need for additional capacity along I-295 within the project limits. This project is listed as "Project Number 130 – SR 9A (I-295) from SR 9B to SR 202 (JTB Blvd.) – Managed Express Lanes Toll Lanes." The project is also listed in the NFTPO Transportation Improvement Plan Fiscal Year 2014/15 – 2018/19 (approved June 12, 2014).

Project # 209537-4

Project Summary

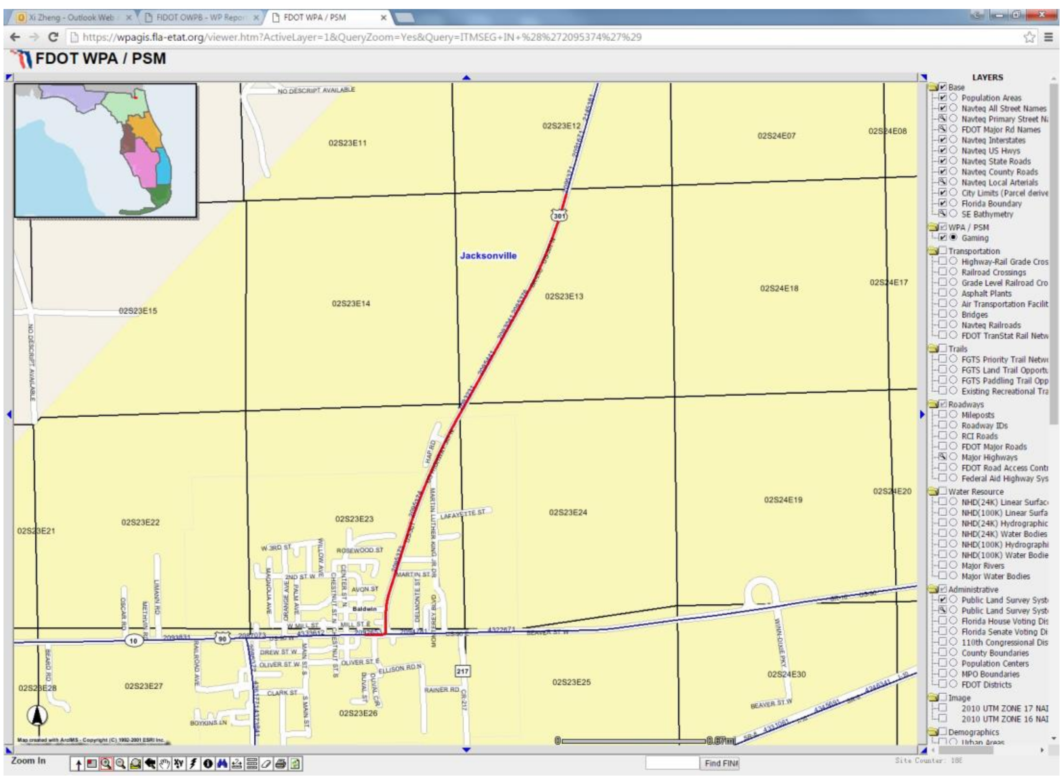
Project Summary

Transportation System: INTRASTATE STATE HIGHWAY — District 02 - Duval County
Description: SR200(US301) FROM S OF BALDWIN TO N OF BALDWIN (BYPASS)
Type of Work: NEW ROAD CONSTRUCTION — View Scheduled Activities
Item Number: 209537-4 — SIS
Length: 7.335 — View Map of Item

Project Detail

Fiscal Year:	2016	2017	2018	2019	2020	2021
Highways/PD & E						*(On-Going)*
Amount:	$5,314					
Highways/Preliminary Engineering						*(On-Going)*
Amount:	$187,363					
Highways/Right of Way						*(On-Going)*
Amount:	$2,845,223	$964,347	$2,678,902			
Highways/Railroad & Utilities						*(On-Going)*
Amount:	$500,000					
Highways/Construction						
Amount:		$63,592,311				
Highways/Environmental						*(On-Going)*
Amount:	$2,113,415					
Item Total:	**$5,651,315**	**$64,556,658**	**$2,678,902**			

