USDOT Region V Regional University Transportation Center Final Report

NEXTRANS Project No 020PY01

Uncertainty-Based Tradeoff Analysis Methodology for Integrated Transportation Investment Decision-Making

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TECHNICAL SUMMARY

NEXTRANS Project No 020PY01 Final Report, October 28

Uncertainty-Based Tradeoff Analysis Methodology for Integrated Transportation Investment Decision-Making

Introduction

Transportation agencies strive to maintain their systems in good condition and also to provide acceptable levels of service to users. However, funding is often inadequate to meet the needs of system preservation and expansion, and thus performance- and budget-constrained optimization continues to be an issue. Adding complexity to this issue is the increasing visibility of different stakeholders who advocate for consideration of a multiplicity of diverse perspectives in the highway decision-making process. Thus agencies are grappling with the issue of how best to incorporate multiple performance objectives in their decision-making processes. Some of these objectives conflict with each other, and therefore a need arises for decision-makers to find optimal solutions that examine the tradeoffs and provide a reasonable balance between the different objectives. Furthermore, there is the issue of uncertainty: outcomes of projects are never exactly what the decision-makers envisage; if such inevitable uncertainties are not duly accounted for, the final decision that may seem optimal may actually be associated with high risk. Finally, at most agencies, the management of highway assets is divided into several sub-areas such as pavements and safety assets. In this management structure, optimal management decisions are carried out separately for specific types of highway assets or management systems but do not always guarantee a global optimal strategy for all the management systems combined. Thus, a decision-making framework that integrates all asset types is needed to enhance decision-making and to ensure more efficient use of scarce funds. Clearly, a need exists for a multi-objective decision-making problem that integrates the various management systems, duly incorporates uncertainty, and helps decision-makers assess the tradeoffs between the performance measures. This study addresses that need.

Findings

This report presents innovative techniques for carrying out multiple-criteria project selection and tradeoff analysis among the different management systems that comprise highway asset management. A key product of this study is the development of a novel project selection framework formulated as a multi-objective optimization problem. This framework can use as its objective any one of the several statistical measures of network-level performance measures that were developed in the study. Demonstrated as an improvement over existing analytical method, the framework overcomes the possible bias that plagues traditional project selection methods. Genetic algorithm techniques are applied to generate the Pareto frontiers for the multiobjective optimization problem. Theoretical constructs and example numerical problems and solutions are provided for tradeoff analysis in a variety of decision-making contexts in highway asset management. The tradeoff curves, tradeoff surfaces, and scatterplot matrices are developed to facilitate visualization of the Pareto frontiers in different dimensions. The four tradeoff contexts established are: tradeoff between projects, tradeoff between performance measures, tradeoff between budget level and performance measures, and tradeoff between budgetary levels of the different sub-areas or management systems. Also, a fifth trade-off, one between overall project benefits and risk, is established for the uncertainty scenario through the use of Monte Carlo simulation to generate the probability distribution for each network performance measure. Using numerical examples, the study finds that the new project selection framework generates optimal solutions that are superior to those of traditional methods. In sum, the study shows that it is possible, on the basis of Pareto frontier visualization, to analyze the several kinds of tradeoffs that involve project comparison, budget shifting analysis, compromise between performance measures, and a balance between benefits and risk.

Recommendations

The study product can be used by highway agency asset managers to enhance their evaluation and decision-making processes. The asset managers can use the theoretical constructs presented in this report to carry out the processes of project selection and subsequently, to analyze tradeoffs in any of the above-mentioned contexts, and to visualize these tradeoffs in different dimensions. Implementing the study product is expected to provide decision-support at highway agencies who continually seek not only to infuse greater transparency and accountability in their investment decisions but also to provide cost-effective and balanced decisions that protect the use of taxpayer funds. In providing methodologies that incorporate multiple performance criteria from different management systems for optimizing decisions under uncertainty and under constraints of budget and performance, and for investigating and quantifying the aforementioned tradeoffs, this study product is poised to help address these issues.

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CHAPTER 1 INTRODUCTION

1.1 Study Background

Highway transportation facilities constitute one of the most important public infrastructure systems in any country. The extensive highway infrastructure system established in the United States largely in the 20th century has provided immense support to the development of the country's economy. At the current time, a large number of the physical components of the highway infrastructure system have reached an advanced age yet travel demand generally continues to increase. Each year, an increasing number of highway facilities reach a point where they need to be maintained, rehabilitated, or reconstructed (ASCE, 2009). Transportation agencies strive to maintain the entire system to ensure good physical condition and to provide acceptable levels of service to users. However, the budgets are always not adequate to meet the financial needs associated with such goals. As part of measures to efficiently and effectively maintain and upgrade the entire highway system, the Federal Highway Administration (FHWA) established the office of asset management in 1999 and encouraged all DOTs to apply the concept of asset management to their management systems. Asset management may be described defined as a systematic process of maintaining, upgrading, and operating physical assets cost-effectively. It combines engineering principles with sound business practices and economic theory, and provides tools to facilitate a more organized, logical approach to decision-making. Thus, asset management provides a framework for handling both short- and long-range planning (FHWA and AASHTO, 1996; FHWA, 1999). In subsequent years, the National Cooperative Highway Research Program (NCHRP) has carried out a series of studies on asset management including the development of a guide, establishment of performance measures, and assessment of asset management at other countries. Also, five core principles of asset management were identified by a NCHRP study: policy-driven, performance-based, analysis of options and tradeoffs, decisions based on quality information, and monitoring to provide clear accountability and feedback (Cambridge Systematics, Inc. et al., 2006).

Another ongoing trend in the highway transportation area is that an increasing number of stakeholders representing a wide diversity of views want their concerns can be considered during decision-making process and also call for more transparency and accountability in such processes. In general, stakeholders include the highway asset owner or its designated operator, the facility users, persons affected by the facility such as residents, workers, pedestrians, social organizations, community groups, environmental groups, etc. For instance, highway agencies may seek, using available funding constraints, to provide best possible service to system users and also to create more jobs for the community; highway users demand superior riding condition, enhanced freeway mobility, greater accessibility of local roads, and safer travel; and environmental groups advocate for sustained quality of the environment such as reduced emissions, lower noise, and minimal damage to the ecology. These concerns translate into a gamut of highway performance measures for decision-making. For example, mobility concerns can be reflected by travel speed performance. Also safety concerns can be represented by crash rate performance. Therefore, to incorporate these concerns in decision-making, multiple performance measures need to be considered and these translate into multiple objectives at the time of the decision-making. Adding to the problem complexity is the fact that some of these objectives conflict with each other. For instance, increasing the speed may lead to greater mobility but increased crashes and air pollution. Such conflicts are exacerbated when the overall budget is fixed and increased funding that enhances one performance measure may very well be to the detriment of another measure. Thus a need often arises for decision-makers to establish decision frameworks that not only take due cognizance of such conflicting performance objectives but also arrive at solutions that reach a reasonable balance between them.

Another context of the decision-making problem that adds complexity to the decision framework is the multi-functional nature of asset decisions at most highway agencies. In the United States, most DOTs use management systems that decompose the management of highway assets into several sub-areas such as pavement management, bridge management, and congestion management. This structure of management provides detailed management strategies, project-level and network-level, for specific types of highway assets associated with those systems. Thus, such decentralized decision-making makes an attempt to efficiently utilize limited funds in each management system (or sub-area) by conducting optimization in each system. A problem, however, is that the sum of the individual sub-area optimal strategies does not always guarantee an optimal strategy for all the sub-areas combined. Therefore, a truly global optimal solution is needed. For this purpose, a decision-making framework (Figure 1.1) can be developed on the basis of the integration of all sub-areas to ensure more efficient use of the limited overall budget. At the same time, the decision-making process should be flexible enough to consider sub-area's budget restrictions. For example, certain parts of the budget can be only used in a certain sub-area due to the funding source.

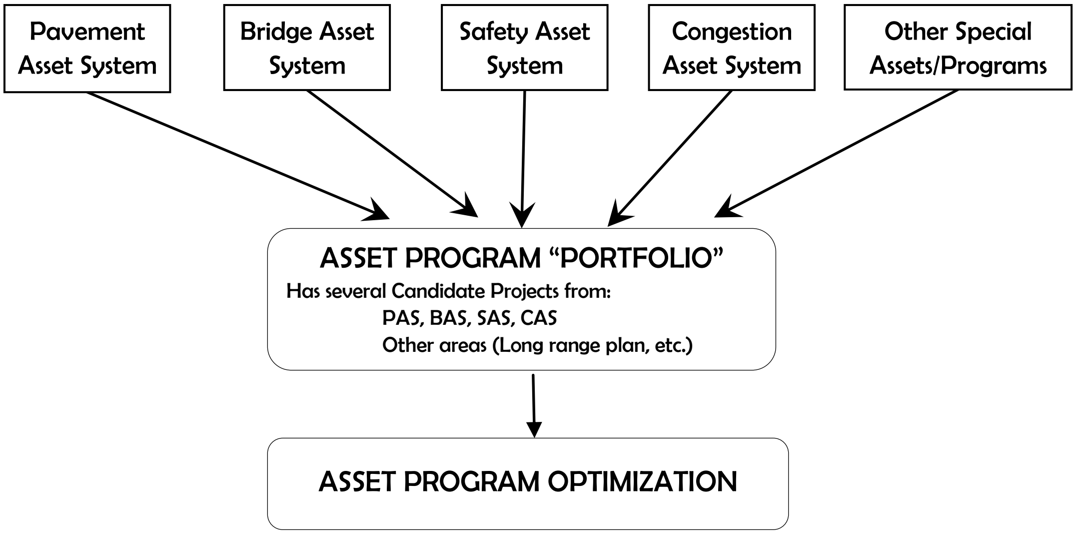


Figure 1.1: A Typical Problem Structure in Asset Management (in Bai et al., 2009)

In a bid to address all of the above issues, the decision-making evolves into a multi-faceted and complex problem and many questions arise during decision-making process. For example, what is the relationship between budget level and system performance? What is the relationship between different pairs of conflicting or nonconflicting performance measures under a given budget limit? How will the crash rate change if the asset manager increases the safety budget? What changes can be expected in system-wide performance if a given funding amount is transferred from one sub-area to another?

The above questions are suggestive of the different kinds of tradeoffs that the asset manager typically encounters in decision-making. To assist decision-makers answer such question, a tradeoff analysis methodology is needed. The original meaning of tradeoff refers to “losing one quality or aspect of something in return for gaining another quality or aspect” (Webster, 2009). It implies a decision to be made with full comprehension of both the promises and perils of all potential decisions. In practice, tradeoff can be extended between one aspect and all the other aspects or a group of some other aspects, or between some groups of aspects, not just between one aspect and another aspect. Tradeoff analysis is a powerful tool for decision-making because it gives decision-makers a full picture of what they gain or lose by making a decision, whether or not that decision is optimal. Thus, tradeoff analysis is needed to complement project selection optimization which merely provides the optimal decision. In this research study, we provide tradeoff analysis methodologies that can help transportation officials not only to make decisions but also to examine the tradeoffs.

Finally, there is the issue of uncertainty. During the project evaluation process, the expected values of asset performance after project implementation are typically predicted by using forecasting methods. In reality, the exact performance values as predicted rarely are achieved. Thus there is uncertainty in the decision-making process. If these uncertainties are not taken into account, the optimization framework may yield an optimal decision that has a wide band of variability in its outcomes. Thus, incorporating uncertainty into the decision-making process and providing a tradeoff analysis methodology to illuminate the relationship between risk and benefit are very useful for highway asset decision-makers.

This study therefore focuses on developing tradeoff analysis methodologies for asset management decision-making, considers multiple performance measures, and addresses uncertainty issues in the transportation decision-making process.

1.2 Contents of this Report

Chapter 2 of this report provides a clear definition of the study objectives, including a verbal description and a mathematical statement thereof. Chapter 3 conducts a comprehensive literature review on each aspect of this study. Chapter 4 presents the study framework, while Chapter 5 develops the tradeoff methodology for the certainty condition. Chapter 6 incorporates the uncertainty into the methodologies developed in Chapter 5 using Monte Carlo simulation, and provides tradeoff analysis between risk and benefit. Chapter 7 demonstrates the methodologies in this study using a case study, while Chapter 8 summarizes this study and provides suggestions for practical application.

CHAPTER 2 PROBLEM DEFINITION

2.1 Problem Need Statement

On the basis of the study background statement in Chapter 1, the problem statement for this study is characterized by the following issues:

Integration of all types of assets

Most highway agencies, at the current time, divide their highway assets into several sub-areas and establish a management system separately for each sub-area. It is desired that the decision-making model in asset management conducts optimization at the entire system level, not at the sub-area level as traditionally done. Thus, the present study integrates all types of assets in its framework. In practice, it is almost impossible to apply a true multi-asset management system immediately due to political and management issues. Therefore, it is required that the proposed method in this research study has enough flexibility to be applied in both the current and future management system structures. The structure should generally be able to work in either one of two contexts at DOTs: (1) Different divisions that manage sub-areas separately identify possible projects, conduct optimization in their sub-areas and select the most deserving projects and propose these projects to asset manager; then the asset manager conducts analysis on all projects submitted from the different sub-areas; (2) Without prior project selection in the sub-areas, the entire population of possible projects from the different sub-areas are proposed directly to asset managers who then conducts optimization to select the project to be implemented.

Multiple performance measures and multiple objectives

In order to incorporate the concerns of different stakeholders, multiple performance measures are needed to evaluate the impact of implementing each project in terms of the multiple objectives.

Uncertainty consideration

Since the values of performance measures after project implementation are not known with exact certainty, some decisions may have high risk even though they may have large benefits. To avoid choosing high-risk projects, uncertainty should be duly considered in the decision-making process to balance risk and benefit.

Practical budget settings

In practice, transportation budgets have different sources. As such, some parts of the budget can be used only in certain sub-areas according to the legislation or policy. Furthermore, there may be some other political requirements for budget distribution among different sub-areas. Therefore, it is desired that the method proposed in this study is able to handle all of these situations.

There are various tradeoff analyses in transportation field. On the basis of the study background for this research, it is needed to focus on the following types of tradeoff analyses.

1. Tradeoff between projects. This type of tradeoff contains two subtypes:

   (a) Tradeoff between two individual candidate projects which may or may not be from the same sub-area. This involves a comparison of two competing candidate projects and identification of the superior one. This is one of the most common types of tradeoff analyses in practice.

   (b) Tradeoff between two sets of projects. Each set may contain several projects from different sub-areas. This type of tradeoff is what many decision-makers really seek but seldom conduct due to the lack of analytical methods. In fact, the first subtype is a special case of this subtype where only one project is included in each set.
2. Tradeoff between performance measures. Decision-makers are often interested in this type of trade-off particularly where the problem involves

multiple (often conflicting) objectives reflecting performance measures. The question here, for example, is “how much of objective A can be bought for a given level of objective B”. So, for instance, one could ask how much the average travel speed will be reduced if we spend more money on safety projects (at the expense of congestion projects) to reduce a certain amount of crash rate.

3. Tradeoff between budget level and performance measures. Decision-makers always seek to ascertain the level of system performance under different budget levels and also to know what level of funding is optimal. In addressing these issues, other questions that arise include: What is the elasticity of system preservation to budget? Do the benefits taper off after a certain level of funding? This kind of tradeoff analysis has been investigated in studies that treated this issue as one related to budgetary constraint changes and their influence on system performance.
4. Tradeoff between sub-area funds (also herein termed “funds shifting” or “budget shifting” analysis). Shifting funds across different sub-areas is a sensitive issue in agencies and could lead to conflict among different management sub-areas if the decision-maker fails to provide incontrovertible evidence that the funds shift will lead to positive overall impact to every party concerned. Therefore, a comprehensive tool is needed to support this kind of tradeoff analysis by offering the possible quantitative performance of the highway system for funds shifting analysis.
5. Tradeoff between risk and benefit. Due to the uncertainty of performance measures, some decisions may have great benefits but also very high risk of such benefits ever being realized. A good decision should have an appropriate balance between risk and benefit. This study developed tradeoff analysis framework between risk and benefit to help the decision-maker reach a reasonable balance between these two performance measures.

Of the above five types of tradeoff analyses, Type 2 and Type 4 are similar. Both of them contain changing sub-area budgets to find the effects on performance measures. However, they have different focus in practice. Type 2 tradeoff analysis seeks the tradeoff relationship between different performance measures without considering the exact amount of different sub-area budgets. Type 4 tradeoff analysis focuses more on sub-area budgets and tries to provide the evidence to support budget shifting actions.

2.2 Mathematical Description of the Problem

According to the need statement above, the problem in the present study can be mathematically described as follows:

There are *n* candidate projects in a universal set of highway projects from *k* types of assets including pavements, bridges, safety assets, mobility assets, etc. The total budget *B* is limited and is not adequate to implement all these candidate projects. Thus, only some of the projects can be implemented. Each sub-area budget sb_i may have a lower bound sb_i^L or an upper bound sb_i^U or both. There are *s* performance measures that are used to evaluate the impact of implementing the selected projects. On the basis of the *s* performance measures, *m* objectives are formulated for carrying out the project selection (*s* may or may not be equal to *m*). Decision-makers seek the best possible levels of each objective. Thus, this is a multi-objective problem as presented in Equation (2-1).

$$\begin{aligned}
&\min(or\,\max) \quad f_1(\vec{x}, p_{ij}) \\
&\min(or\,\max) \quad f_2(\vec{x}, p_{ij}) \\
&\quad\cdots \\
&\min(or\,\max) \quad f_m(\vec{x}, p_{ij})
\end{aligned} \tag{2-1}$$

Where:

$\vec{x}$ is a vector of the decision variables ($x_1, x_2, ..., x_i, ..., x_n$), x_i (i =1, 2, …, n) is a binary variable used to indicate whether a project is selected or not. $x_i = 1$ indicates the i^{th} candidate project is selected; $x_i = 0$ means it is not selected;

p_{ij} is the value of the j^{th} performance measure for i^{th} candidate project (i =1, 2, …, n; j = 1, 2,…, s);

f_i is the decision-makers’ objective in terms of the performance measures.