Project Map



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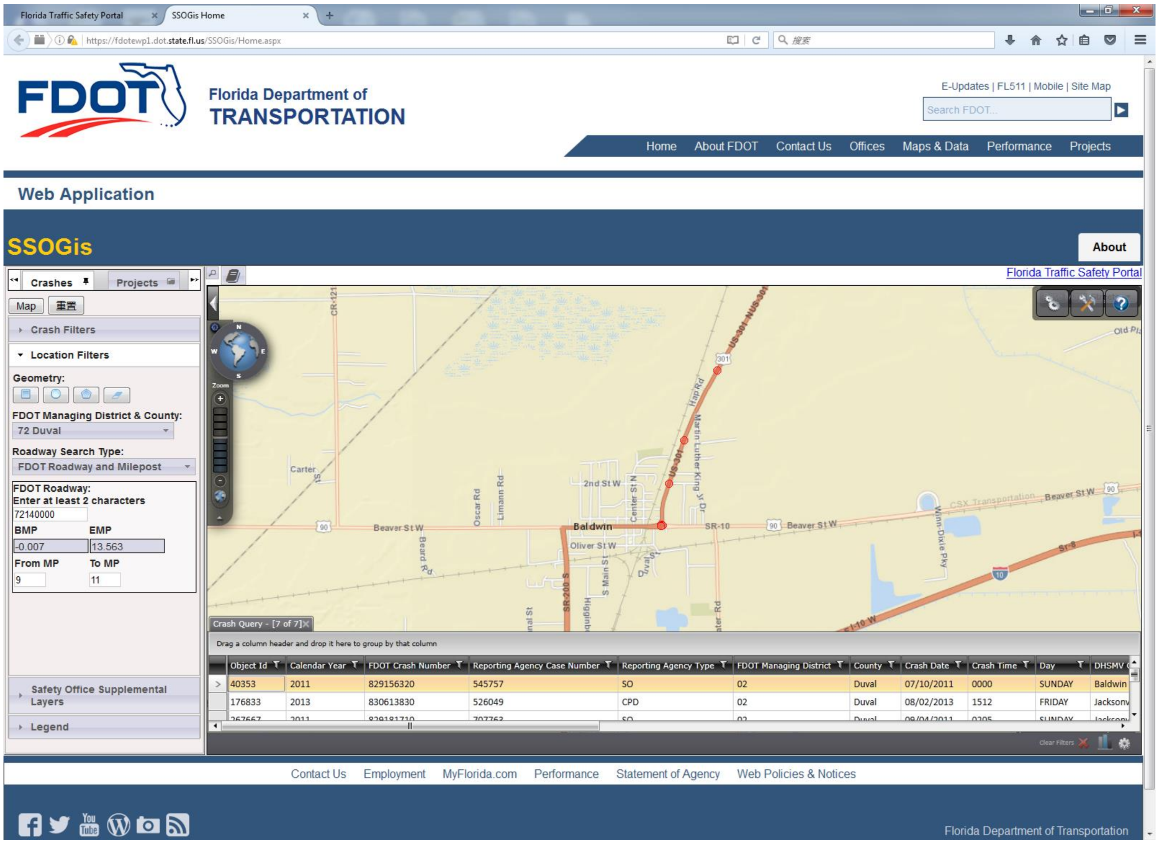
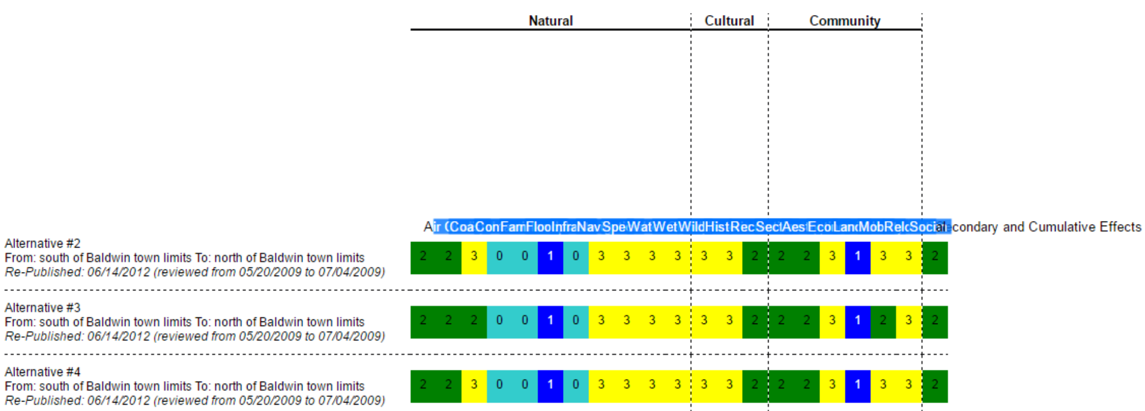


Environmental Impact



Project # 209658-4

Project Summary

Project Summary

Transportation System: INTRASTATE INTERSTATE — District 02 - Duval County

Description: I-295(SR9A) FROM DAMES POINT BRIDGE TO NORTH OF PULASKI

Type of Work: ADD LANES & RECONSTRUCT — View Scheduled Activities

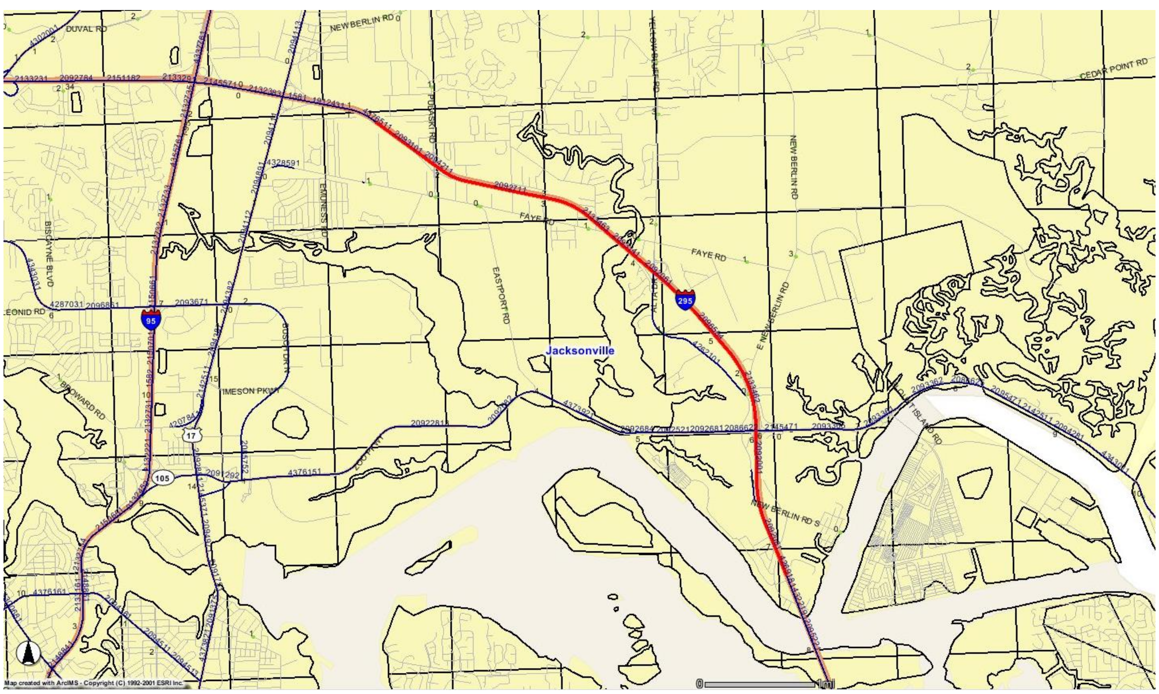
Item Number: 209658-4 — SIS

Length: 6.075 — View Map of Item

Project Detail

Fiscal Year:	2016	2017	2018	2019	2020	2021
Highways/PD & E						*(On-Going)*
Amount:	$6,431					
Highways/Preliminary Engineering						*(On-Going)*
Amount:	$9,701					
Highways/Right of Way						*(On-Going)*
Amount:	$2,867,597	$2,208,234	$816,965			
Highways/Railroad & Utilities						*(On-Going)*
Amount:						
Highways/Environmental						
Amount:						$3,225,000
Item Total:	**$2,883,729**	**$2,208,234**	**$816,965**			**$3,225,000**