This study seeks an appropriate methodology for a number of contexts of tradeoff analyses. These contexts are discussed in Section 2.1, and their mathematical descriptions are presented below:

(1) Tradeoff between projects.
  (a) Tradeoff between two projects *i* and *j*, that is, to determine the difference in level of each performance objective under the following situations :
    (i) $x_i = 1$ and $x_j = 0$;
    (ii) $x_i = 0$ and $x_j = 1$.
  (b) Tradeoff between two sets of projects A and B. Set A contains n_A projects and Set B contains n_B projects. The difference on each objective under the following situations:
    (i) the decision variables x_i for all the projects in Set A equal to 1 and the decision variable x_i for all the projects in Set B equal to 0 if they are not also in Set A;
    (ii) the decision variable x_i for all the projects in Set B equal to 1 and the decision variables x_i for all the projects in Set A equal to 0 if they are also not in Set B.

(2) Tradeoff between objectives. Determine the relationship between objective f_i and objective f_j, or between objective f_i and two other objectives or more.

(3) Tradeoff between budget level and objectives. This is to determine the value of objectives to be obtained under different budget levels.

(4) Tradeoff between sub-area budgets. This is to determine the changes in objectives f_i if some funds are shifted from one sub-area to another, i.e., $sb_{i,\text{new}} = sb_{i,old} + \Delta$ and $sb_{j,\text{new}} = sb_{j,old} - \Delta$.

(5) Tradeoff between risk and benefit. When the performance measures p_{ij} are not fixed values but follow different distributions, there is a need to determine the expected value of each objective $E(f_i)$ and its variance, and then determine the balance between the risk and benefit for the final decision.

Finally, an important part of the problem statement is to provide an appropriate multi-objective optimization method to determine the optimal solution under given constraints, i.e., to establish a vector $(x_1, x_2, \ldots, x_i, \ldots, x_n)$ based on tradeoff analyses.

2.3 Chapter Summary

This chapter first analyzes the problem statements for this study and then indentifies five types of tradeoff analyses: tradeoff between projects, tradeoff between performance measures, tradeoff between budget level and performance measures, tradeoff between sub-area budgets, and tradeoff between risk and benefit. Finally, the problem statement for the study is described using mathematical notation.

CHAPTER 3 LITERATURE REVIEW

In this chapter, a comprehensive literature review is presented on the basis of problem definition stated in Chapter 2.

3.1 Transportation Asset Management

Transportation asset management is a growing concept in transportation field. Of the several definitions of Asset management, a few are herein presented.

“Asset management is a systematic process of maintaining, upgrading, and operating physical assets cost-effectively. It combines engineering principles with sound business practices and economic theory, and it provides tools to facilitate a more organized, logical approach to decision-making. Thus, asset management provides a framework for handling both short- and long-range planning.” (FHWA and AASHTO, 1996; FHWA, 1999)

“Asset management may be defined as a comprehensive and structured approach to the long term management of assets as tools for the efficient and effective delivery of community benefits. The emphasis is on the assets being a means to an end, not an end in themselves.” (Austroads,1997)

“A systematic process of maintaining, upgrading and operating assets, combining engineering principles with sound business practice and economic rationale, and providing tools to facilitate a more organized and flexible approach to making the decisions necessary to achieve the public’s expectations”. (OECD, 2001)

“Transportation asset management can be treated as s set of concepts, principles, and techniques leading to a strategic approach to managing transportation infrastructure. It enables more effective resource allocation and utilization, based upon quality information and analyses, to address facility preservation, operation, and improvement”. (AASHTO, 2001)

The above definitions are similar and include common core elements. For example, asset management is seen as a resource allocation tool and includes project selection on the basis of condition assessment and performance modeling. NCHRP report 511 summarized five core principles for asset management (Table 3.1). It may be noticed that the third principle is “Analysis of Options and Tradeoffs” which is the focus of the present study. The present study goes further to incorporate more advanced issues such as uncertainty. The entire framework for asset management can be presented as shown in Figure 3.1.

Table 3.1: Core Principles of Asset Management (Cambridge Systematics et al., 2006)

Index	**Core Principles**	**Description**
1	Policy-Driven	Resource allocation decisions are based on a well-defined and explicitly stated set of policy goals and objectives. These objectives reflect desired system condition, level of service, and safety provided to customers and are typically tied to economic, community, and environmental goals.
2	Performance-Based	Policy objectives are translated into system performance measures that are used for both day-to-day and strategic management.
3	Analysis of Options and Tradeoffs	Decisions on how to allocate resources within and across different assets, programs, and types of investments are based on understanding how different allocations will affect the achievement of policy objectives and what the best options to consider are. The limitations posed by realistic funding constraints also must be reflected in the range of options and tradeoffs considered.
4	Decisions Based on Quality Information	The merits of different options with respect to an agency’s policy goals are evaluated using credible and current data. Decision support tools are applied to help in accessing, analyzing, and tracking these data.
5	Monitoring to Provide Clear Accountability and Feedback	Performance results are monitored and reported for both impacts and effectiveness. Feedback on actual performance may influence agency goals and objectives, as well as future resource allocation and use decisions.

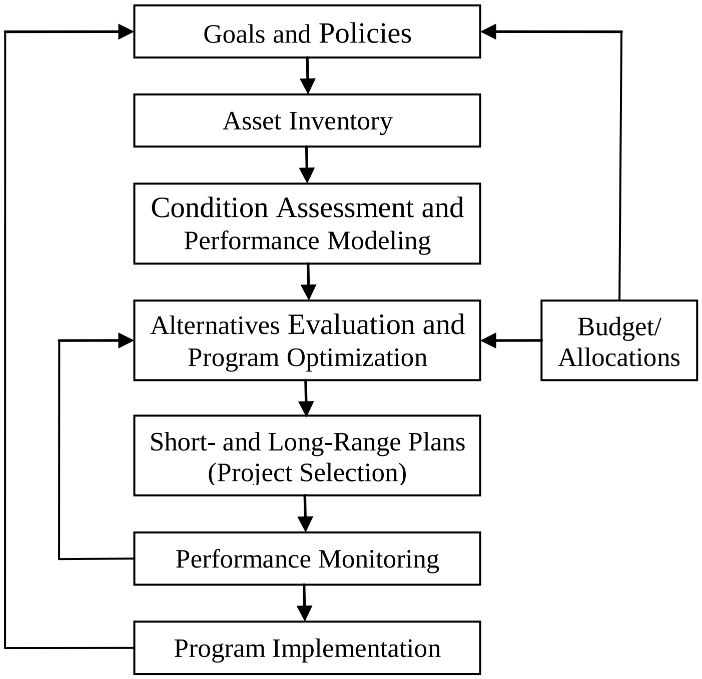


Figure 3.1: Basic Framework of Transportation Asset Management (FHWA, 1999)

3.2 Transportation Performance Measures

Highway performance measures can be used to evaluate the performance of a specific highway facility or an entire highway network. Good performance measures can correctly guide a transportation agency’s decision-making processes and facilitate efficient allocation of budgets. For these reasons, performance measures are an important element of asset management. Performance measures reflect the goals and policies of transportation agencies and their decision-makers. Considerable research and documentation on performance measures has been carried out in the past few decades (Turner et al. 1996; Cambridge Systematics, 2000; Shaw, 2003; Sinha and Labi, 2007). In this report, we focus on the recent studies on performance measures for transportation asset management.

NCHRP sponsored a synthesis study in 2003 to investigate various performance measures used by state DOTs for monitoring the performance of highway system (Shaw et al., 2003) and assessed the relative strengths and weaknesses of these performance measures. That study gave transportation agencies a platform to examine the performance measures in use at other state DOTs and to learn from each other. Also, AASHTO in 2006 examined the performance measures used by different DOTs and proposed a number of comparative performance measures. It encouraged DOTs to use comparative performance measures so different DOTs can have enhanced communication and can identify best practices and innovations to improve the overall performance of highway system (AASHTO, 2006). In 2006, NCHRP carried out another research on performance measures for asset management (Cambridge Systematics et al., 2006). Table 3.2 presents other research studies on performance measures for asset management.

Table 3.2: Selected Studies on Transportation Asset Management Performance Measures

Index	Year	Name
1	1991	NCHRP 20-24 (06): Performance Measures for State Highway and Transportation Agencies
2	1996	Measures of Effectiveness for Major Investment Studies
3	1997	NCHRP Synthesis 238: Performance Measurement in State Departments of Transportation
4	2003	NCHRP Project 20-60: Performance Measures and Targets for Transportation Asset Management
5	2007	Performance measures for enhanced bridge management

3.3 Multi-criteria/Multi-objective Decision-Making in Highway Project Selection

Using multi-criteria/multi-objective decision-making in project selection is typical in many fields. In the highway transportation field, several methods for multi-criteria/multi-objective optimization or prioritization have been developed in the past few years. In the bridge management system developed by Sinha et al. (1989), bridge projects were ranked on the basis of their combined impacts in terms of safety, community effects, bridge condition, and cost. Also, a multi-modal evaluation study for San Francisco’s Metropolitan Transportation Commission (Younger, 1994) involved an approach in which experts provided scores depicting the extent of their desirability for each level of a given performance criterion. This was done for the following performance measures: physical system preservation, system efficiency enhancement, effectiveness improvement in terms of safety, congestion and freight mobility, system expansion, external impacts of land use, air quality, and energy conservation. For each performance criterion, a score was established for each transportation alternative using the scale established for that criterion by a panel of experts representing transportation and environmental interests. The same panel also developed weights of each performance measure. For each project, a weighted and scaled value was synthesized to represent the overall performance of that project, and projects were ranked and chosen on the basis of such overall performance. In a similar study in Greece, Tsamboulas et al. (1999) solicited input from a panel of experts from transportation policy establishments, academia, and industry, and developed multi-attribute utility functions for economic efficiency (internal rate of return), safety, and the environment. Also, in the Northeast Area Transportation Study for Sacramento, Speicher et al. (2000) described a "collaborative workshop process" whereby participants first established "scales of desirability" for various levels of several performance criteria and then used such scales to evaluate and screen candidate projects. Li and Sinha (2004) developed a multi-criteria decision-making methodology in highway asset management for Indiana Department of Transportation. In that study, utility theory (Keeney and Raffia, 1976) was used to develop multi-attribute utility functions to determine the benefit of each project's implementation, and a knapsack-based optimization was used to select the projects that maximize the total project benefit under given budgetary constraints. In developing an analytical methodology for coordinating and prioritizing multimodal investments in the state of Virginia, Lambert et al. (2005) asked experts and stakeholders to assign values to represent the desirability of each hypothetical level of a performance measure. This was done for all performance measures considered for that study: safety and security, preservation and management, efficient movement of people and goods, economic vitality, and quality of life. That way, the overall desirability associated with each candidate intervention was calculated. Li and Puyan (2006) followed up in a similar fashion, formulating the highway project selection process as a stochastic multi-choice multidimensional Knapsack problem with Ω-stage budget constraints to maximize the total project utility and solving it by Lagrangian relaxation techniques. In a study similar to Li and Puyan's, Patidar et al. (2007) developed a multi-objective optimization method for bridge management systems using utility theory and an incremental utility-cost heuristic involving 0/1 optimization method to solve multi-choice multidimensional Knapsack problem in a more time-efficient way.

These studies have made significant contributions to the development of analytical procedures for facilitating project selection in highway asset management. Most of these studies adopted the scalarization technique or utility theory to transform different units of criteria/objectives to dimensionless unit or the monetary units; and then combine all criteria/objectives to yield a single value that represents the benefit/impact of each project's implementation. Based on the single value for each project, comparison, prioritization and optimization were conducted to select the final projects. In these studies, the optimization problem was formulated as a Knapsack Problem. Depending on the constraints, Knapsack problems can be classified as simple Knapsack problems, multi-criteria Knapsack problems, or multi-criteria multi-dimensional Knapsack problems.

3.4 Tradeoff Analysis in Asset Management

A tradeoff refers to losing one quality or aspect of something in return for gaining another quality or aspect (Webster, 2009). Hening and Buchanan (1997) provided pair-wise tradeoff where all but two of the objectives/criteria are fixed and Sakawa and Yano (1990) established a general tradeoff formulation by calculating tradeoff ratio. In practice, tradeoffs have a wider meaning and are not limited to between one "aspect" and another but may also be between groups of aspects. Tradeoff analysis constitutes an interesting "game" in decision-making and can help decision-makers quickly envision the consequences of each alternative decision and finally make a choice. As discussed in Chapter 1, in the transportation asset management, there are several kinds of tradeoff analyses between various aspects of the decision problem.

Tradeoffs are often conducted between different aspects that typically have different units (such as travel time (hours) and monetary cost (dollars)). In order to conduct such tradeoffs, traditional methods transform them into a uniform unit or dimensionless unit by scalarization (Nakayama et al. 2009) or utility function (Keeney and Raffia, 1976). Transformation methods include linearly weighted sum method, Tchebyshev scalarization function, etc. After transformation, a partial derivative is applied to determine the tradeoff curve and then to establish the tradeoff ratio at any given point – this is referred to as the "marginal rate of substitution" in economics. One of such types of tradeoff method is the surrogate worth tradeoff method (Haimes and Hall, 1974). However, these kinds of methods require the objective functions to be continuous and differentiable. In our problem context, however, the decision variable is discrete. In this case, the Pareto frontier becomes an alternative technique to exhibit the relationships between multiple objectives and offers the decision-makers a platform to visualize their tradeoffs (Nakayama et al. 2009). However, this method can only handle the case with only two or three objectives. Effective methods for tradeoff analysis with discrete decision variables seem to be unavailable in the literature.

In the highway transportation field, a number of tradeoff studies have been conducted. Tsao and Hall (1997) developed tradeoff analysis between safety and efficiency for automated highway system. Amekudzi et al. (2001) addressed the analysis of investment tradeoffs for competing infrastructure in the context of uncertainty using Shortfall Analysis to determine minimum levels of investments for heterogeneous facilities and applying Markowitz Theory to analyze the marginal utilities of investments in competing facilities in the context of data uncertainty. Li and Sinha (2004) used the utility theory to establish the foundation of tradeoff for certainty and risk situation, using Shackle's Model to address the uncertainty situation. Based on these methods, they developed a highway asset management framework and software package to conduct project selection across different program areas for the Indiana Department of Transportation. Cambridge Systematics, Inc. (2004) carried out on NCHRP study, "Development of a Multimodal Tradeoffs Methodology for Use in Statewide Transportation Planning", and developed a five-step evaluation process to carry out rating-based tradeoff analysis. That study listed two applications to demonstrate the tradeoff methodology. In 2005, Cambridge Systematics et al. carried another NCHRP study and developed two tools for asset management: AssetManager NT and AssetManager PT that contain tradeoff analysis functions. Mrawira and Amador (2009) developed a cross-asset tradeoff analysis based on multiple criteria by using a weighted-sum form of objective functions.

3.5 Uncertainty Consideration in Highway Asset Management

As stated above, performance measures are the primary building block in transportation asset management. In the process of decision-making, typically there is a need to forecast the value of performance measure as an impact of potentially implementing a candidate project. In some studies, the values of performance measures in the future are viewed as deterministic; that is, a fixed value represents the level of the performance measure after project implementation. This method simplifies the process of decision-making, however, it fails to consider the possible risk that the performance measures may not achieve the exact predicted value upon project implementation. There has been a few studies that have incorporated this kind of uncertainty into the decision-making process (Carnahan et al. 1987; Feighan et al. 1988; Ben-Akiva et al. 1993; Li and Sinha, 2003,).

There are two kinds of uncertainty situations regarding the outcome of a project in terms of a given performance measure: one is the situation where the set of all possible outcomes of a performance measure is known and the probability distribution of the outcomes is also known; the other is the situation where only part of all possible outcomes of an performance measure is known, but the probability distribution of such outcomes is not fully definable for a lack of reliable information (Young, 2001). Some studies refer to the former as the risk situation, while the latter is referred to as the uncertainty situation.

For the risk situation, there are two commonly-used ways to deal with the problem. One is when decision-maker uses utility theory to select projects, expected utility can be used based on the expected value of the performance measures (Li and Sinha, 2003); or the expected value is used for decision-making. The other way is to use Monte Carlo simulation to obtain the distribution of the final benefit and make a decision based on that distribution. In both cases, the distribution of the performance measures needs to be determined. The traditional way to derive the distribution is to use historical data to calibrate the distribution of a performance measure, but it is usually difficult to obtain such data. Thus, in practice some researchers simply assume the distribution of the performance measure using expert judgment (Li and Sinha, 2004).

For the uncertainty situation, it is even more difficult to develop a both theoretical and practical reasonable method to deal with this situation. One method to account for the uncertainty about predicted performance measures is the stochastic optimization approach based on the Markov decision process (Carnahan et al. 1987; Feighan et al. 1988; Ben-Akiva et al. 1993). Li and Sinha (2004) also examined uncertainty issues in highway project selection using Shackle's Model which involves the establishment of a degree of surprise function as a measure of uncertainty.

3.6 <u>Chapter Summary</u>

In order to solve the problem defined in Chapter 2, this chapter provides a comprehensive literature on transportation asset management, transportation performance measures, multicriteria/multi-objective decision-making in highway project selection, tradeoff analysis in asset management, and uncertainty considerations in highway transportation asset management. It is found that the problem in this study is one of the core problems in asset management. Also, it is seen that several studies have provided sets of performance measures for highway project evaluation and these can be used in this study. However, few studies developed effective tradeoff analyses methods that can solve the problem defined Chapter 2.

CHAPTER 4 STUDY FRAMEWORK

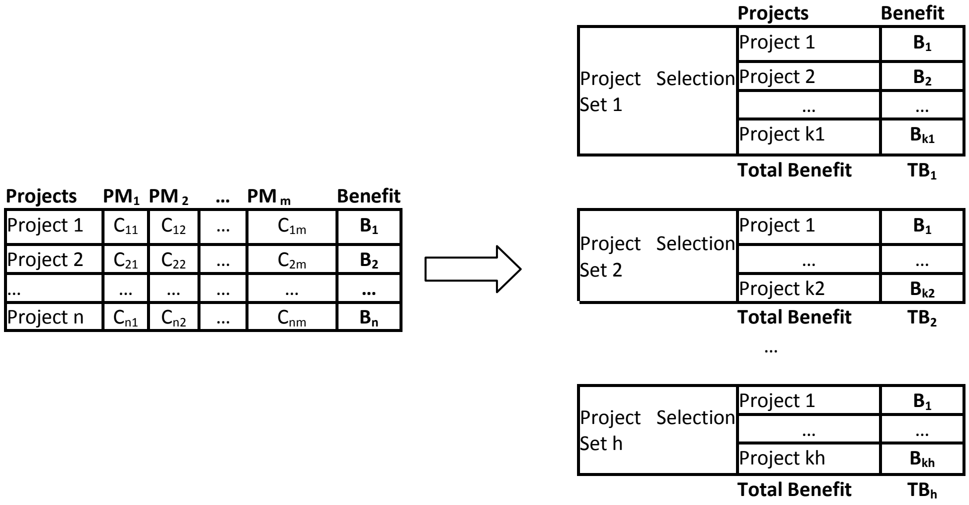
This chapter describes the various methodologies that constitute the framework developed to help highway decision-makers analyze tradeoffs in cases of certainty and uncertainty. The chapter first indentifies conceptual flaws that limit the efficiency of traditional frameworks and offers a framework that addresses the problem statement without being affected by the identified limitations of earlier research.

4.1 Transportation Project Selection Framework

4.1.1 Shortcomings of the Traditional Frameworks

The problem statement discussed in Chapter 2 is consistent with resource allocation problem, i.e., project selection under budget limits. For solving these types of problems, most past studies adopted a general analytical structure that is presented as Figure 4.1. First, the impact/benefit of each candidate project was assessed in terms of the established performance measures (PM_i); scalarization and amalgamation were applied to the different performance measures to yield a single value (B_i) that represents the benefit/impact of implementing each project; Knapsack formulation was used to represent the decision structure, and the problem was solved using integer programming, that is, the project set that produces the greatest total benefits (TB_i) under budgetary limitations and other constraints was selected. This solution structure is probably due to the inherent nature of the decision-making process where decision-makers compare individual projects with each another and ascertain the superior project. The primary merit of this solution structure is that its optimization component is the Knapsack problem which is linear and can solved rather easily by a linear 0/1 programming

(Winston et al. 2002). As explained in the Chapter 3, the literature on the subject is dominated by this traditional framework.



Projects	**PM_1**	**PM_2**	**…**	**PM_m**	**Benefit**
Project 1	C_{11}	C_{12}	…	C_{1m}	**B_1**
Project 2	C_{21}	C_{22}	…	C_{2m}	**B_2**
…	…	…	…	…	**…**
Project n	C_{n1}	C_{n2}	…	C_{nm}	**B_n**

	Projects	**Benefit**
Project Selection Set 1	Project 1	**B_1**
	Project 2	**B_2**
	…	…
	Project k1	**B_{k1}**
	Total Benefit	**TB_1**

Project Selection Set 2	Project 1	**B_1**
	…	…
	Project k2	**B_{k2}**
	Total Benefit	**TB_2**

…

Project Selection Set h	Project 1	**B_1**
	…	…
	Project kh	**B_{kh}**
	Total Benefit	**TB_h**

Identify the largest total benefit TB_j from TB_1, TB_2, …, TB_h (under constraints) and choose the corresponding project set as the optimal solution.

Legend: PM_i=Performance measure i;
C_{ij}= the value of performance measure j for project i;
B_i = the benefit of implementing project i;
TB_j=the total benefit of the implementing project selection set j.

FIGURE 4.1: Traditional Project Selection Framework

However, there are some communication issues, subtle analytical biases and conceptual flaws associated with this framework. First, the optimal solution shows only the maximum total benefit (TB_i) of the best set of selected projects, and this benefit is typically presented in the form of a single utility (such as a dimensionless unit or its monetary equivalent). Clearly, the language of the framework output is at variance with that of the end users: a total benefit that is expressed as a utility cannot be easily communicated across to legislators, interest groups, the general public, and other stakeholders. It is more appropriate to obtain an optimal solution that is expressed directly in terms of the raw (or unscaled) performance measures such as asset condition, average travel speed, and average crash rate (Pagano et al. 2005). Secondly, the traditional method may generate biased results in certain situations. To illustrate this issue, we consider the following simple, hypothetical example.

Example

Assume there are four alternative projects in a small network of assets: A, B, C, and D. Two performance measures are used to evaluate each project: the number of reduced crashes (PM_1) and the number of increased jobs (PM_2). The value of these performance measures and project costs are listed in Table 4.1.

Table 4.1: Hypothetical Project Information

Projects	Cost ($M)	No. of reduced crashes	No. of created new jobs
Project A	80	70	260
Project B	20	30	60
Project C	50	40	150
Project D	50	40	150

Assume that the total budget is $100 million which means it is possible to implement only projects A and B only or projects C and D only.

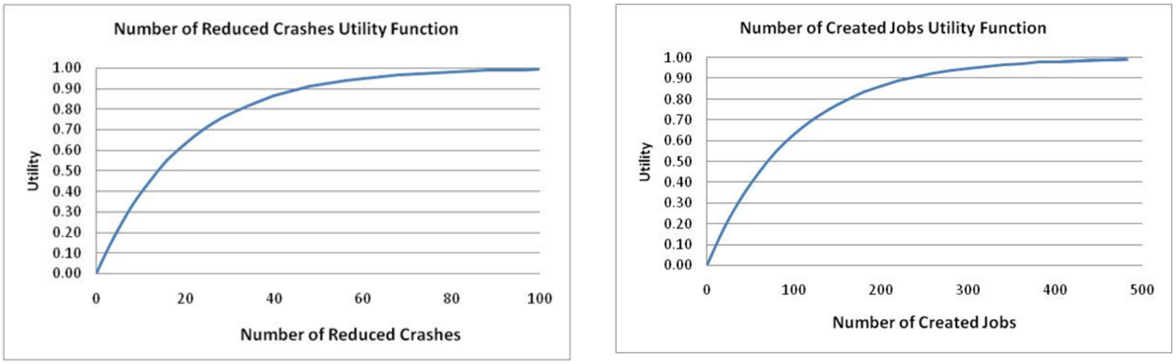
Assume that the utility functions of the two performance measures are:
$u_1(PM_1) = 1 - e^{-0.05\mathbf{P}M_1}$ and

$u_2(PM_2) = 1 - e^{-0.01PM_2}$ (commonly-used utility function form) as presented in Figure 4.2. An additive utility function is applied to conduct project evaluation. Also, assume that the two performance measures are equally weighted. Thus, the final utility of a project can be calculated as $U = 0.5 * u_1(PM_1) + 0.5 * u_2(PM_2)$.

In the traditional method, the decision-maker seeks to maximize the total utility of project implementation. The utilities of the four projects are:

U(A) =0.5* 0.97+ 0.5* 0.93= 0.95 U(B) =0.5* 0.78+ 0.5* 0.45= 0.615

U(C) =0.5* 0.86+ 0.5* 0.78= 0.82 U(D)= 0.5* 0.86+ 0.5* 0.78= 0.82



(a) $u_1(PM_1) = 1 - e^{-0.05PM_1}$ (b) $u_2(PM_2) = 1 - e^{-0.01PM_2}$

FIGURE 4.2: Utility Functions used in the Example

Since (U(C) + U(D)) > (U(A)+U(B)), it is clear that a solution set comprising projects C and D is the optimal solution. However, the decision-maker intuitively may choose projects A and B because their combined number of reduced crashes and created jobs exceed those of projects C and D. In this example, if the decision-maker chooses A and B, the total number of reduced crashes of the small network is 100 and the total number of increase jobs of the small network is 320; and if the decision-maker chooses C and D, the corresponding values are 80 and 300 so the decision-maker should choose A and B. If the decision-maker adopted other kinds of utility functions and combination forms (such as multiplicative form), the result may also have the same problems as shown in the above example. Thus, it is seen that the traditional framework may not be able to identify correctly the optimal solution in such cases.

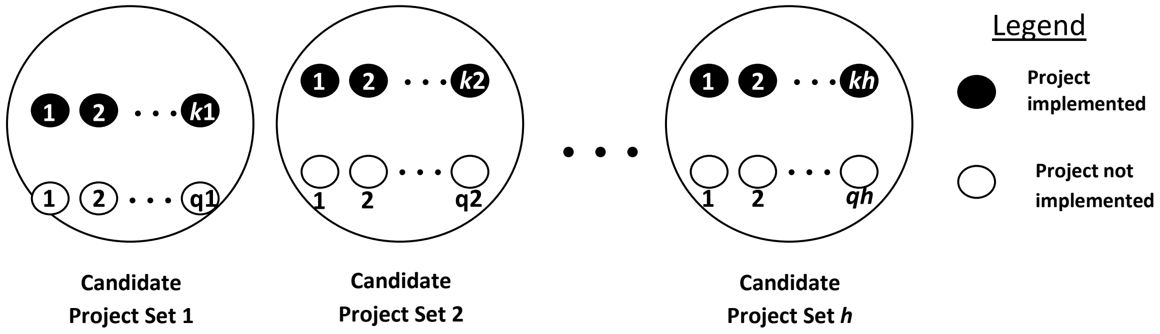
From the real definition of performance measures, it is seen that some project-level performance measures do not always include full performance information. For instance, crash rate (number of crashes per million of vehicle-mile traveled (VMT)) is a common performance measure to evaluate the impact of a highway project on safety. If Project A and Project B have the same cost, but Project A's implementation can reduce the crash rate by 1 crash/ million VMT, and Project B implementation can reduce crash rate by 2 crash/ million VMT. The question is whether Project B's implementation can be said to yield a greater safety benefit compared to Project A. While the decision-maker may be inclined to claim that B is superior in this respect, the question again is whether it would be more beneficial to examine the total number of reduced crashes and VMT for both cases. Project A may have a much larger VMT than Project B in which case the actual number of reduced crashes of A exceeds that of B.

The obvious bias and fallacy of the traditional optimization framework as evidenced in the examples above can be attributed to the separate evaluation of individual projects in terms of performance measures in such frameworks. These performance measures may not be able to reflect full performance information. Also, in their scaling and amalgamating to a dimensionless unit, these performance measures lose some original information thus compromising the integrity of the project evaluation process.

4.1.2 Proposed Project Selection Framework in This Study

To address the limitations and bias inherent in the traditional approach, this study proposes a simple framework (Figure 4.3) that first places candidate projects into sets, and considers each set as an alternative or a "candidate" for implementation. The evaluation is carried out on the basis of the performance impacts of each set of projects, not in terms of a single utility synthesized from the individual measures but in terms of the raw or unscaled values of the measures. So, for each candidate set, the impact of each constituent project's implementation is determined in terms of performance measures (C_{ij}). For each set, the overall performance (NPM_{ij}) can be expressed in terms of some statistical function of the performance measures. The statistical function may be the simple mean, the percentage of assets whose performance levels exceed some specified threshold, etc. Then a multiple objective optimization is carried out to determine which set is optimal and can produce the most positive impact/benefit (NB_i) under given performance and/or cost constraints.

In practice, DOT decision-makers may not be interested in the performance of the best project selection set but rather may seek the consequences of the optimal solution on the overall highway network performance, such as the crash rate of the entire highway network or the average travel speed in the network. To address this issue, the consequences of the optimal project selection set on the overall performance of the entire network can be derived mathematically. This is discussed in greater detail in Chapter 5.



(a) Simplified View of the Framework

	Projects	**PM_1**	**PM_2**	**…**	**PM_m**
Project Selection Set 1	Project 1	C_{11}	C_{12}	…	C_{1m}
	Project 2	C_{21}	C_{22}	…	C_{2m}
	…	…	…	…	…
	Project k1	C_{k11}	C_{k12}	…	C_{k1m}
	Network PM	**$N\ PM_{11}$**	**$N\ PM_{12}$**		**NPM_{1m}**

Project Selection Set 2	Project 1	C_{11}	C_{12}	…	C_{1m}
	…	…	…	…	…
	Project k2	C_{k21}	C_{k22}	…	C_{k2m}
	Network PM	**NPM_{21}**	**NPM_{22}**		**NPM_{2m}**

…

Project Selection Set h	Project 1	C_{11}	C_{12}	…	C_{1m}
	…	…	…	…	…
	Project kh	C_{kh1}	C_{kh2}	…	C_{knm}
	Network PM	**NPM_{h1}**	**NPM_{h2}**		**NPM_{hm}**

⇨

Project Sets	**PM_1**	**PM_2**	**…**	**PM_m**	**Benefit**
Project Set 1	NPM_{11}	NPM_{12}	…	NPM_{1m}	**NB_1**
Project Set 2	NPM_{21}	NPM_{22}	…	NPM_{2m}	**NB_2**
…	…	…	…	…	**…**
Project Set h	NPM_{h1}	NPM_{h2}	…	NPM_{hm}	**NB_h**

Indentify the largest NB_i from NB_1, NB_2, …, NB_h (under constraints) and choose the corresponding project set as the optimal solution.

Legend:
PM_i= Performance measure i;
NPM_i= Network-level Performance measure i;
C_{ij}= the value of performance measure j for project i;
NB_i=the total benefit of implementing project selection set i based on network performance measures.

(b) A More Detailed View of the Framework

FIGURE 4.3: Proposed Project Selection Framework

In contrast to the traditional framework (Figure 4.1), the proposed framework (i) focuses on network-level performance measures directly (note that in the decision process, decision-makers can clearly, quickly, and directly ascertain the network performance of the outcome of the decision clearly and thus can conduct tradeoff analysis between competing actions on the basis of the raw performance measures), (ii) avoids the conceptual bias inherent with the traditional approach as illustrated in the example provided in Section 4.1.1 of this chapter.

4.2 Study Framework

Tradeoff analysis, which is the main part of this study, is follow-up on the project selection framework described in Section 4.1. In tradeoff analysis, the decision-maker seeks the tradeoff ratio (also referred to as the marginal rate of substitution) between different performance measures or other aspects. In multi-objective optimization formulation, the tradeoff ratio of objective f_i with respect to objective f_j is expressed as (Nakayama et al, 2009):

$$t_i = \frac{\partial f_j}{\partial f_i} \tag{4-1}$$

Where f_i is the *i*th objective.

However, this definition is based on continuous objective functions. In our problem, the decision variables are discrete so the objective functions are also discrete. Therefore, three adjacent optimal solutions may not connect as presented in Figure 4.4. As such, in this study, instead of using formula (4-1), Equation (4-2) will be adopted to calculate the tradeoff relation between two adjacent optimal solutions.

$$t_i = \frac{f_{j1} - f_{j2}}{f_{i1} - f_{i2}} \tag{4-2}$$

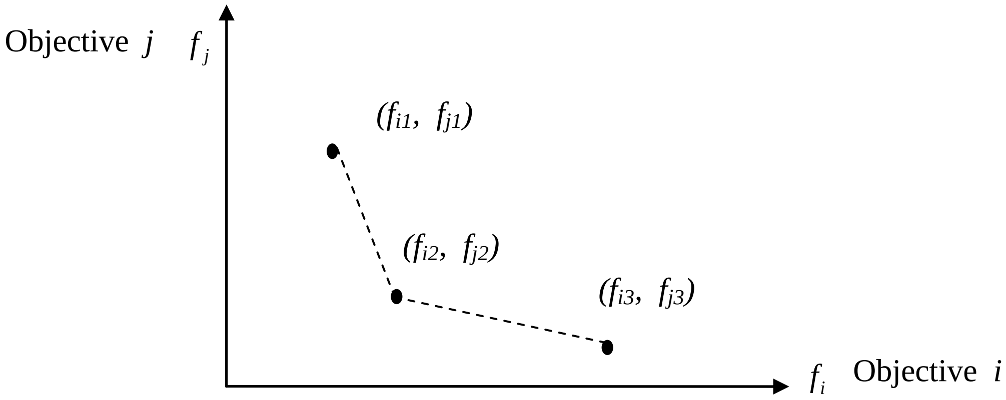


Figure 4.4 Tradeoff Analysis in Multi-objective Decision-Making involving Discrete Decision Variables

In practice, decision-makers may seek the tradeoff trend across the entire range of the objectives. This information can be provided easily by tradeoff curves in the continuous case, and Equation (4-2) can be used to conduct tradeoff analysis between any two candidate solutions. For the discrete case (as in this study), the frontier is connected, using regression analysis, with smooth curves to show the tradeoff trend between objectives. Because this curve is not the actual traditional tradeoff curve, it is herein referred to it as the pseudo-tradeoff curve (see Figure 4.5).