Project Map



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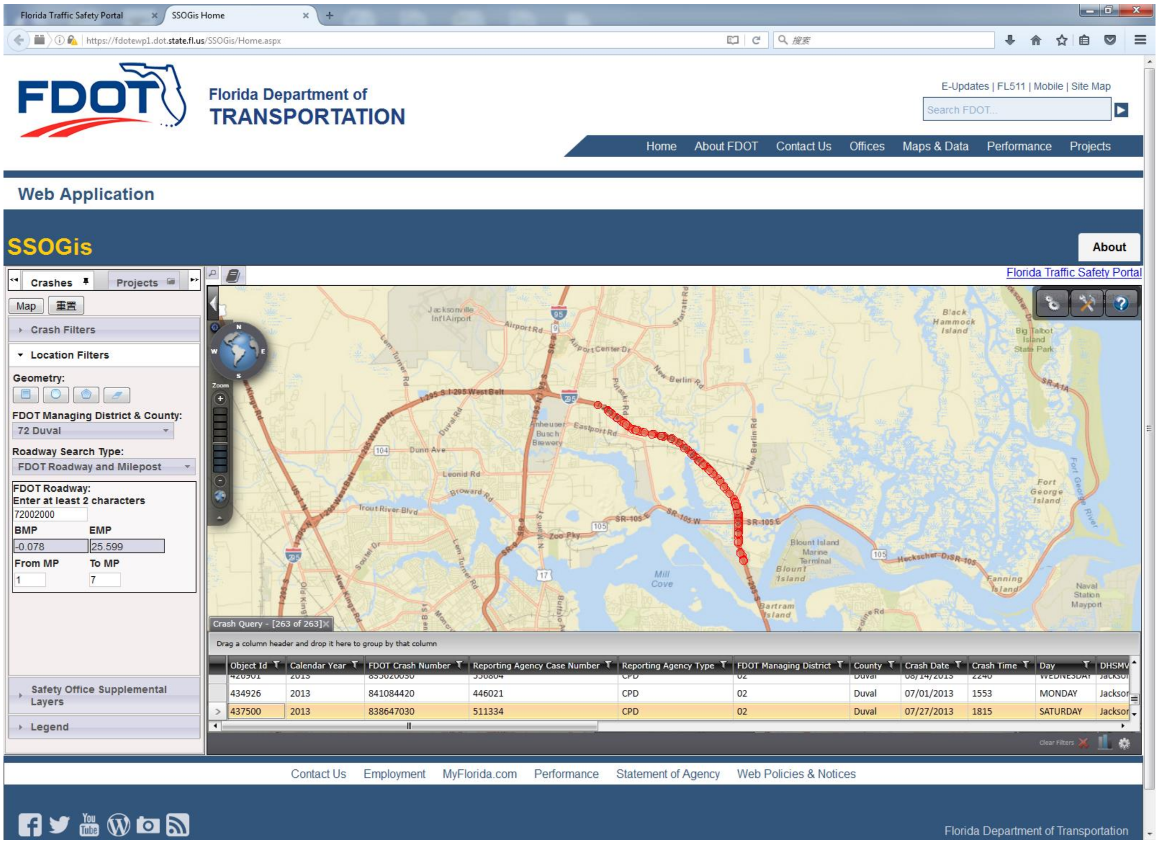


Project # 209659-3

Project Summary

Project Summary

Transportation System: INTRASTATE INTERSTATE — District 02 - Duval County

Description: I-10 (SR 8) INTERCHANGE AT SR 10 (US 90) AND SR 23

Type of Work: INTERCHANGE IMPROVEMENT — View Scheduled Activities

Item Number: 209659-3 — SIS

Length: 3.224 — View Map of Item

Construction Contract Information

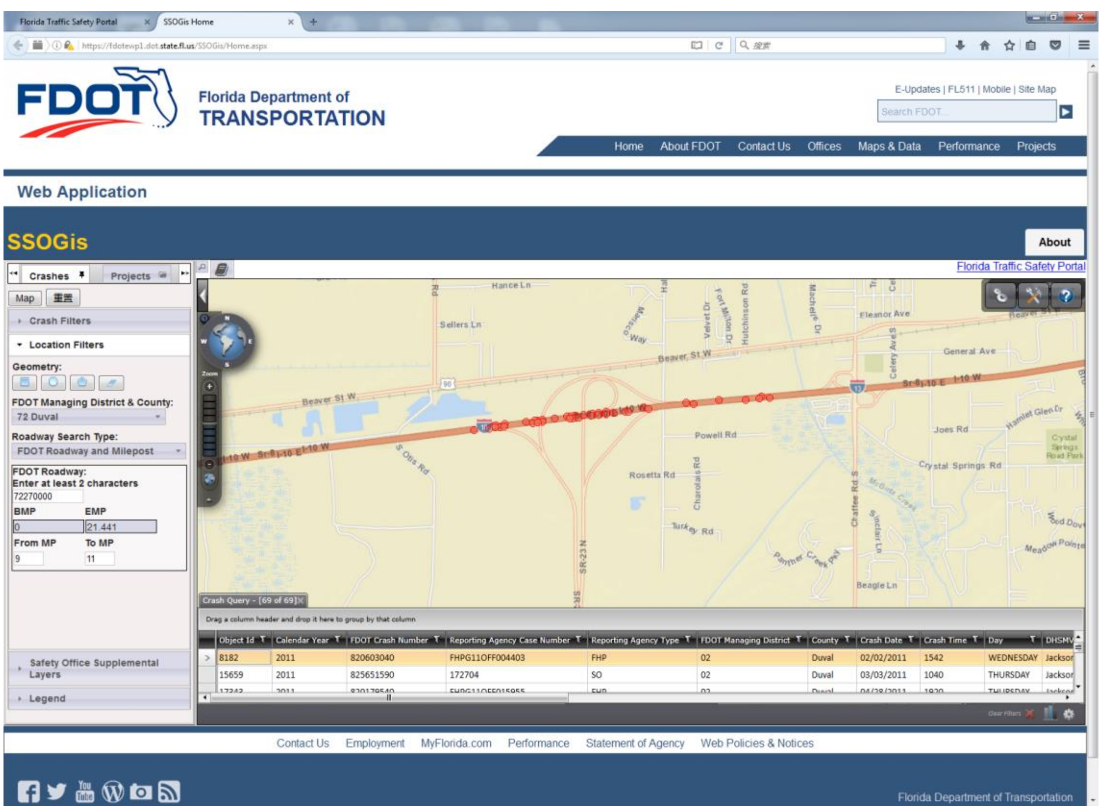
Notice to Proceed Date	Work Begun Date	Present Contract Days	Contract Days Used	Percent Days Used
06/29/2015	07/06/2015	927	259	27.94%
Vendor Name: J.B. COXWELL CONTRACTING,INC.				