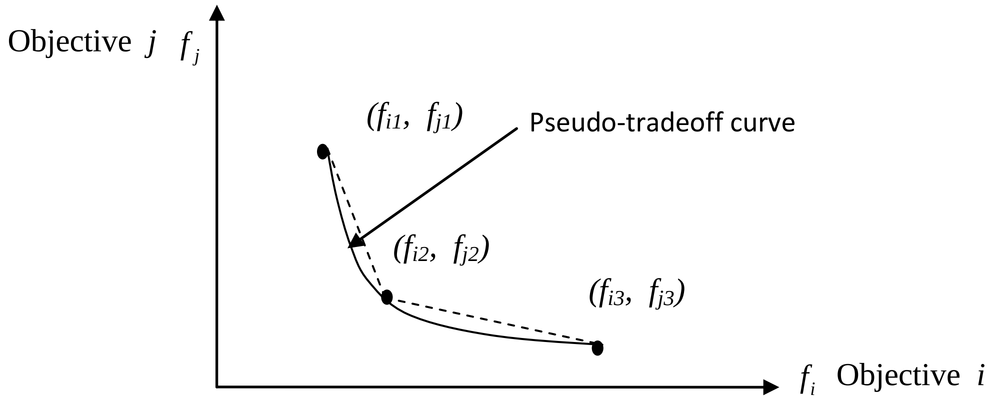


Figure 4.5 Pseudo-Tradeoff Curves for Multi-objective Decision-Making Involving Discrete Decision Variables

To establish a pseudo-tradeoff curve, the first step is to establish the Pareto frontiers (Pareto, 1906) for the multi-objective optimization problem. An efficient way to generate the Pareto frontiers is using Genetic Algorithms (Nakayama et al., 2009). This technique is used in the present study.

Furthermore, the process of tradeoff analysis often involves a variety of constraints on the objectives (performance measures) that are being traded off. When the constraints change, the tradeoff relationship between objectives may also change. Thus, in the decision-making process, tradeoff analysis may be repeated several times until a final solution is obtained. Tradeoff analysis helps decision-makers be familiar with the relationship between different objectives under certain limits and to ascertain the consequences of any input changes on the final decision. So, while tradeoff analysis is the focus of the present study, it is only a tool for decision-making and follows naturally from project selection. Based on the above analysis, the study framework of this research is presented in Figure 4.6.

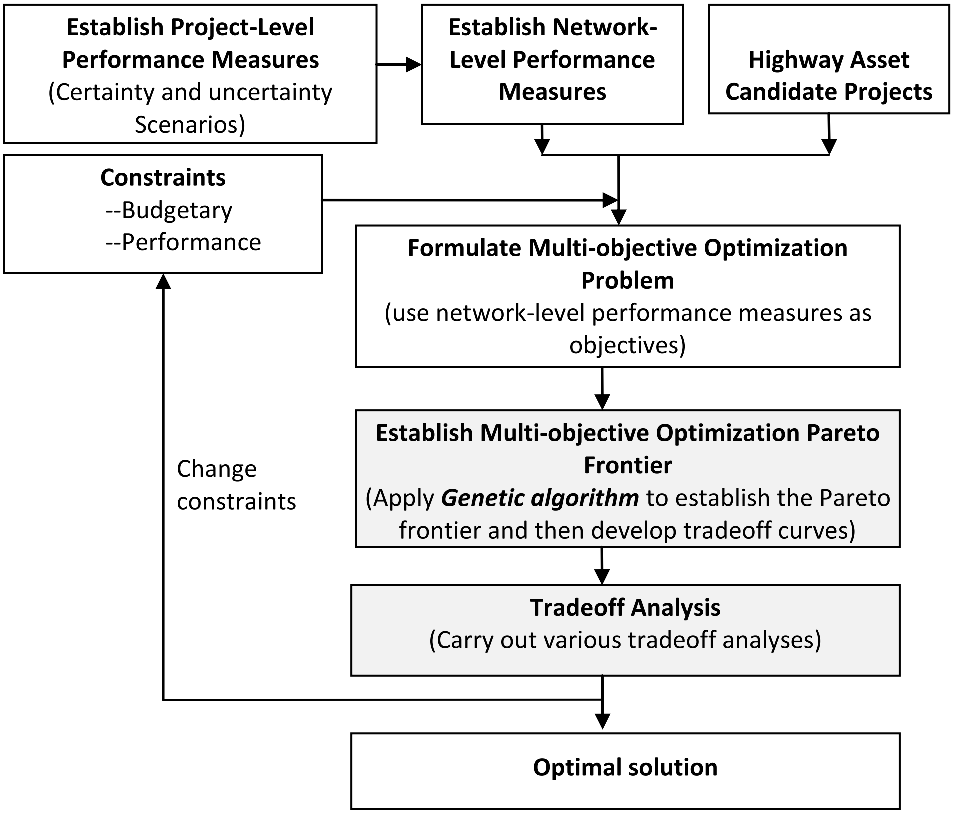


Figure 4.6 Study Framework for Solving the Tradeoff Problem

For the uncertainty scenario, Monte Carlo simulation was used to establish the distribution of each objective based on the distribution of the raw performance measures of each project (Figure 4.7). Then tradeoff analysis was conducted to determine a balance between the risk and benefit associated with the final decision.

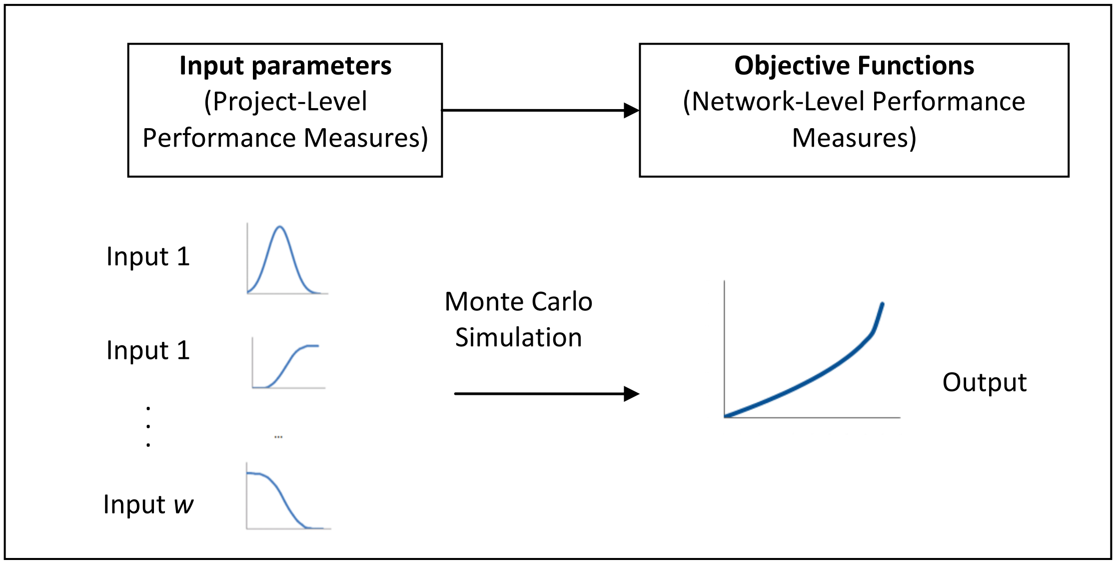


Figure 4.7 Uncertainty Considerations in Tradeoff Analysis

4.3 Chapter Summary

This chapter first analyzes the shortcomings of traditional project selection and tradeoff analysis methods in the highway transportation field and finds that the traditional project selection methods may cause bias in some cases. A simple example is provided to illustrate this shortcoming. To overcome this shortcoming, a new project selection framework which adopts network performance measures as the problem objectives, is proposed. This framework formulates the problem as a multi-objective optimization problem with network performance measures as the objectives, focuses tradeoff analyses by generating Pareto frontiers, and incorporates uncertainty consideration in the decision-making process.

CHAPTER 5 TRADEOFF ANALYSIS METHODOLOGY UNDER CERTAINTY

In this chapter, algebraic expressions for network-level performance evaluation are discussed and derived, and detailed multi-objective optimization formulations are provided. This is followed by a presentation on how genetic algorithm is used to establish the Pareto frontier for the multi-objective optimization problem. On the basis of the Pareto frontier, the chapter presents four types of tradeoff analyses under the certainty scenario.

5.1 Algebraic Expressions for Network-Level Performance

As stated in Chapter 4, this study uses network-level (or, system-wide) performance measures as the objectives of the optimization. Examples of network-level performance measures include average travel speed in the network, the percentage of bridges above fair condition, and the minimum remaining service life of any safety asset. Network-level performance measures are consistent with the goals of asset managers because they reflect the performance of the entire network which could reflect the performance of the transportation agency itself. There are many network-level performance measures that can be used to evaluate various aspects of highway network physical condition or operational characteristics. Most of these can be expressed in any one of several statistical forms, such as:

- a simple average of the performance of all relevant assets, such as average crash rate

- a percentage of all assets whose performance satisfy some specified thresholds related to the entire universe of assets, such as the percentage of bridges above fair condition (bridge condition rating is equal to or greater than 5)
- the sum of performance measures, where the performance associated with all assets in the network at added algebraically, such as the total number of created jobs
- the minimum performance of any relevant asset in the network, such as the minimum remaining service life of any safety assets

During the project selection process, the estimated final value of network-level performance depends on which projects are selected. Thus, the proposed approach which directly involves a calculation of network-level performance levels measures, presents an improvement over the traditional approach for multi-criteria project selection.

The sections below present the expressions derived in the present study for the first three of the above statistical expressions of network-level performance.

Average Form

State transportation agencies typically express the overall performance of their systems using a simple arithmetic mean value of performance. The computation of a network-level average for a given year is often made more complex when the system inventory is expanded by new assets constructed in that year. In other words, the projects in the optimal solution may include some new construction projects which produce new assets in the network. Thus, in calculating the network performance, both the existing and new assets should be considered. In this respect, a general formula for the average form of network-level performance measures is derived as follows:

$$NPM_{Average} = \frac{\sum_{\mathrm{i=1}}^{\mathrm{n_0}} PM_{\mathrm{i}} F_i + \sum_{\mathrm{i=1}}^{\mathrm{n_{imp}}} (1-x_i) PM_i^0 F_i + \sum_{\mathrm{i=1}}^{\mathrm{n_{imp}}} \mathrm{x_i} PM_i^1 F_i + \sum_{\mathrm{i=1}}^{\mathrm{n_{new}}} \mathrm{x_i} PM_{\mathrm{i}} F_i}{\sum_{\mathrm{i=1}}^{\mathrm{n_0}} F_i + \sum_{\mathrm{i=1}}^{\mathrm{n_{imp}}} F_i + \sum_{\mathrm{i=1}}^{\mathrm{n_{new}}} x_i F_i} \tag{5-1}$$

Where:

$NPM_{Average}$ is the network-level performance measure in an average form;

n_0 is the number of assets outside the candidate pool in the network (that is, for those assets no project was initially recommended);

n_{imp} is the number of existing assets in the candidate project pool (that is, for which a project was initially recommended);

n_{new} is the number of new construction projects in the candidate project pool;

$n_{imp} + n_{new}$ is the total number of projects in the candidate project pool;

PM_i is the value of performance measure of facility *i*;

PM_i^0 is the value of performance measure if the candidate project *i* is not selected/ implemented;

PM_i^1 is the estimated value of performance measure of candidate project *i* if candidate project *i* is implemented;

F_i is a variable in terms of which the performance measure for project *i* is measured (see Table 5.1)

x_i = 1 (project *i* is selected) or 0 (project *i* is not selected).

Table 5.1 presents the meanings of some parameters for some commonly-used performance measures.

TABLE 5.1: Parameters for "Average" Form of Expressing Network Performance

Network-Level Performance Measure (PM)	PM_i	PM_i^0	PM_i^1	F_i
Average IRI	IRI on road segment *i*	IRI of candidate project *i* if it is not selected	Estimated IRI of candidate project *i* if it is implemented	Length of candidate project *i*
Average Crash Rate	Crash rate on road segment *i*	Crash rate of candidate project *i* if it is not selected	Estimated crash rate of candidate project *i* if it is implemented	VMT of candidate project *i*
Average Travel Speed	Average travel speed on road segment *i*	Average travel speed of candidate project *i* if it is not selected	Estimated average travel speed of candidate project *i* if it is implemented	Traffic volume of candidate project *i*
Average Bridge Condition Rating	Average condition rating of bridge *i*	Bridge condition of candidate project *i* if it is not selected	Estimated bridge condition rating of bridge *i* if it is implemented	1

Percentage Form

In practice, some agencies are more interested in the percentage of assets in their jurisdictions that satisfy some specified threshold (Pagano et al., 2005). The threshold may be a value established by legislature, or agency top managers, an average value of that performance measure in the previous year, etc. For instance, an agency may seek to choose the optimal projects to be implemented such that the percentage of structurally deficient bridges does not exceed 25%. For the percentage form of expressing network performance, the general formula for calculating the required percentage is:

$$NPM_{Percentage} = \frac{\sum_{i=1}^{n_0} Y_i + \sum_{i=1}^{n_{imp}} Y_i^1 - \sum_{i=1}^{n_{imp}} (1 - \mathrm{x_i}) Y_i^0 + \sum_{i=1}^{n_{new}} \mathrm{x_i} Y_i^n}{n_0 + n_{imp} + \sum_{i=1}^{n_{new}} x_i} \tag{5-2}$$

Where:

$NPM_{Average}$ is the network-level performance measure in a percentage form;

n_0, n_{imp}, and n_{new} have the same meanings as those in Equation (5-1);

Y_{i} = 1 if the performance measure of the highway facility *i* achieves a certain level; 0 otherwise;

Y_{i}^{0} = 1 if the performance measure of the highway facility that receives project *i* achieves a certain level if it is not implemented; 0 otherwise;

Y_{i}^{1} = 1 if the estimated performance measure of highway facility that receives project *i* achieves a certain level if it is implemented; 0 otherwise;

$Y_{\mathrm{i}}^{\mathrm{n}}$ = 1 if the estimated performance measure of new construction project *i* achieves a certain level if it is implemented; 0 otherwise;

x_i = 1 (project *i* is selected) or 0 (project *i* is not selected).

Additive Form

There is certain unique set of performance measures that are best evaluated on a sum basis. Examples of these include the total number of jobs created and the total emissions of pollutants in an area. In choosing projects based on this expression of network performance, the additive form is used. The general formula is:

$$NPM_{sum} = \sum_{i=1}^{n_{imp}+n_{new}} x_i PM_i \tag{5-3}$$

Where:

$NPM_{Average}$ is the network-level performance measure in an additive form;

n_0, n_{imp}, and n_{new} have the same meanings as in Equation (5-1);

PM_i is the value of performance measure for project i;

$x_i = 1$ (project i is selected) or 0 (project i is not selected).

Apart from the above commonly-used three forms, there are other ways of expressing the overall performance – these are often in more complex forms. For example, "the minimum performance of any relevant asset in the network" (mentioned in the previous part) is a performance threshold for each asset in the network. For another example, if it is sought to include network accessibility impacts as a performance measure, then the total distance between major locations can be used a performance indicator *(*Ingram, 1971*)*. However, the value of total distance is based on the structure of the whole network and cannot be expressed by a single formula.

5.2 Multi-objective Optimization Formulation

In Chapter 2, this report presented a mathematical statement of the problem in this study. This section further elaborates the statement by providing a detailed multi-objective optimization formulation.

Objective functions

Assume there are *m* network-level performance measures. For each performance measure, the objective is to minimize or maximize its value. This means that there are *m* objectives:

$$\begin{aligned} &\min(or \max) \quad f_1(\vec{x}) \\ &\min(or \max) \quad f_2(\vec{x}) \\ &\quad \cdots \\ &\min(or \max) \quad f_m(\vec{x}) \end{aligned} \tag{5-4}$$

Where:

$\vec{x}$ is a decision variable vector (x_1, x_2, ..., x_i, ..., x_n), each x_i can be 0 or 1 (1 means that project i is selected and 0 otherwise), and n is the number of candidate projects;

$f_i(\vec{x})$ is the ith network-level performance measure (objective).

Since $f_i(\vec{x})$ may be in average form, percentage form, additive form, or other more complex forms, and both average and percentage forms contain 0/1 decision variable in the denominator. Thus the problem can be considered as a nonlinear 0/1 multi-objective optimization problem.

Constraints

The constraints depend on agency policy, and typically include:

(1) **Constraints on Budget(s).** Often in the practice, not only is there a overall budget ceiling for all highway asset types, but also there is a budgetary ceiling and/or budgetary floor for assets of each type (in certain agencies, asset types are categorized by the management systems – bridge, pavement, congestion, and safety). This situation arises from the nature of funding source (for example, it may be that certain federal funds can be used only for safety assets). Thus, there could be constraints on overall budgetary constraint and/or asset-specific budgetary constraints as follows.

$$\sum_{i=1}^{n_{imp}+n_{new}} x_i c_i \le B \tag{5-5}$$

$$sb_j^L \le \sum_{i=1}^{n_{imp}+n_{new}} x_i y_i^j c_i \le sb_j^U \qquad j = 1,2,\cdots,k \tag{5-6}$$

Where

k is the total number of asset types;

x_i = 0 (project *i* is not selected) or 1 (project *i* is selected);

y_i^j = 0 (project *i* does not belong to asset type *j*) or 1 (project *i* belongs to asset type *j*);

c_i is the cost of project *i ;*

sb_j^L is the minimum budget for asset type *j;*

sb_j^U is the maximum budget for asset type *j*.

In constraint (5-6), typically not all the asset types have a budgetary ceiling or floor. If an asset type does not have such constraints, the decision-maker simply assigns the values 0 and ∞ to sb_j^L and sb_j^U, respectively.

(2) **Constraints on Performance Measures.** Under some conditions, the decision-maker may wish that the levels of certain network performance should achieve thresholds or specified targets. Thus, it is helpful to include such information in formulating the performance constraints. Depending on whether the threshold is upper bound or lower bound, the performance measure constraints are typically expressed as:

$$f_i(\bar{x}) \le Level_i \text{ or } f_i(\bar{x}) \ge Level_i,\ i = 1, 2, \cdots, m \tag{5-7}$$

Where m is the number of objectives (or network-level performance measures) and $Level_i$ represents a certain level of performance measure i.