Project Detail

Fiscal Year:	2016	2017	2018	2019	2020	2021
Highways/PD & E						*(On-Going)*
Amount:						
Highways/Preliminary Engineering						*(On-Going)*
Amount:	$1,375					
Highways/Railroad & Utilities						*(On-Going)*
Amount:	$330,000					
Highways/Construction						*(On-Going)*
Amount:	$1,309,004	$51,250				
Highways/Environmental						*(On-Going)*
Amount:						
Item Total:	**$1,640,379**	**$51,250**				

Project Map

Crash Data



Project # 210711-2

Project Summary

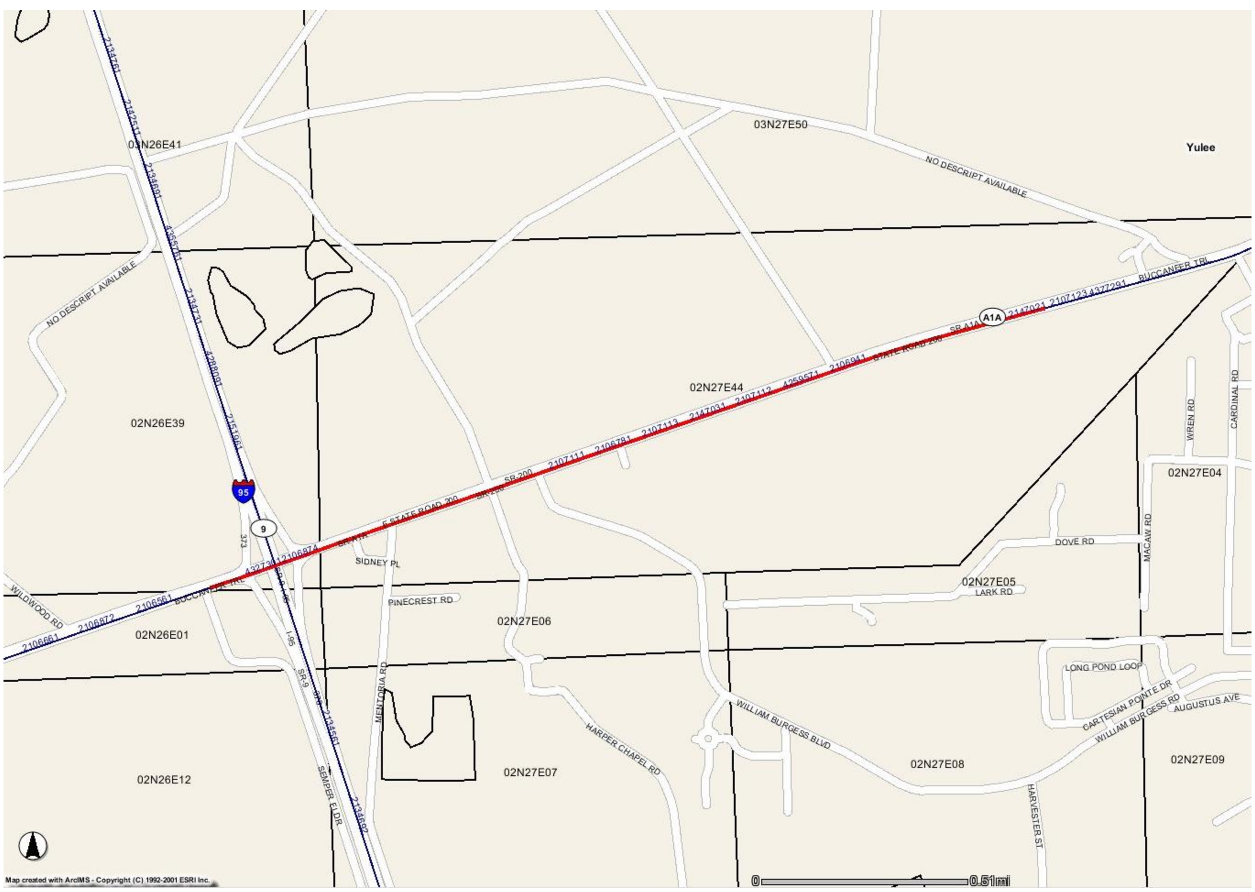
Project Summary

Transportation System: INTRASTATE STATE HIGHWAY — District 02 - Nassau County
Description: SR200(A1A) FROM I-95 TO W OF STILL QUARTERS RD/INCLUDES I95 LIGHTING
Type of Work: ADD LANES & RECONSTRUCT - Concrete — View Scheduled Activities
Item Number: 210711-2 — SIS
Length: 2.167 — View Map of Item

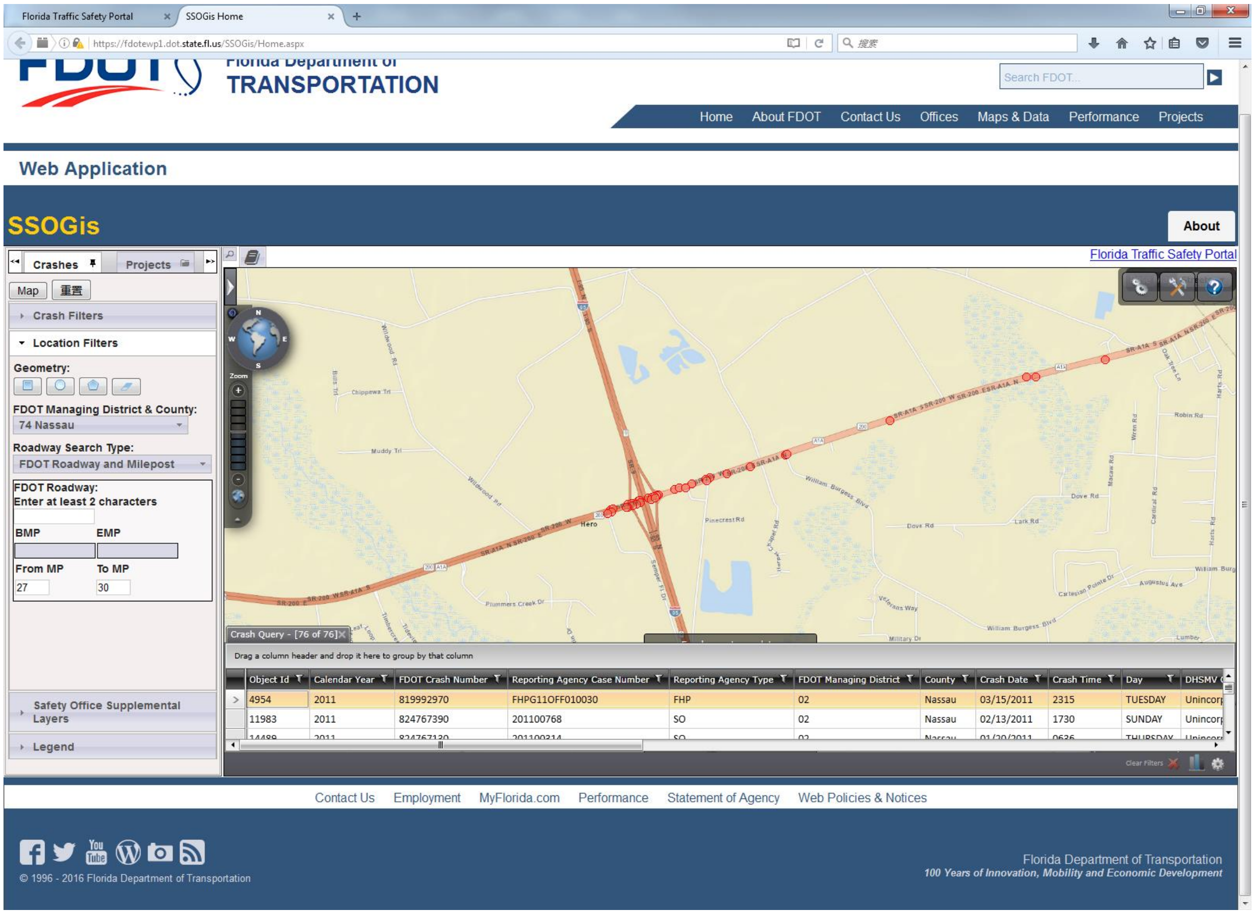
Project Detail

Fiscal Year:	2016	2017	2018	2019	2020	2021
Highways/Preliminary Engineering						*(On-Going)*
Amount:	$28,741					
Highways/Right of Way						*(On-Going)*
Amount:	$1,613,631	$983,612	$500,000	$500,000		
Highways/Railroad & Utilities						
Amount:		$245,056				
Highways/Construction						*(On-Going)*
Amount:	$4,497	$42,653,821	$252,720	$259,680		
Highways/Environmental						*(On-Going)*
Amount:						
Item Total:	**$1,646,869**	**$43,882,489**	**$752,720**	**$759,680**		

Project Map



Crash Data



Florida Traffic Safety Portal
SSOGis Home
https://fdotewp1.dot.state.fl.us/SSOGis/Home.aspx
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Maps & Data
Performance
Projects
Web Application
SSOGis
About
Florida Traffic Safety Portal
Crashes
Projects
Map
Crash Filters
Location Filters
Geometry:
FDOT Managing District & County:
74 Nassau
Roadway Search Type:
FDOT Roadway and Milepost
FDOT Roadway:
Enter at least 2 characters
BMP
EMP
From MP
To MP
27
30
Safety Office Supplemental Layers
Legend
Crash Query - [76 of 76]
Drag a column header and drop it here to group by that column
Object Id | Calendar Year | FDOT Crash Number | Reporting Agency Case Number | Reporting Agency Type | FDOT Managing District | County | Crash Date | Crash Time | Day
4954 | 2011 | 819992970 | FHPG11OFF010030 | FHP | 02 | Nassau | 03/15/2011 | 2315 | TUESDAY
11983 | 2011 | 824767390 | 201100768 | SO | 02 | Nassau | 02/13/2011 | 1730 | SUNDAY
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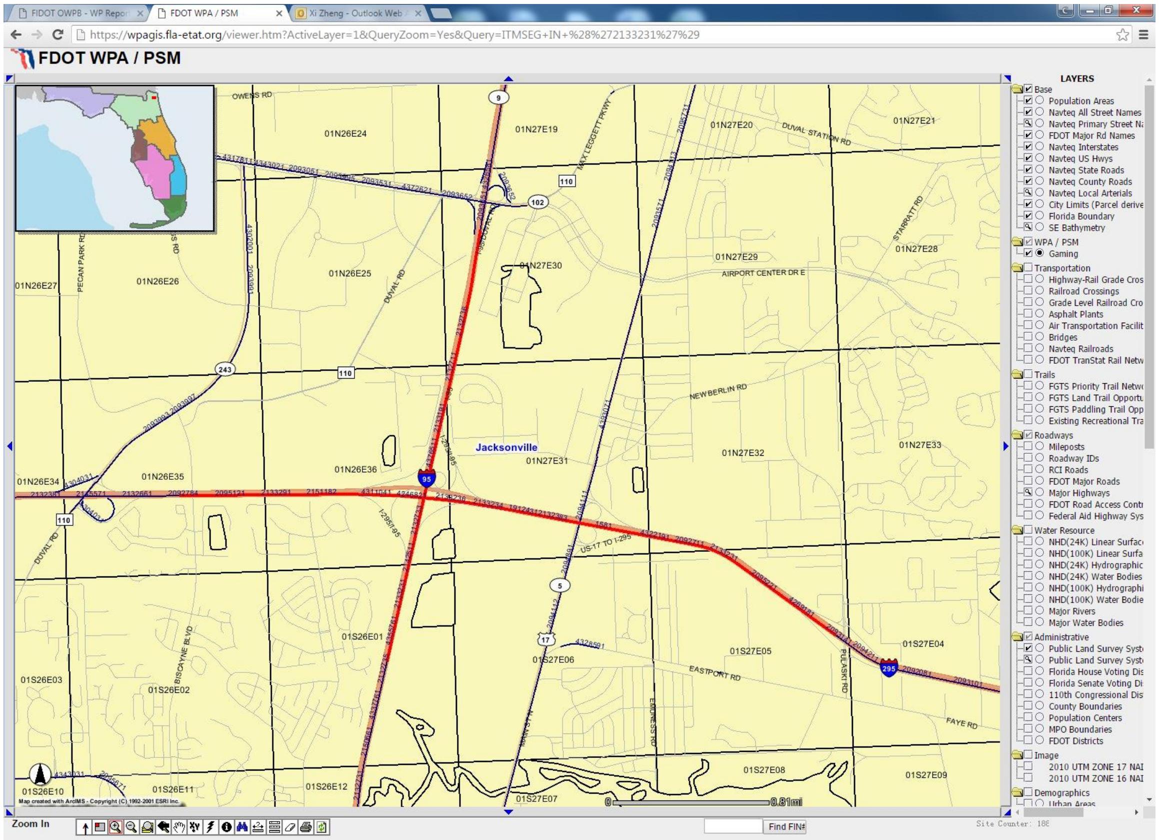
Project # 213323-1