In the above formulation, the budget information is formulated as constraints. In the problem statement in Chapter 2, there is a need to consider the possible of shifting funds across the different areas of asset management. To handle this situation, budget information can be formulated as objectives instead. In this case, when the decision-maker conducts tradeoff analysis, full tradeoff information about the budget levels and performance can be provided.

5.3 Generation of Pareto Frontier for the Multi-objective Optimization Problem Using Genetic Algorithms

5.3.1 Generation of Pareto Frontier Using Genetic Algorithms

A large number of multi-objective optimization methodologies simply seek a way to transform the multiple objectives to a single objective and then solve them by single objective optimization methods. These methods typically just provide the final result to decision-makers without a visible analysis process. This is probably one of the reasons why these methods have not gained a solid foothold in current asset management practice.

In multi-objective optimization, solution S_1 dominates solution S_2 if S_1 has better value than S_2 in all objectives. In most cases, there is no solution that dominates all the other possible solutions in the multiple objective space. On the contrary, there are many solutions that are not dominated by others. These solutions are described as *Pareto Solution* (Pareto, 1906). In a multi-objective optimization problem with all the objectives to be maximized, a Pareto solution can be defined as: For $\vec{x}^*$, if there is no such a feasible solution $\vec{x}$ that for all objectives

$$f_i(\vec{x}) \geq f_i(\vec{x}^*) \ (i = 1,2,\cdots,n)$$

and at least for one objective $f_j(\vec{x}) < f_j(\vec{x}^*)$, then $\vec{x}^*$ is called a Pareto solution. The set of all Pareto solutions is called Pareto frontier (Nakayama et al., 2009). Pareto frontiers are very important for decision-makers to conduct analysis and examine their real preference structure.

To generate the Pareto frontier for a multi-objective optimization with discrete decision variables, the most accurate method may be enumeration. In the problem at hand, if there are n candidate projects, there will be 2^n possible combination of different projects. This is classified as *N-hard* problem in optimization (Winston et al., 2002). When the n is very large, it is almost impossible to enumerate all possible solutions to determine the Pareto frontier. Fortunately, genetic algorithm (GA) techniques can be applied to generate a Pareto frontier (Nakayama et al., 2009).

Genetic algorithm is a kind of evolutionary algorithm that adopts the mechanism of natural selection to search for the best solution. It was originally introduced by Holland (1975) and as first applied on optimization by Jong (1975). Figure 5.1 presents the basic search structure of genetic algorithm (Nakayama et al., 2009).

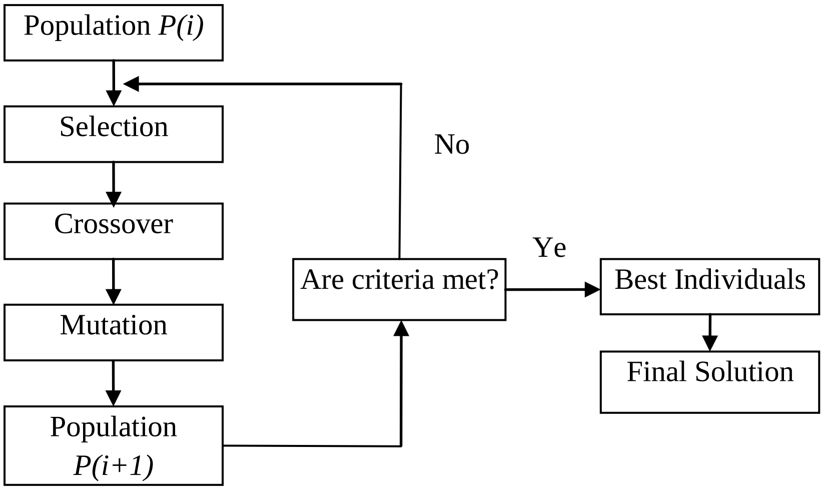


Figure 5.1: Basic Structure of a Genetic Algorithm

Genetic algorithms have been widely applied in various optimization problems in many fields. An important difference across these applications is the fitness function in the “selection” part in Figure 5.1. The fitness function is used to decide which individuals can be selected for producing next generation. Different fitness function designs can be used to solve different problems. For multi-objective optimization, Fonseca and Flemming (1993) successfully developed multi-objective genetic algorithms using ranking method to formulate the fitness function and to generate Pareto solutions for multi-objective optimization problem. However, as Yun et al. (2001) pointed out, this method cannot generate a smooth Pareto frontier. Deb et al. (2000) proposed the use of the Elitist Nondominated Sorting Genetic Algorithm (NSGA-II) to overcome the shortcomings of the ranking method. However, it may sometimes lose its convergence to the real Pareto frontier (Nakayama et al. 2009). Data envelopment analysis (DEA) method (Arakawa, 1998) can yield almost all non-dominated individual solutions but can only generate convex curves of the Pareto frontier. Yun et al. (2001) provided a generalized data envelopment analysis (GDEA) method, and it overcomes all the shortcomings in the previous study. In the present study, the GEDA method is used to generate the Pareto frontier.

The process of GDEA method process is presented as follows (Yun et al., 2001) :

Step 1: Set default values. Provide default value of population size *s*, the number of generations *n*, crossover rate p_c, and the mutation rate p_r.

Step 2: Initialization. Generate *s* feasible solutions randomly.

Step 3: Crossover and Mutation. Make *s/2* pairs randomly among the initial population. Conducting crossover each pair generates a new population. Mutate them according to the given probability of mutation.

Step 4: Evaluation of fitness by GDEA. Evaluate the fitness of each population from Step 3 by the following method.

$$\begin{aligned}
&\underset{\theta,u,v}{Max} \quad \theta \\
&subject \quad to \\
&\qquad \theta \leqq \tilde{d}_j + \alpha\left(\sum_{k=1}^{n} u_k (y_{ko} - y_{kj}) + \sum_{i=1}^{m} v_i (-x_{io} + x_{ij})\right) \\
&\qquad j = 1, \cdots, s \\
&\qquad\quad \sum_{k=1}^{n} u_k + \sum_{i=1}^{m} v_i \quad = 1 \\
&\qquad\quad u_k \geq \varepsilon \quad k = 1, \cdots, n \qquad v_i \geq \varepsilon \quad i = 1, \cdots, n
\end{aligned}$$

Where

$$\tilde{d}_j := \max_{\substack{k=1,\cdots,n \\ i=1,\cdots,m}} \left\{ v_k (y_{ko} - y_{kj}), u_i (-x_{io} + x_{ij}) \right\}$$

and α is a constant and ε is a sufficiently small positive number.

Step 5: Selection. Select *s* individual from the current population based on the fitness evaluation in Step 4.

Step 6: Reach the number of generation *n*? If yes, end; else, go to Step 3.

Even though the genetic algorithm cannot generate all the solutions in the Pareto solution set, it can generate (by increasing the number of iterations in the algorithm) adequate solutions for developing the needed tradeoff curves or surfaces.

5.3.2 Visualization of Pareto Frontier for Multi-objective Optimization

When the genetic algorithm is adopted to generate a Pareto frontier for multi-objective optimization, not all of the generated solutions are Pareto solutions as presented in Figure 5.2. Therefore, after generating the solutions using genetic algorithm, there is a need to select Pareto solutions from them, in consistency with the definition of a Pareto solution.

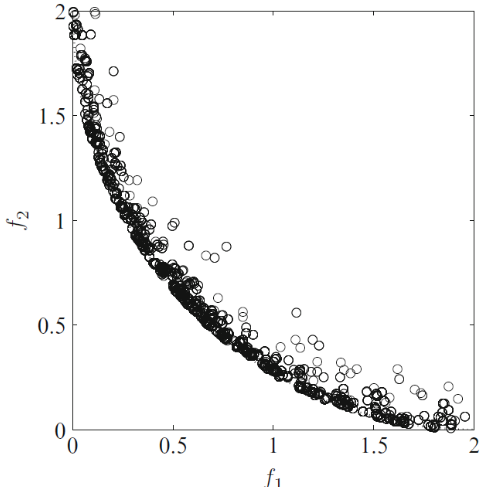


Figure 5.2: Pareto Frontier in Two Dimensions (Nakayama et al., 2009)

Pareto solutions generated using genetic algorithms are discrete points. When the objectives are continuous functions, these discrete points just provide the trends of the Pareto frontier, not the real Pareto frontier. Thus, these points are subsequently smoothed to yield curves or surfaces to represent the frontier. In our problem, the decision variables are discrete and then the objective functions are also discrete. Even though we may smoothen the Pareto solution points to yield curves or surfaces, not all the points on the smoothed curves or surface are the actual solutions to our problem. As such, we herein refer to these curves or surface as pseudo-frontier curves /surface, or pseudo-tradeoff curves /surface.

Visualization of Pareto frontiers can provide a visible tool for decision-makers to conduct tradeoff analysis. When there are only two objectives, Pareto solutions can be represented on a plane and can be easily visualized by plotting them on a two-dimensional space (see Figure 5.2). Figure 5.3 presents a Pareto frontier surface (i.e., pseudo-tradeoff surface) in three dimensions representing three objectives f_1, f_2, and f_3. This is only an approximated surface based on some Pareto solution points, and thus may be not very smooth.

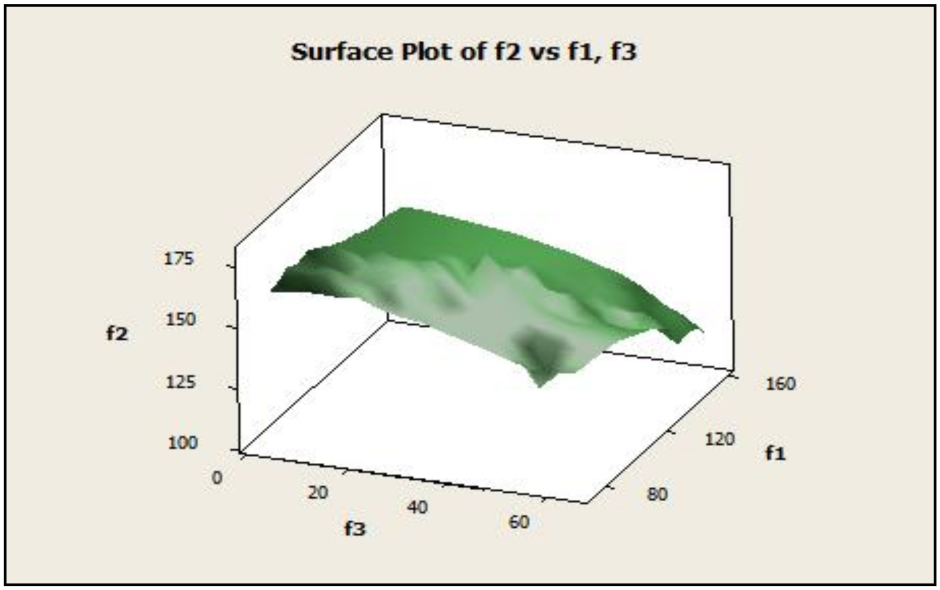


Figure 5.3: Pareto Frontier Surface in Three Dimensions

When there are four or more dimensions, the frontier “surface” cannot be visualized using a 3D plot. There are several techniques that can visualize the Pareto frontier for such situations such as animation of decision maps (Branke et al. 2008), heatmaps graphs (Pryke et al. 2007) and scatterplot matrix method. For visualizing multi-dimensional Pareto frontiers in the present study, the Scatterplot matrix method is used.

A scatterplot, which can present the results from pairs of objectives on a panel, is a square matrix of panels each of which presents one pair of objective functions. The dimension of the matrix remains the same as the number of objectives. This way, the matrix can present the frontier when there are three or more objectives. The scatterplot matrix, introduced by Meisel in 1973, has been widely used in the management field (Nakayama et al., 2009). Figure 5.4 presents the scatterplot matrix corresponding to Figure 5.2. Each panel shows partial tradeoffs between two objectives. A scatterplot matrix can be also applied in the situation where there are more than three objectives.

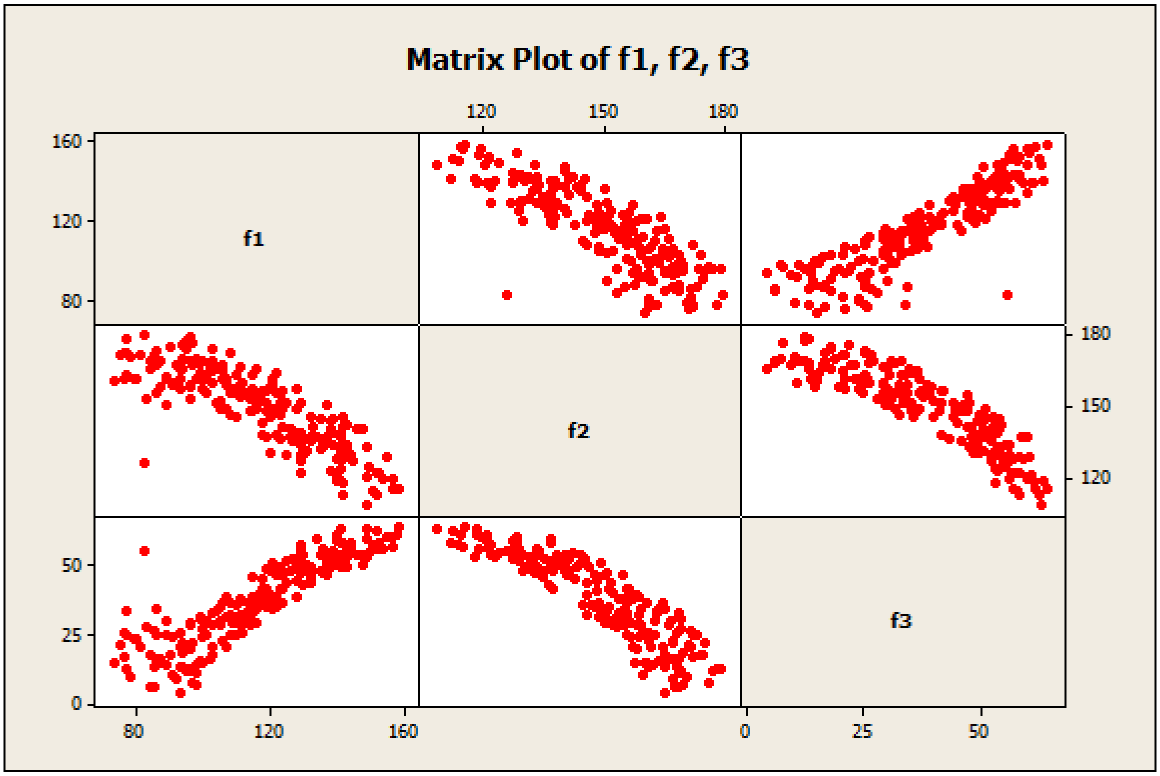


Figure 5.4: Scatterplot Matrix for Three Objectives

In fact, even if we could visualize the frontier using a scatterplot matrix, it is still hard to make the complex relationships clear to decision-makers. In practice, in most cases, decision-makers only focus on two objectives each time so the visualization is decomposed into a series of two-dimensional tradeoff curves. Thus, two-dimensional tradeoff curves may be the most appropriate form for presenting Pareto frontiers to decision-makers.

5.4 Tradeoff Analysis

In this section, four of the five tradeoff analyses identified in Chapter 2 are discussed.

5.4.1 Tradeoff between Alternative Individual Projects

In the most typical decision-making setting of asset management, decision-makers compare different projects and choose some of them for implementation. The most commonly-used comparison is that conducted between two individual projects which may or may not from the same sub-area. For example, there may be a need to compare a bridge project and a pavement project. To compare two projects i and j, actually, is to compare the following two performance vectors:

$$(pm_{i1}, pm_{i2}, \ldots, pm_{im}) \text{ vs. } (pm_{j1}, pm_{j2}, \ldots, pm_{jm})$$

Where pm_{ik} is the value of the kth performance measure for project i.

For this comparison, several methods can be used. These methods typically scale the performance measures to the same unit or a dimensionless unit and then conduct the comparison (Nakayama et al., 2009). A common method is to apply utility theory (Keeney and Raiffa, 1976) to scale these performance measures and combine them by additive utility functions or multiplicative utility functions to yield a single value to represent the overall desirability/impact of the project, and then to choose that which has greater desirability (Li and Sinha, 2004). While this method is easy to conduct, it is not consistent the overall network objectives because such comparison seeks to ascertain the project that has superior project-level performance. However, the overall objective of the problem is to find the solution that can have superior network-level performance (see Section 5.2). When we conduct comparison with this method, we do not consider their impact on the network-level performance. In some (but not all) cases, these two objectives are consistent.

Thus, instead of taking two individual projects out from other projects and comparing them, this study puts these two individual projects into all the other selected projects and then makes a decision based on the overall performance of the whole network. As an extension, we can use this method to compare one set of projects with another set of projects. Each set can have one or many projects. Also, the number of projects in each set could be different. The transformation is presented in the Figure 5.5. In the figure, n_1 and n_2 can be 1 or greater than one.