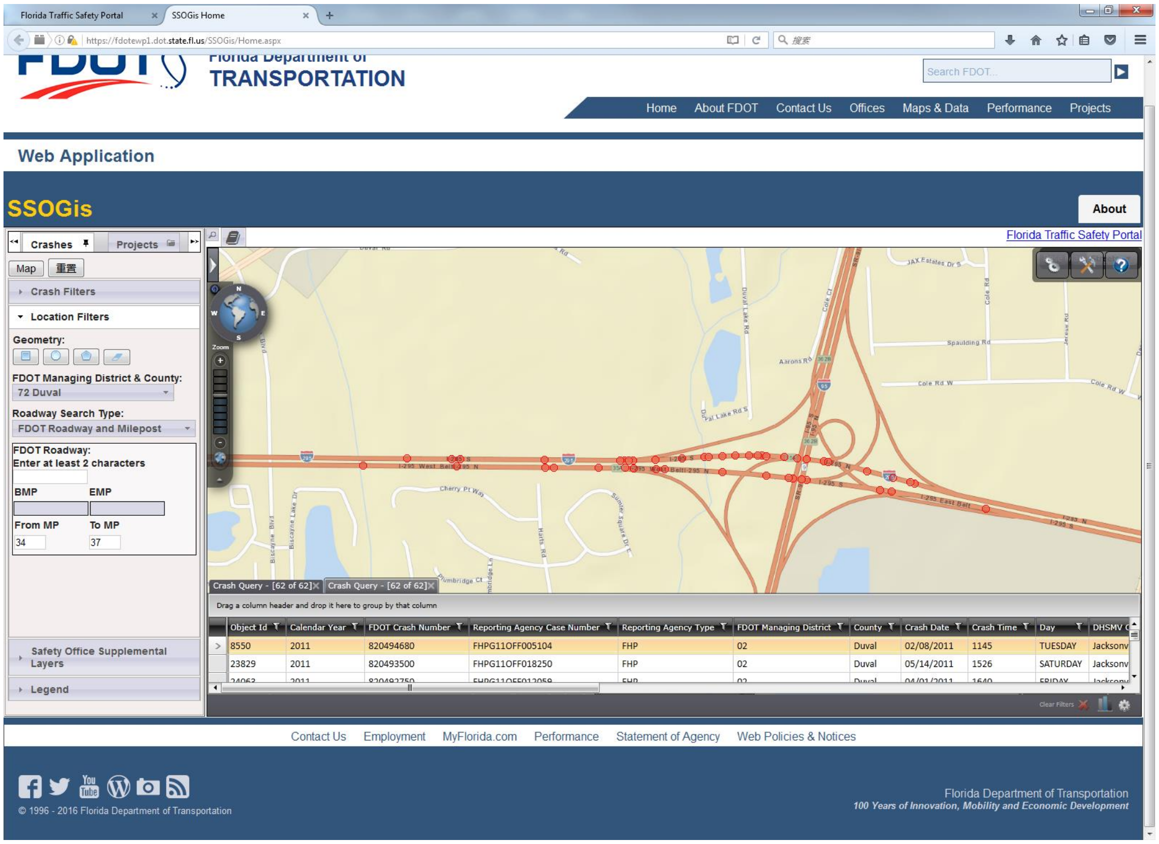
Project Summary

Project Summary						
Transportation System: INTRASTATE INTERSTATE						District 02 - Duval County
Description: I-95(SR9) @ NORTH I-295 INTERCHANGE						
Type of Work: INTERCHANGE RAMP (NEW) - Concrete						View Scheduled Activities
Item Number: 213323-1						SIS
Length: 7.855						View Map of Item
Project Detail						
Fiscal Year:	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Highways/PD & E						***(On-Going)***
Amount:						
Highways/Preliminary Engineering						***(On-Going)***
Amount:	$2,426,555					
Highways/Right of Way						***(On-Going)***
Amount:	$1,109,871	$519,961				
Highways/Railroad & Utilities						***(On-Going)***
Amount:	$1,633,648					
Highways/Environmental						***(On-Going)***
Amount:						
Highways/Design Build						
Amount:	$190,445,522	$15,375				
Item Total:	**$195,615,596**	**$535,336**				

Project Map



Crash Data



Project # 213345-7

Project Summary

Project Summary	
Transportation System: INTRASTATE INTERSTATE	District 02 - Duval County
Description: I-295 (SR 9A) FROM BUCKMAN BRIDGE TO I-95 MANAGED LANES	
Type of Work: ADD LANES & RECONSTRUCT	View Scheduled Activities
Item Number: 213345-7	SIS
Length: 4.299	View Map of Item

Construction Contract Information

Notice to Proceed Date	Work Begun Date	Present Contract Days	Contract Days Used	Percent Days Used
07/25/2014	07/25/2014	870	605	69.54%
Vendor Name: DRAGADOS USA, INC.				