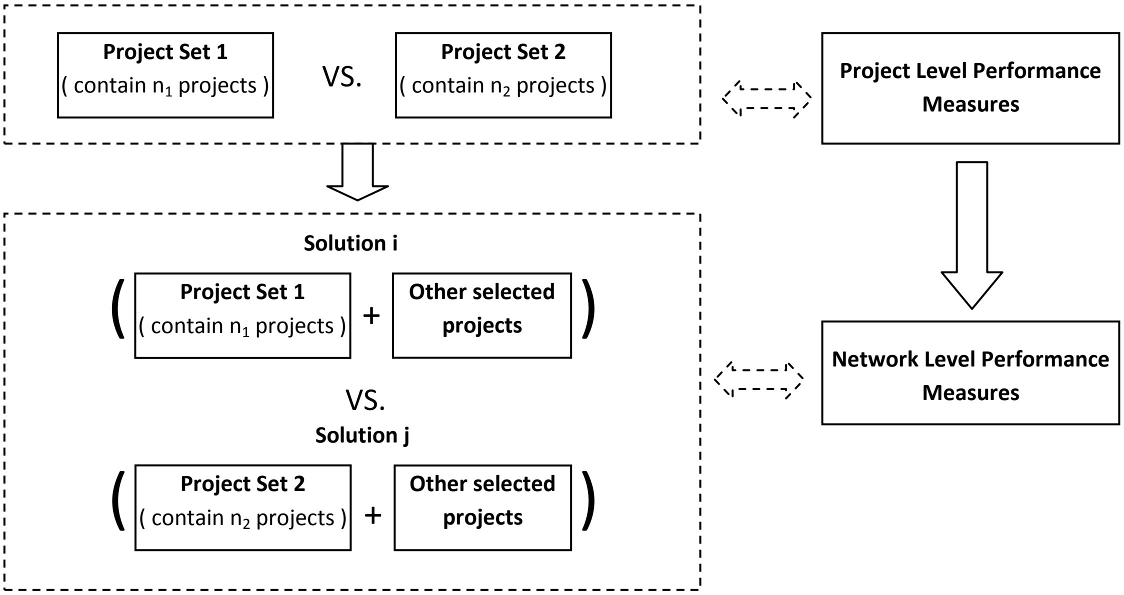


Figure 5.5: Transformation Comparison

From the comparison results, we can get two new vectors NPM_i and NPM_j , indicating the network performance solution *i* and *j*, respectively. Thus, again, we seek to compare the following two vectors:

$$(npm_{i1}, npm_{i2}, \ldots, npm_{im}) \text{ vs. } (npm_{j1}, npm_{j2}, \ldots, npm_{jm})$$

For vector comparison, there are preference-based methods and non-preference-based methods. Non-preference-based methods refer to the traditional scalarization methods that do not consider decision-makers' preference structure. Preference-based methods, such as the utility theory method, conduct scalarization based on the decision-makers' preference structure. For some performance measures, in the field of highway transportation management, the preference levels of decision-makers or users are not linearly related to the value of performance measure. For instance, drivers may perceive small difference between the satisfaction of driving at 60 miles mph and driving at 70 mph, but have significant difference of satisfaction between driving at 15 mph and driving at 25 mph. In other words, for drivers, it is more valuable to improve the travel speed from 15 mph to 25 mph than from 60 mph to 70 mph, which is suggestive of non-linearity in their preference structure. Therefore, non-preference-based methods that contain objective normalization (such as linear normalization) are not suitable for problems of this kind. In preference-based methods, the most commonly-used one is utility theory, which transforms the multi-objective problem into a single-objective one by capturing decision-makers' preference structure. The basic element in utility theory is the utility function that reflects the preference structure of decision-makers. In the process of decision-making, if a vector contains m elements ($X_1, X_2, \ldots, X_m$), ($x_{i1}, x_{i2}, \ldots, x_{im}$) and ($x_{j1}, x_{j2}, \ldots, x_{jm}$) are the value vectors for any two alternatives *i* and *j*, and if $u(x_{i1}, x_{i2}, \ldots, x_{im}) \geq u(x_{j1}, x_{j2}, \ldots, x_{jm})$ ($u(\ldots)$ is the utility function), then we can conclude that decision-maker prefer alternative *i* to alternative *j*. Thus in the present study, we use this method to conduct tradeoff between different sets of projects. Furthermore, the mathematical form of this function could be additive or multiplicative.

At this point, a pertinent question is why scalarization or utility function are being used here even though their use, in a certain context, has been associated with bias as earlier indicated in this report. Indeed, almost all multi-objective optimization problems require some kind of scalarization to transform the different units of various objectives to common units and then to generate a single value for each alternative for process of comparison. The point is that the scalarization or utility function can be applied for the final comparison between different alternatives, not for any interim transformation of alternatives. More specifically, in the project selection problem, our aim is to select a project selection set with a certain number of projects. Therefore, it is sought to compare the performance of the selection set. Thus it is not imprudent to adopt scalarization at this level, unlike at the earlier project level stage of the process. In the previous example in Chapter 2, the scalarization was conducted at project level, and thus lost some performance information when it came to the final stage where a comparison was made of two sets of projects, causing bias in the process, as seen in the numerical example.

5.4.2 Tradeoff between Performance Measures

In some cases, the total budget is limited, and yet decision-makers seek to increase the performance in a certain aspect (e.g., reduce the network crash rate). Recognizing that this may have adverse consequences on the other measures of performance, the decision-makers often seek a tool to investigate the impact of this situation on other performance measures such as average travel speed and IRI. In the problem at hand, the performance measures are reflected by the objectives in the multi-objective optimization. When there are two objectives, this tradeoff can be conducted by drawing the pseudo-tradeoff curve; where there are three objectives, it can be achieved by generating Pareto solutions and figuring out the three-dimension tradeoff surface; where there are more than three objectives, a scatterplot can be applied to help decision-makers carry out the tradeoff analysis. In fact, even though there are many objectives, decision-makers usually focus on two objectives at a time, so the most useful tradeoff analyses are those involving two dimensions. The detailed methods to established tradeoff curves, tradeoff surfaces, and scatterplots are discussed in Section 5.3.

5.4.3 Tradeoff between Budget Level and Performance Measures

This kind of tradeoff analysis contains two cases in practice: the first is the case where the decision-makers seek the network performance under different budget levels and then to determine the optimal investment budget; the second is when there is a requirement of thresholds for some performance measures and the decision-makers seek the minimum required budget. The procedure of the first case is presented in Figure 5.6. Also, an example of an analysis result is shown in Figure 5.7. Another way to conduct the analysis is to draw a set of tradeoff curves, each of which shows the tradeoff of budget level vs. performance measures.

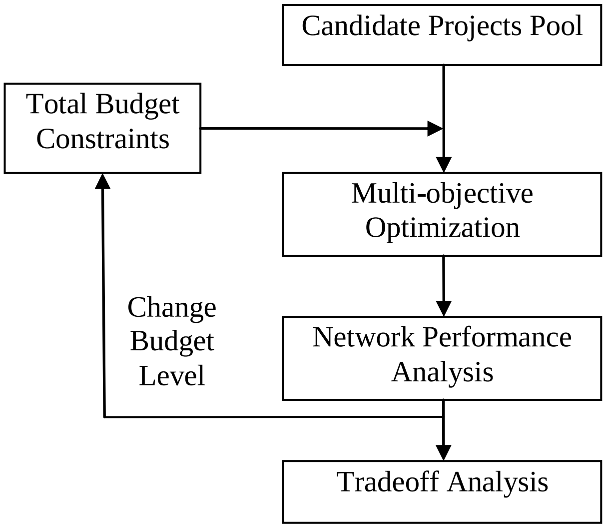
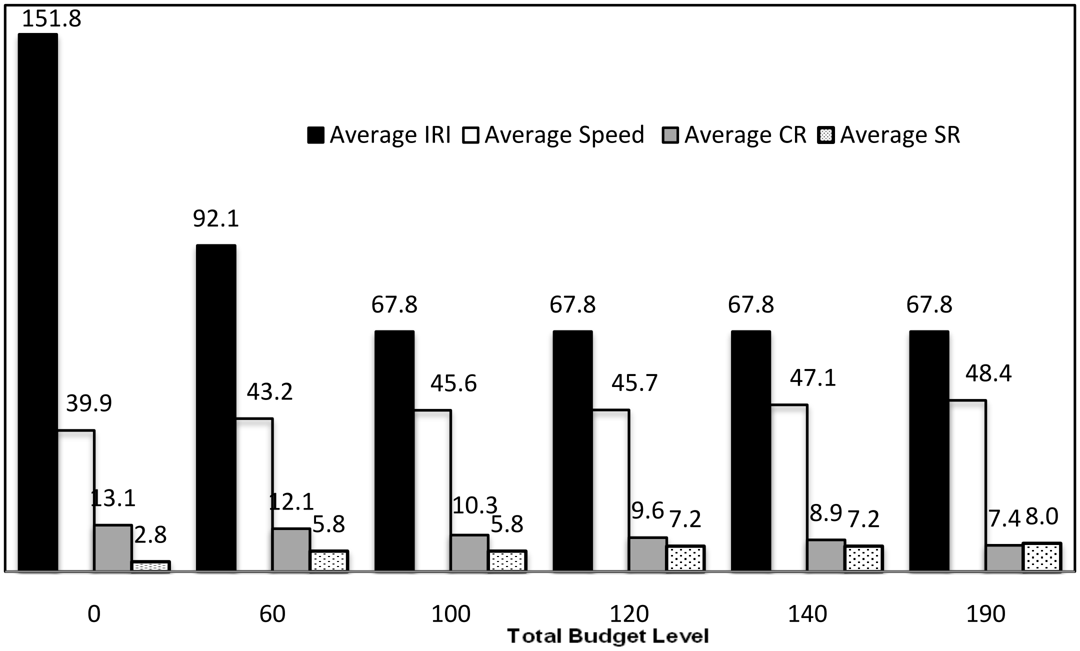


Figure 5.6: Procedure for Tradeoff Analysis between Budget Level and Performance Measures



Note: IRI—International Roughness Index, SR—Sufficiency Rating, CR—Crash Rate

Figure 5.7: Example of Tradeoff Analysis between Budget Level and Performance Measures (Bai et al. 2009)

For the second case, the procedure is presented in Figure 5.8. In this procedure, the optimization is actually a single objective optimization whose objective is to minimize the total budget under performance threshold constraints. An example of an analysis result is shown in Figure 5.9.

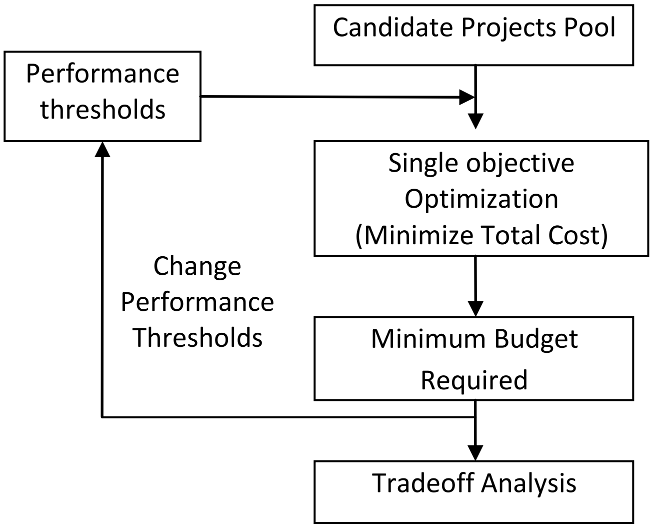


Figure 5.8: Procedure for Tradeoff Analysis between Performance Thresholds and Budget Levels

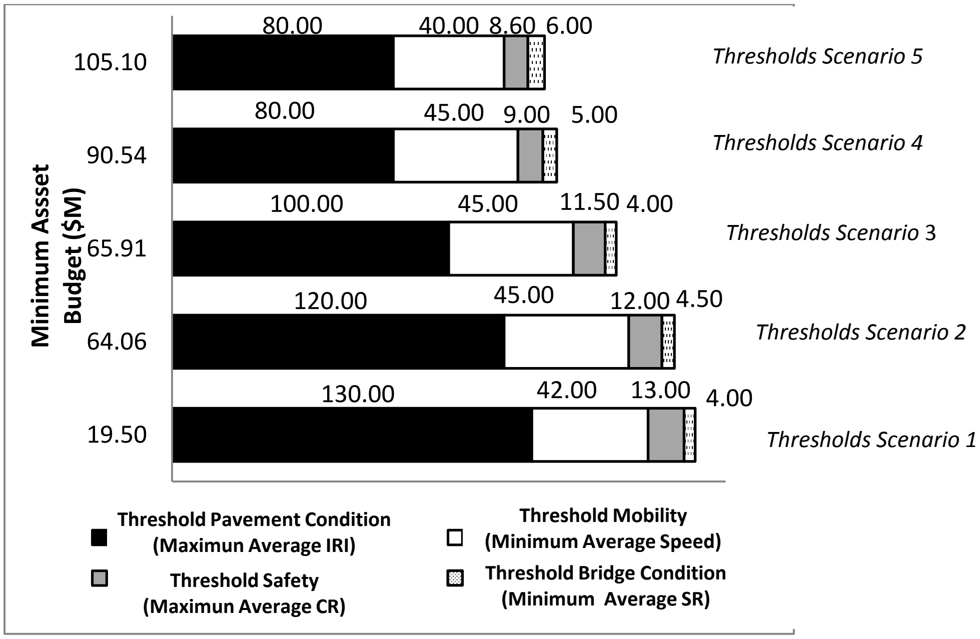


Figure 5.9: Example of Tradeoff Analysis between Performance Thresholds and Budget Levels (Bai et al. 2009)

5.4.4 Tradeoff Analysis between Sub-area Budgets

This kind of tradeoff analysis may be referred as shifting funds analysis that can be used to determine the effect of shifting budget between different sub-areas. This is important in agency decision-making because shifting funds between budgets of different sub-areas can be controversial and may cause conflict between the sub-areas. Also, this kind of tradeoff analysis can present the effects of shifting funds and provides decision-makers a tool to calculate the benefit of one shifting funds strategy and an evidence to ascertain the true consequences of such actions in terms of each performance measure. The procedure is presented as Figure 5.10.

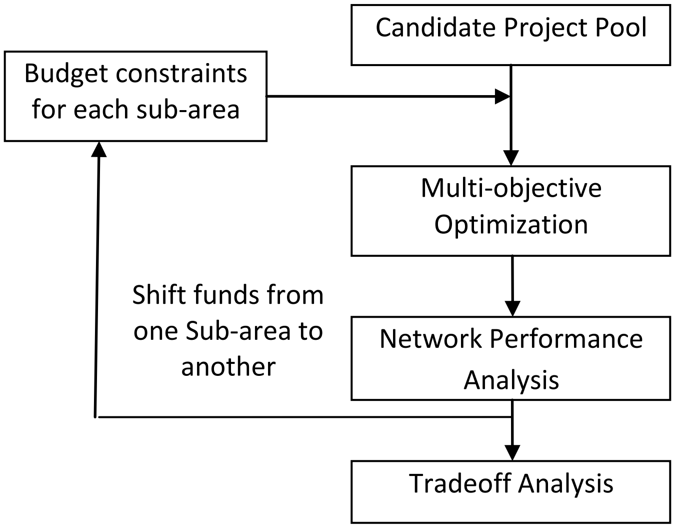


Figure 5.10: Procedure for Tradeoff Analysis between Sub-area Budgets

Fund shifting analysis can also be viewed as a kind of tradeoff between two performance measures. This is because in practice budget shifting comes from the concept of increasing one performance measure by the payment of decreasing another performance measure through shifting budgets. For example, if funds are transferred from pavement projects to safety projects, this will generally mean more safety projects and fewer pavement projects can be implemented leading to decrease pavement condition (increase in IRI) but increase in safety (decrease in crash rate).

Sections 5.4.1 to 5.4.4 discussed four types of tradeoff analyses. Theoretically, some of these are similar, such as the second and the fourth, but they have different applications in practice. These tradeoff methods can help decision-makers conduct analysis under different situations.

5.5 Multi-objective Optimization Solution Method

The final purpose for the project selection problem is to determine an optimal project selection set to be implemented. The tradeoff methods presented in previous sections help decision-makers figure out the relationships between performance measures, and between budget levels and performance. Thus, after a series of tradeoff analyses, there is still a need to choose an optimal solution. In the problem statement of the present study, each solution (i.e., project selection set) comes out with a vector ($npm_{i1}, npm_{i2}, \ldots, npm_{im}$) that represent the network performance of the implementation of a project selection set i . Decision-makers need to identify the best one from these vectors. Therefore this comes to the same problem as that stated in 5.4.1. In this respect, utility theory (Keeney and Raiffa, 1976) is applied to scale and combine the objectives using additive utility functions or multiplicative utility functions to form a single value that represents the desirability/impact of the project. Finally, the project selection set with the highest desirability is identified as the optimal solution (Li and Sinha, 2004).

5.6 Chapter Summary

This chapter first provides algebraic expressions for three types of commonly-used expressions of network-level performance. On the basis of these algebraic expressions of network-level performance measures, the formulation for the multi-objective optimization is presented with detailed statement of various constraints. A genetic algorithm is used to generate Pareto solutions of the multi-objective optimization, and tradeoff curves, tradeoff surfaces and scatterplot matrix are developed to visualize the Pareto frontiers. On the basis of visualized Pareto frontiers, four types of tradeoff analyses are developed. They are tradeoff between projects, tradeoff between performance measures, tradeoff between budget level and performance measures, and tradeoff between sub-area budgets. Finally, utility theory is adopted help decision-makers choose an optimal project selection set.

CHAPTER 6 TRADEOFF ANALYSIS METHODOLOGY UNDER UNCERTAINTY

In this chapter, the uncertainty issue in asset management is considered and the tradeoff analysis between benefit and risk is developed.

6.1 Uncertainty Considerations in Transportation Asset Management

In Chapter 5, various tradeoff methods were developed to help decision-makers conduct analysis for the multi-objective optimization problem. In these analyses, an important element is the network-level performance measure which is derived from project-level performance measures of each individual project on the highway network. During the decision-making process, these project-level performance measures need to be predicted using highway facility performance modeling. For example, unpredictable climate and traffic patterns could lead to deviations in deterioration rates from those predicted; differences in contractor quality can lead to different performance changes after a project, changes in the regional economy or gas price fluctuations may cause traffic volumes and speeds to be different from what was predicted prior to implementing a congestion mitigation project.

Thus, the methods proposed in Chapter 5 (where deterministic values were used for each performance measure) only yield deterministic outcomes for each project selection set. However, it is possible that a project set may have large benefits in terms of the performance measures but also may have a large uncertainty associated with these benefits.

To provide more robust results for tradeoff analysis and decision-making, it is important to incorporate uncertainty in the decision-making process. Uncertainty could exist in one of two forms: where the set of all possible outcomes of a performance measure is known and the probability distribution of these outcomes is also known; and where only part of all possible outcomes of an performance measure is known, but the probability distribution of such outcomes is not fully definable for a lack of reliable information (Young, 2001). The second type of uncertainty is often referred as total uncertainty. Li and Sinha (2003) proposed Shackle's model to deal with this kind of uncertainty where decisions were analyzed on the basis of surprise functions. In the highway transportation field, almost all consequences of interventions on key performance measures are known, even though their distributions may not be known. Thus, the second uncertainty case is not common in the highway transportation field and is not considered in the present study. This chapter focuses on the first type of uncertainty with a distribution for each performance measure that is calibrated using historical data on the performance measures.

In highway transportation, different performance measures may have different distributions. However, because the possible outcomes of most performance measures such as physical asset conditions, agency and user costs, travel speed, crash rates, etc. are bounded by non-negative minimum and maximum values and the distributions of the possible outcomes could be either symmetric or skewed, such characteristics can be modeled by the general beta distribution (Li and Sinha, 2004). The general beta distribution has four parameters: lower range (L), upper range (H), and two shape parameters referred to as α and β. The beta density function is given by:

$$f\left(x \middle| \alpha, \beta, L, H\right) = \frac{\Gamma(\alpha+\beta)\cdot(x-L)^{\alpha-1}\cdot(H-x)^{\beta-1}}{\Gamma(\alpha)\cdot\Gamma(\beta)\cdot(H-L)^{\alpha+\beta-1}} \quad (L \le x \le H) \tag{6-1}$$

Where:

L is the lower bound of x;

H is the upper bound of x;

α and β are shape parameters.

The Γ -function factors are used to normalize the distribution. The mean and variance for the beta distribution are:

$$\mu = \frac{\alpha}{\alpha+\beta} \text{ and } \sigma^2 = \frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}.$$

When $0<\alpha<\beta$, the mean converges to L and the distribution is skewed to the right;

When $0<\beta<\alpha$, the mean closes to H and the distribution is skewed to the left;

When $\alpha = \beta$ the distribution is symmetric.

In addition, for a given α/β ratio, the mean is a fixed value and the variance varies inversely with the absolute range of $\alpha + \beta$. Thus, increasing α and β by proportionate amounts will decrease the variance while keeping the mean constant. Conversely, decreasing α and β by proportionate amounts will cause the variance to increase while the mean remains unchanged (Li and Sinha, 2004). In practice, the skewness and variance can be categorized as high, medium or low based on the α and β. Table 6.1 presents the combinations of skewness and variance for beta distributions that best approximate the risk factor. Figure 6.1 provides the graphs for beta distributions (in Table 6.1) at medium and low levels.

Table 6.1: Approximate Values of Shape Parameters for the Beta Distributions (Li and Sinha, 2004)

Combination Type	Skewness	Variance	α	β
1	Skewed to the left	High	1.50	0.50
2	Symmetric	High	1.35	1.35
3	Skewed to the right	High	0.50	1.50
4	Skewed to the left	Medium	3.00	1.00
5	Symmetric	Medium	2.75	2.75
6	Skewed to the right	Medium	1.00	3.00
7	Skewed to the left	Low	4.50	1.50
8	Symmetric	Low	4.00	4.00
9	Skewed to the right	Low	1.50	4.50

For calibrating the beta distribution for each performance measure, historical data are used. For discrete performance measures, the beta distribution can also be used to establish an approximation of the outcomes.

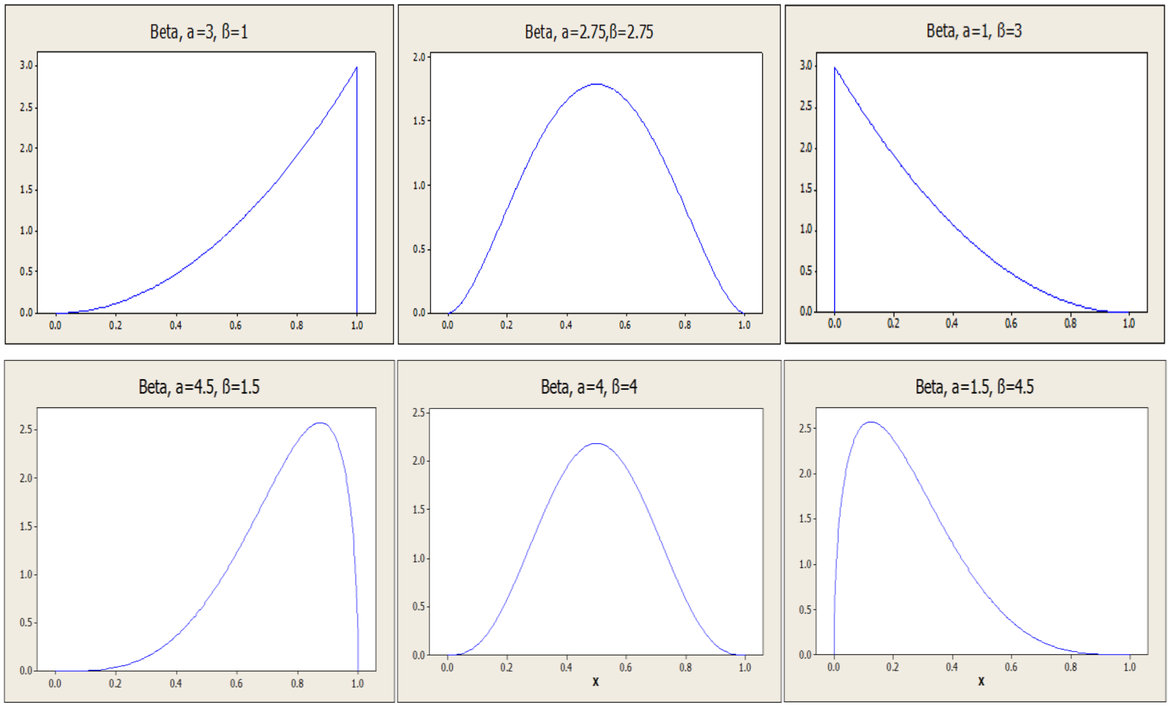


Figure 6.1: Examples of the Beta Distribution

6.2 Tradeoff Analysis under Uncertainty

In the problem statement for the present study, the objectives in the optimization process are derived from network-level performance measures which, in turn, are derived from project-level performance measures. The distribution of the project-level performance measures can be calibrated using the method described in the previous section. Then Monte Carlo simulation can be used to obtain the distribution for each network performance measure. For the four types of tradeoff analyses developed in Chapter 5, the expected value of network-level performance measure is used. For the final decision (i.e., project selection), there is a need to consider the risk of network performance measures to balance the benefit and risk.

As stated in Chapter 5, for the final decision, each project selection set has a vector with values for all the objectives. In order to compare these vectors, utility theory was used to form a single value that can represent the desirability or benefit (denote it as

Z_i for ith project selection set) of the implementation of a project selection set. The distribution of Z_i can also be derived from Monte Carlo simulation based on the distribution of different network performance measures. Then the following formulation can be used to conduct tradeoff analysis between benefit and risk (Gabriel et al., 2006).

$$Minimize \quad (1-w)E(Z_i) - wVar(Z_i) \tag{6-2}$$

Where

$E(Z_i)$ is the expected value of the benefit/desirability of project selection set i;

$Var(Z_i)$ is the variance value of the benefit/desirability of project selection set i;

w is the weight of risk that lies between 0 and 1. A larger weight w implies that the decision-makers is more concerned about the risk; while a smaller weight w implies that the decision-maker is more concerned about the expected benefit.

If $w = 0$, the decision-maker is not concerned about the risk and only pursues the alternative with the largest benefit.

If $w = 1$, the decision-maker is very concerned about the risk, and wants only to choose the alternative with the lowest risk.

The value of w can be derived from weighting survey with decision-makers as the respondents.

6.3 Chapter summary

This chapter first describes the source of uncertainty in highway asset management and points out that the forecast performance measures of each project after implementation has inherent uncertainty. Then a general distribution, beta distribution, is used to describe the various distributions of different performance measures. It is then shown that on the basis of these input distributions, the distributions of the outcomes, i.e., network-level performance measures can be generated using Monte Carlo simulation. Finally, a new tradeoff method is presented for conducting tradeoff analysis between risk and benefit.

CHAPTER 7 CASE STUDY

7.1 Problem and Data Description

Due to the limitations in data availability, hypothetical data are used to demonstrate the proposed study methodologies. We consider a small hypothetical network with twenty candidate projects (Table 7.1) involving four asset types: pavements, bridges, safety assets, and mobility (or congestion mitigation) assets. For each asset type, there are five locations where an intervention (project) is being considered. The table also presents the data on other facilities or locations on the network that are not being considered for any intervention. The decision-maker seeks the optimal set of projects on the basis of the following network-level performance measures: (a) average pavement condition measured using surface roughness or IRI; (b) bridge condition using bridge condition rating; (c) safety measured in terms of a network crash rate, and (d) total number of jobs created; (e) average remaining service life in years; and (f) mobility measured in terms of average travel speed. It is sought that the percentage of bridges above fair condition should be greater or equal to 5; and to maximize pavement and bridge condition, minimize crash rate and to maximize travel speed. There is a budgetary constraint and it is sought to maximize the overall performance in terms of the above performance measures.

Problem Formulation

On the basis of the network-level performance measures stated above, the following objectives are established:

- Minimize network average pavement IRI
- Maximize percentage of bridges above Fair condition (BCR $\geq$ 5)

- Maximize total number of created jobs
- Minimize network average crash rate
- Maximize average remaining service life (RSL)
- Minimize network average travel speed

Table 7.1: Project Information

Index	Projects	Project Type	Total Cost ($M)	Length (Mile)	AADT	Performance Measure											
						IRI (inches/mile)		BCR (Rating)		RSL (years)		Crash Rate (crashes / 100 million VMT)		Average Travel Speed (mph)		Number of Created Jobs	
						Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
1	Pavement Project 1	Rehabilitation	5.63	2.67	9336	231	78	--	--	--	--	156	124	40.5	45.51	--	102
2	Pavement Project 2	New construction	12.16	1.42	46272	--	60.2	--	--	--	--	--	100	--	46.7	--	161
3	Pavement Project 3	Rehabilitation	8.32	3.92	52272	204.6	68.6	--	--	--	--	148	119	32.8	38.76	--	70
4	Pavement Project 4	New construction	20.32	3.25	71354	--	58.8	--	--	--	--	--	98	--	40.97	--	450
5	Pavement Project 5	Rehabilitation	7.89	3.76	23511	208.8	72.8	--	--	--	--	138	113	26.8	39.82	--	118
6	Bridge Project 1	Rehabilitation	5.68	0.089	11321	--	--	2	8	--	--	132	112	49.2	52.16	--	56
7	Bridge Project 2	Rehabilitation	3.62	0.095	79074	--	--	5	8	--	--	126	102	27.7	36.68	--	50
8	Bridge Project 3	New construction	10.96	0.078	29806	--	--	--	9	--	--	--	98	--	46.24	--	284
9	Bridge Project 4	Rehabilitation	1.08	0.046	24846	--	--	4	7	--	--	128	96	56	59.02	--	27
10	Bridge Project 5	Rehabilitation	5.64	0.115	45856	--	--	3	6	--	--	146	103	30.3	34.31	--	95
11	Safety Project 1	Rehabilitation	6.46	3	69136	--	--	--	--	8	12	196	122	--	--	--	51
12	Safety Project 2	Rehabilitation	4.68	1.92	5101	--	--	--	--	6	10	184	118	--	--	--	16
13	Safety Project 3	Rehabilitation	7.65	3.83	77358	--	--	--	--	4	9	165	116	--	--	--	31
14	Safety Project 4	Rehabilitation	9.68	3.56	39483	--	--	--	--	6	10	170	120	--	--	--	40
15	Safety Project 5	New	6.12	2.52	79410	--	--	--	--	5	10	150	132	--	--	--	31
16	Congestion Project 1	New construction	18.42	3.07	115956	--	--	--	--	--	11	136	124	32	41	--	313
17	Congestion Project 2	New construction	17.5	1.25	98385	--	--	--	--	--	10	122	118	17.6	37.59	--	75
18	Congestion Project 3	New construction	26.6	2.32	118112	--	--	--	--	--	9	149	123	24.3	36.33	--	220
19	Congestion Project 4	New construction	19.1	3.82	111855	--	--	--	--	--	11	150	128	38.4	52.43	--	248
20	Congestion Project 5	New construction	25.05	3.21	106992	--	--	--	--	--	8	136	119	34.7	45.69	--	224

Hypothetical data for other highway facilities in the network

Total Pavement Length	20 mile	Average Pavement IRI	120 inches/ mile
Number of Bridge	10	Number of brides above fair condition	8
Number of Safety and congestion facilities	10	Average RSL of Safety and congestion facilities	8 year
Total AADT	600,000 vehicles/day	Average Crash Rate	140 crashed per 100 million VMT
Average Travel speed	30 miles /hour		
Total Budget	$ 135 Million		

Note: "--" means not applicable; "Before" means the performance measure value before the project is implemented and "after" means performance measure value after the project is implemented.

Objective functions

The above seven objective functions are then formulated as follows:

$$\text{Min} \quad \text{IRI}_{\text{Average}} = \frac{\sum_{\text{i}=1}^{\text{n}_0} IRI_{\text{i}} L_i + \sum_{\text{i}=1}^{\text{n}_{\text{imp}}} (1-x_i) IRI_i^0 L_i + \sum_{\text{i}=1}^{\text{n}_{\text{imp}}} \text{x}_{\text{i}} IRI_i^1 L_i + \sum_{\text{i}=1}^{\text{n}_{\text{new}}} \text{x}_{\text{i}} \text{I}RI_{\text{i}} L_i}{\sum_{\text{i}=1}^{\text{n}_0} L_i + \sum_{\text{i}=1}^{\text{n}_{\text{imp}}} L_i + \sum_{\text{i}=1}^{\text{n}_{\text{new}}} x_i L_i}$$

$$\text{Max} \quad \text{BCR}_{\text{Percentage}} = \frac{\sum_{\text{i}=1}^{\text{n}_0} Y_{\text{i}} + \sum_{\text{i}=1}^{\text{n}_{\text{imp}}} Y_i^1 - \sum_{\text{i}=1}^{\text{n}_{\text{imp}}} (1\text{-}\text{x}_{\text{i}}) Y_i^0 + \sum_{\text{i}=1}^{\text{n}_{\text{new}}} \text{x}_{\text{i}} Y_{\text{i}}}{\text{n}_0 + \text{n}_{\text{imp}} + \sum_{\text{i}=1}^{\text{n}_{\text{new}}} x_i}$$

$$\text{Max} \quad \text{Total Jobs} = \sum_{\text{i}=1}^{\text{n}_{\text{imp}} + n_{new}} \text{x}_{\text{i}} Job_i$$

$$\text{Min} \quad \text{CR}_{\text{Average}} = \frac{\sum_{\text{i}=1}^{\text{n}_0} \text{C}R_{\text{i}} VMT_i + \sum_{\text{i}=1}^{\text{n}_{\text{im}}} (1\text{-}\text{x}_{\text{i}}) \text{C}R_i^0 VMT_i + \sum_{\text{i}=1}^{\text{n}_{\text{imp}}} \text{x}_{\text{i}} CR_i^1 VMT_i + \sum_{\text{i}=1}^{\text{n}_{\text{new}}} \text{x}_{\text{i}} \text{C}R_{\text{i}} VMT_i}{\sum_{\text{i}=1}^{\text{n}_0} VMT_i + \sum_{\text{i}=1}^{\text{n}_{\text{imp}}} VMT_i + \sum_{\text{i}=1}^{\text{n}_{\text{new}}} x_i VMT_i}$$

$$\text{Max} \quad \text{RSL}_{\text{Average}} = \frac{\sum_{\text{i}=1}^{\text{n}_0} RSL_{\text{i}} + \sum_{\text{i}=1}^{\text{n}_{\text{im}}} (1-x_i) RSL_i^0 + \sum_{\text{i}=1}^{\text{n}_{\text{imp}}} \text{x}_{\text{i}} RSL_i^1 + \sum_{\text{i}=1}^{\text{n}_{\text{new}}} \text{x}_{\text{i}} RSL_{\text{i}}}{\text{n}_0 + \text{n}_{\text{imp}} + \sum_{\text{i}=1}^{\text{n}_{\text{new}}} x_i}$$

$$\text{Max Speed}_{\text{Average}} = \frac{\sum_{\text{i}=1}^{\text{n}_0} Speed_{\text{i}} AADT_i + \sum_{\text{i}=1}^{\text{n}_{\text{imp}}} (1-x_i) Speed_i^0 AADT_i - \sum_{\text{i}=1}^{\text{n}_{\text{imp}}} \text{x}_{\text{i}} Speed_i^1 AADT_i + \sum_{\text{i}=1}^{\text{n}_{\text{new}}} \text{x}_{\text{i}} Speed_{\text{i}} AADT_i}{\sum_{\text{i}=1}^{\text{n}_0} AADT_i + \sum_{\text{i}=1}^{\text{n}_{\text{imp}}} AADT_i + \sum_{\text{i}=1}^{\text{n}_{\text{new}}} x_i AADT_i}$$

Where $\text{IRI}_{\text{Averag}e}$ is the average IRI in the entire network;

IRI_i is the IRI of pavement segment *i* in the network;

$IRI_i^{\,0}$ is the pre-project IRI of pavement segment *i* in the candidate pool;

$IRI_i^{\,1}$ is the estimated post-project IRI of pavement segment *i* in the candidate pool;

L_i is the length of pavement segment *i*;

$\text{BCR}_{\text{Percentage}}$ is the percentage of bridges above the fair condition (BCR > 5);

$Y_i = 1$ if the condition rating of bridge *i* is ≥ 5, otherwise 0;

$Y_i^0 = 1$ if the pre-project condition rating of bridge *i* in the candidate pool is ≥ 5, otherwise 0;

$Y_i^1 = 1$ if the estimated post-project condition rating of bridge *i* in the candidate pool ≥ 5, otherwise 0;

Job_i is the number of new jobs that project *i* (in the candidate projects) generates;

$CR_{Average}$ is the average crash rate of the entire network;

CR_i^0 is the pre-project crash rate of project *i* (in the candidate pool);

CR_i^1 is the estimated post-project crash rate of project *i* (in the candidate pool);

VMTi is the Vehicle Mile Traveled on road segment *i*;

$RSL_{Average}$ is the average remaining service life of safety and congestion facilities in the whole network;

RSL_i^0 is the current RSL project *i* (in the candidate pool) ;

RSL_i^1 is the estimated post-project RSL of project *i* (in the candidate pool);

$speed_{Average}$ is the average travel speed in the entire network;

$speed_i^0$ is the pre-project average travel speed on project *i* (in the candidate pool);

$speed_i^1$ is the estimated post-project average travel speed at project *i* (in the candidate pool);

$AADT_i$ is the Annual Average Daily Traffic volume on road segment *i*.