Project Detail

Fiscal Year:	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Highways/PD & E						***(On-Going)***
Amount:						
Highways/Preliminary Engineering						***(On-Going)***
Amount:	$16,481					
Highways/Right of Way						***(On-Going)***
Amount:	$1,374,742					
Highways/Railroad & Utilities						***(On-Going)***
Amount:						
Highways/Environmental						***(On-Going)***
Amount:						
Highways/Operations						
Amount:	$100,000	$210,000	$369,000	$369,000	$369,000	
Highways/Design Build						***(On-Going)***
Amount:	$3,205,362					
Maintenance/Bridge/Roadway/Contract Maintenance						
Amount:	$1,001	$350,000	$478,000	$478,000	$478,000	
Item Total:	**$4,697,586**	**$560,000**	**$847,000**	**$847,000**	**$847,000**	

Project Map

Jacksonville
SUNBEAM RD
HARTLEY RD
HOOD RD
LOSCO RD
GREENLAND RD
LORETTO RD
MANDARIN RD
OLD ST AUGUSTINE RD
ST AUGUSTINE RD
HOOD LANDING RD
SHAD RD
03S27E28
03S27E32
03S27E33
03S27E34
04S27E03
04S27E02
04S27E05
04S26E04
04S27E06
04S27E08
04S27E09
04S27E10
04S27E12
04S27E07
04S27E16
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04S27E14
04S27E17
04S27E18
04S26E13
04S27E20
04S27E21
04S27E22
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04S26E24
04S27E19
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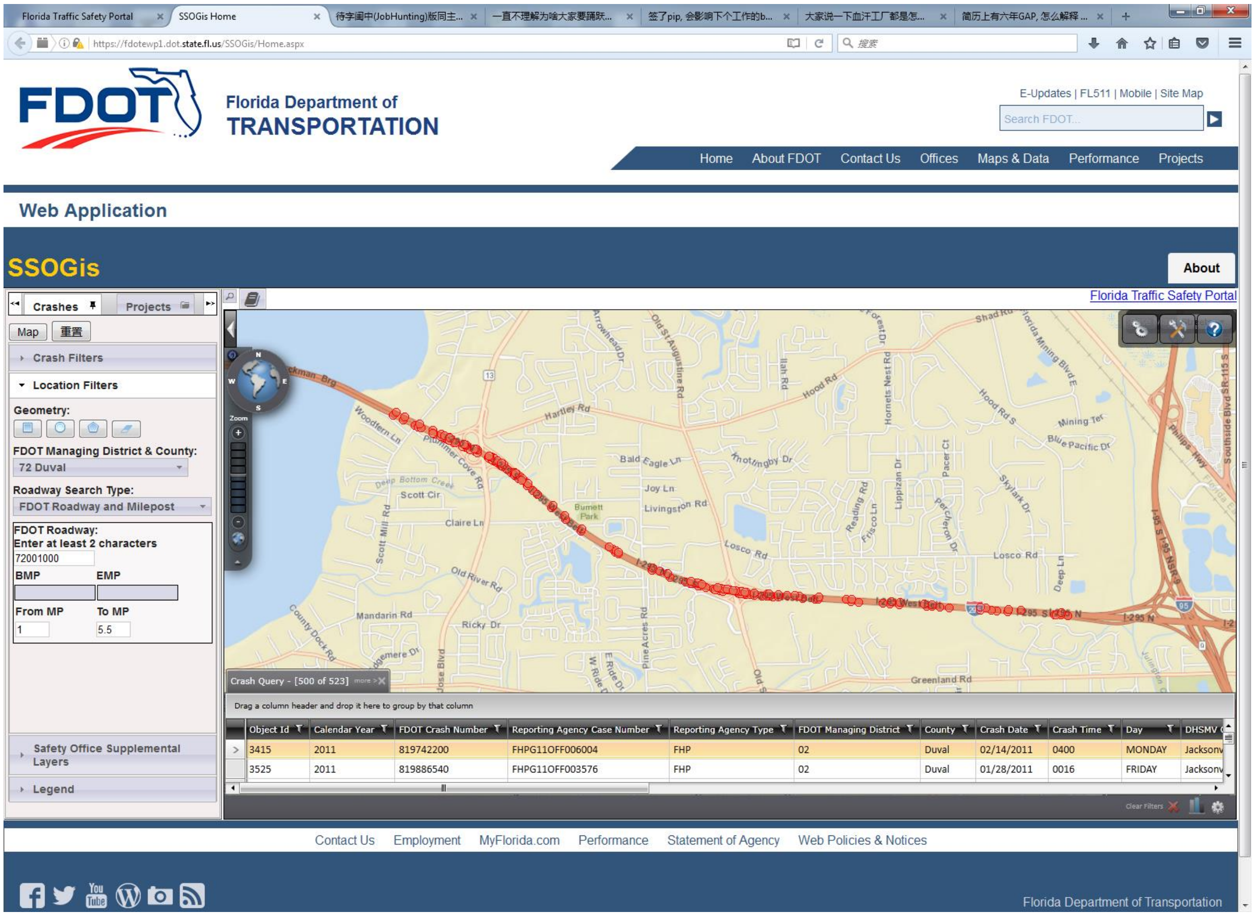
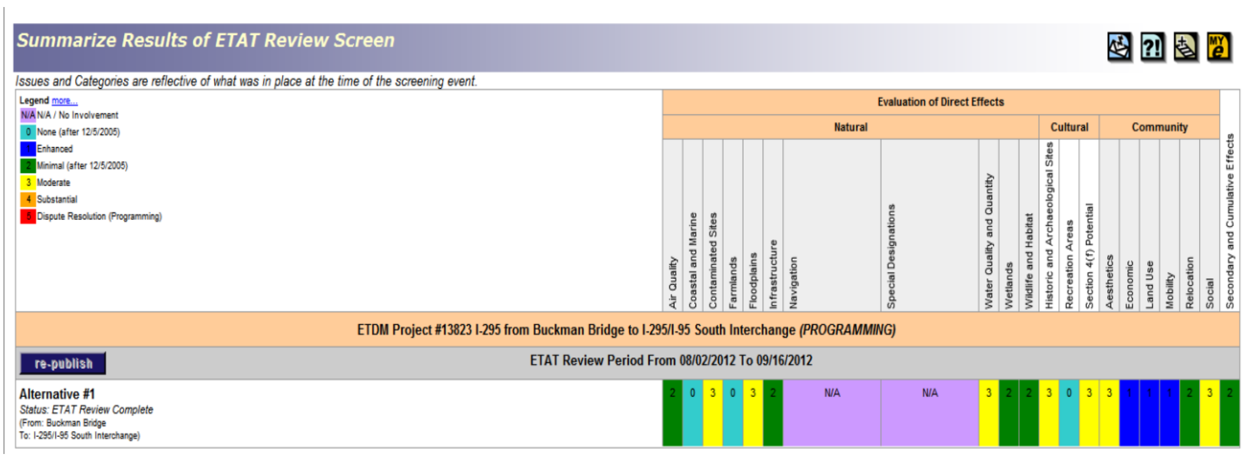
Crash Data



Environmental Impact



Project # 428865-1

Project Summary

Project Summary

Transportation System: INTRASTATE INTERSTATE — District 02 - Duval County

Description: I-10 (SR 8) / SR 200 (US 301) INTERCHANGE OPERATIONAL IMPROVEMENTS

Type of Work: INTERCHANGE IMPROVEMENT - Concrete — View Scheduled Activities

Item Number: 428865-1 — SIS

Length: 1.990 — View Map of Item

Construction Contract Information

Notice to Proceed Date	Work Begun Date	Present Contract Days	Contract Days Used	Percent Days Used
12/30/2015	02/29/2016	1200	21	1.75%

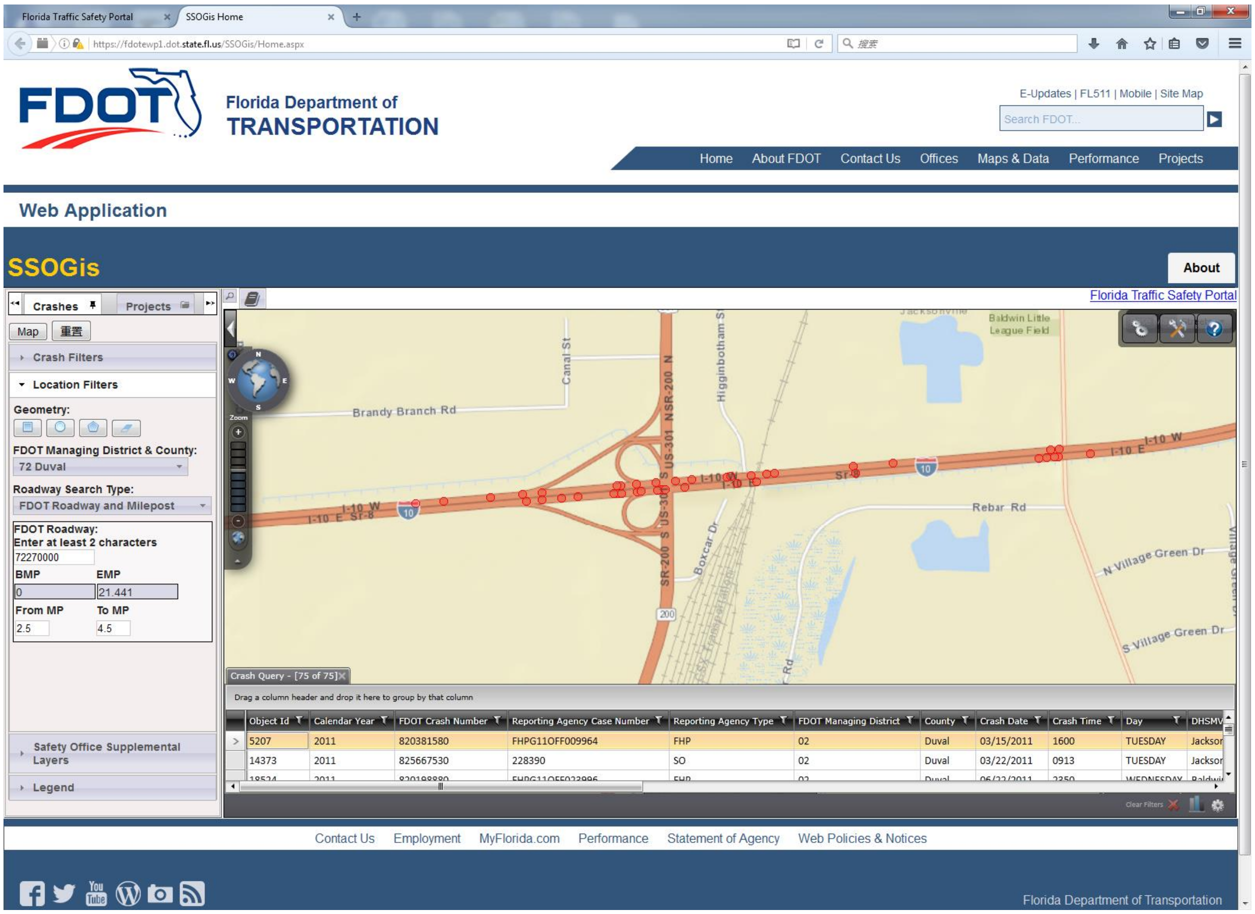
Vendor Name: SUPERIOR CONSTRUCTION COMPANY O

Project Detail

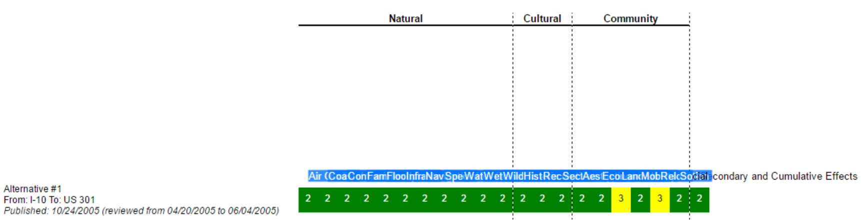
Fiscal Year:	2016	2017	2018	2019	2020	2021
Highways/PD & E						*(On-Going)*
Amount:						
Highways/Preliminary Engineering						*(On-Going)*
Amount:	$21,844					
Highways/Right of Way						*(On-Going)*
Amount:	$641,850	$1,301,128				
Highways/Railroad & Utilities						*(On-Going)*
Amount:	$4,961,931					
Highways/Construction						*(On-Going)*
Amount:	$74,360,693	$96,189	$355,096			
Highways/Environmental						*(On-Going)*
Amount:						
Item Total:	**$79,986,318**	**$1,397,317**	**$355,096**			

Project Map

Crash Data



Environmental Impact



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BIOGRAPHICAL SKETCH

Xi Zheng earned a bachelor's degree in civil engineering from Tongji University, Shanghai in 2005. He worked for China Merchants Chongqing Communications Research & Design Institute Co. Ltd. and enjoyed being an engineer there during 2005-2009. He received a Master of Science degree in civil engineering from University of Florida in May 2011 and then decided to continue with the PhD program in the same department. He was also admitted to the Master of Science program in finance at University of Florida and graduated from the program in May 2014. He specialized in project financing, cash flow management, and construction project optimization. He received his Ph.D. in civil engineering in August 2016, under the guidance of Dr. Ralph Ellis. He plans to find a career that can integrate his extensive knowledge in finance with real engineering and project management practice.