The meanings of the rest of the variables in above equations are explained in the Table 5.1 and in the notations for Equation (5-1) and Equation (5-2).

Constraints

With regard to the budgetary constraints in this case study, only the overall budget constraint ($135 million) is considered. Thus, the constraint is:

$$\sum_{i=1}^{n_{imp}+n_{new}} x_i c_i \leq B$$

Where c_i is the cost of candidate project i and x_i is the decision variable.

7.2 Tradeoff Analysis

7.2.1 Tradeoff between Alternative Individual Projects

As stated in Chapter 5, when there is a need to compare two individual projects, each of the two projects should be put into all the other selected projects to form two project selection sets. Then the comparison is conducted between the two project selection sets. Consider, for example, the case where decision-makers want to compare Pavement Project 3 and Congestion Project 1 in Table 7.1. Assume the following project are already been decided to be implemented: Pavement Project 2 & 5 , Bridge Project 2, Safety Project 2 & 5, Congestion Project 2, 3, 4, and 5 . Then put Pavement Project 3 and Congestion Project 1 into the selected projects and form two groups of projects. The network performances of these two sets of projects are presented in Table 7.2.

Table 7.2: Network Performance of Two Sets of Projects

Network Performance	Group 1 (Contain Pavement Project 3)	Group 2 (Contain Congestion Project 1)
Average IRI	114.728	131.508
Percentage Of Bridges Above Fair Condition (BCR ≥ 5)	0.64286	0.64286
Total Number Of Created Jobs	8.21053	8.35
Network Average Crash Rate	149.699	138.42
Average Remaining Asset Service Life	36.1501	36.6557
Average Travel Speed	1213	1456

Now we need to compare the two vectors that contain two sets of network performance in the above table. Utility theory is employed to transform the multiple objectives function to yield a function that has a single objective. The following additive utility function is applied.

$$U = \sum_{i=1}^{n} w_i u_i (PM_i)$$

Where U is the final utility of a decision; $u_i(PM_i)$ is the utility function of network performance measure PM_i, w_i is the weight of of network performance measure PM_i.

For the utility function $u_i(PM_i)$ of each objective, functions from a previous study (Li and Sinha, 2004) can be applied:

$$U(\mathrm{IRI}_{\mathrm{Average}}) = 1.0729 \times e^{0.000044 IRI^2}\ ; \qquad U(\mathrm{RSL}_{\mathrm{Average}}) = 1.1659 \times (1 - e^{-0.0195 RSL^2})\ ;$$

$$U(speed) = 1.0425 \times (1 - e^{-0.0005 Speed^2})\ .$$

Assume other utility functions are U ($Jobs$) = $Jobs$/3,000, $U(BCR_{\text{Percentage}})= \text{BCR}_{\text{Percentage}}$,

$$U(CR_{Average}) = 1.0425 * e^{-0.00012(CR-80)^2}$$

In addition, the study team conducted a weighting survey in 2008 on the JTRP highway asset management study which provided the weights w_i that are used in this case study. The weights of the performance measures/objectives are listed in Table 7.3. By using the utility function, the final results are presented in Table 7.4.

Table 7.3: Weights of Performance Measures

Index	Performance Measures	Weights
1	Average IRI	0.175
2	Percentage Of Bridges Above Fair Condition (BCR ≥ 5)	0.175
3	Average Remaining Asset Service Life	0.175
4	Network Average Crash Rate	0.22
5	Average Travel Speed	0.165
6	Total Number Of Created Jobs	0.09
Total		1.0

Table 7.4: Comparison Results

Index	Alternative groups	Utility
1	Set 1 (Contain Pavement Project 3)	0.614
2	Set 2 (Contain Congestion Project 1)	0.632

It is seen that group 2 has higher utility, so congestion project 1 is preferred to pavement project 3.

The above example is the comparison between two individual projects. If we compare two sets of projects, the basic method is the same, and is achieved by a simple replacement of the two individual projects by two sets of projects.

7.2.2 Tradeoff between Performance Measures

Following the procedure presented in Chapter 5, Pareto solutions of the multi-objective optimization problem are first generated. Then tradeoff analyses were conducted based on these Pareto solutions. Figure 7.1 presents the three-dimension tradeoff surface between crash rate, average travel speed and the total number of created jobs.

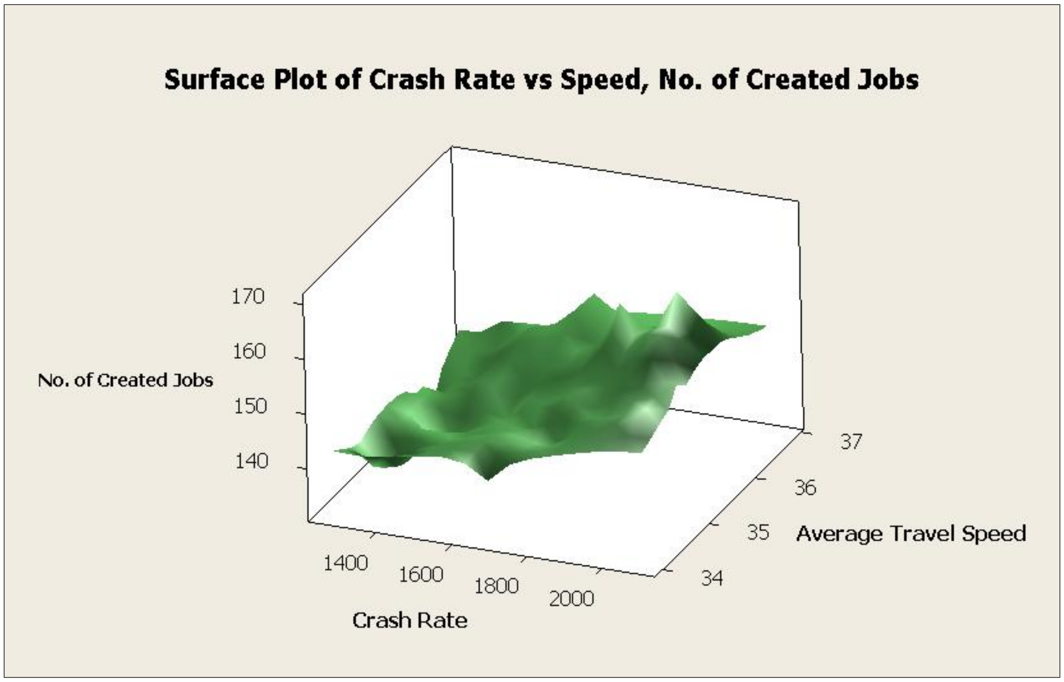


Figure 7.1: Tradeoff Surface for Performance Objectives involving Crash Rate, Average Travel Speed and the Total Number of Jobs Created

It can be seen that the solution surface shown in Figure 7.1 is not smooth. This may be due to the small number of candidate projects in this example, thus there were inadequate points for obtaining a smooth surface. However, using the figure, it is clear that when the crash rate increases, the number of created jobs generally increases. This is obviously because the safety projects in the data created relatively fewer jobs than others. When the budget is fixed and fewer safety projects are implemented, the crash rate will be higher; but the “saved” funds could be used to implement other projects to yield enhanced levels of other measures of performance such as job creation.

If we seek to analyze the tradeoffs among four performance measures, a scatterplot matrix is needed. For example, Figure 7.2 shows the tradeoff between IRI, crash rate, average travel speed, and the total number of created jobs.

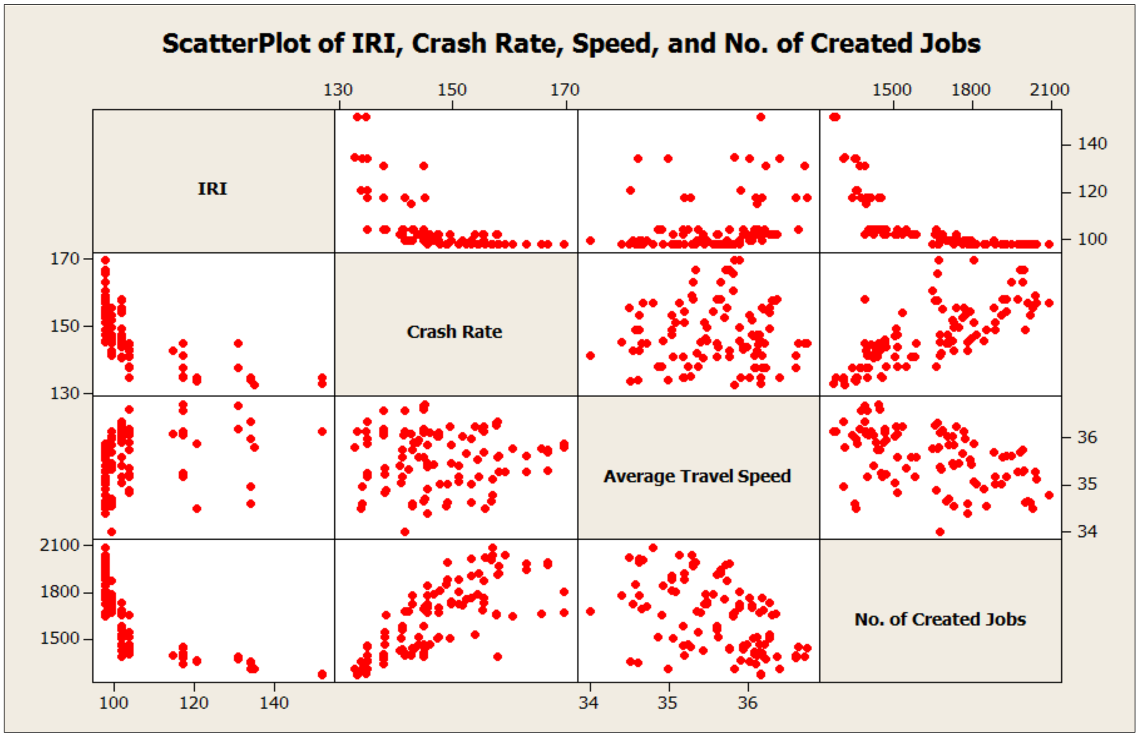


Figure 7.2: Scatterplot Matrix for Tradeoff between Pavement Condition, Crash Rate, Average Travel Speed, and the Total Number of Jobs Created

Figure 7.1 and 7.2 show some relationships between the performance measures. These relationships are only approximate and may not be used for quantitative analysis. As stated previously, the most common tradeoffs are between two performance measures as illustrated in Figures 7.3 to 7.6. In these figures, the stacked lines can be used to calculate the tradeoff ratio between two adjacent points; and the broken-line curves are the pseudo-tradeoff curves. From Figure 7.3, it is seen that when the IRI increases, the crash rate decreases. This is because greater spending to implement safety projects reduces the available funding for the pavement budget, and thus crash rate is reduced at the expense of pavement condition. A similar relationship can be found in Figure 7.4 – when the total budget if fixed and more funds are used to increase mobility at the expense of safety budget, the crash rate increases due to fewer funds for safety projects.

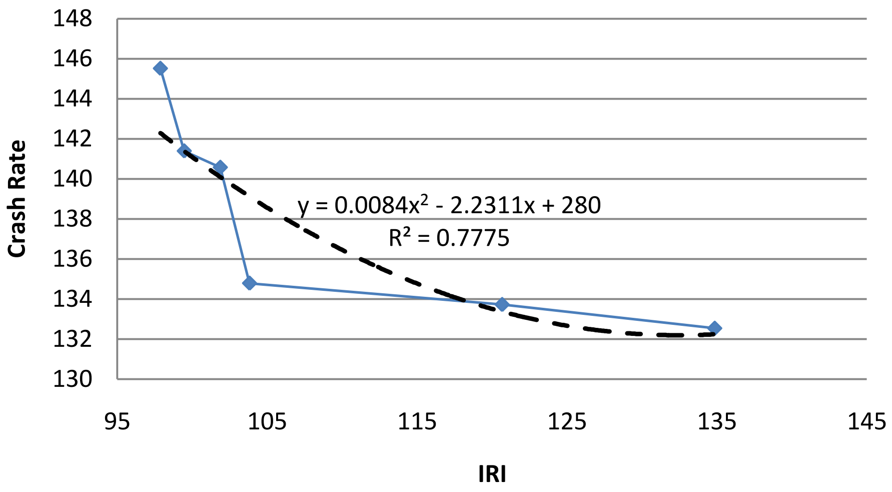


Figure 7.3: Tradeoff between Pavement Condition and Crash Rate

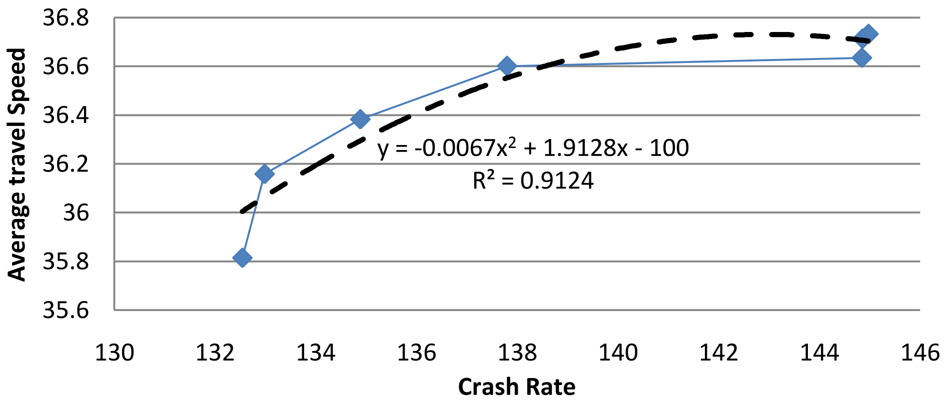


Figure 7.4: Tradeoff between Average Travel Speed and Crash Rate

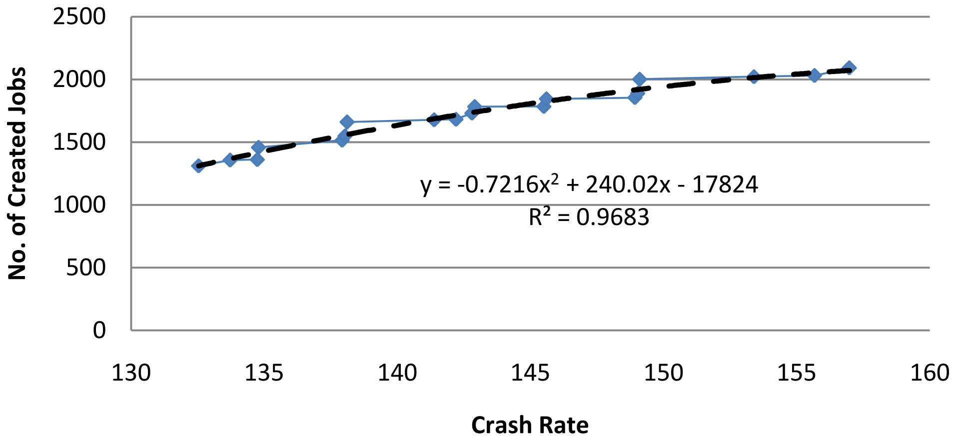


Figure 7.5: Tradeoff between Crash Rate and Number of Jobs Created

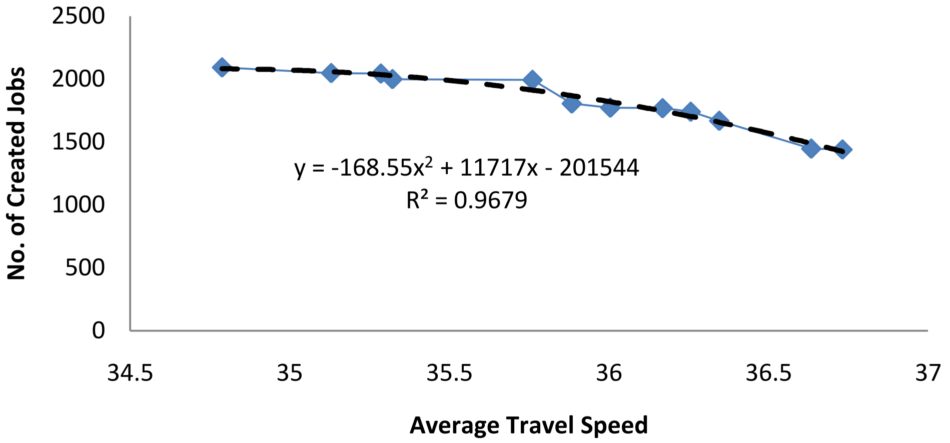
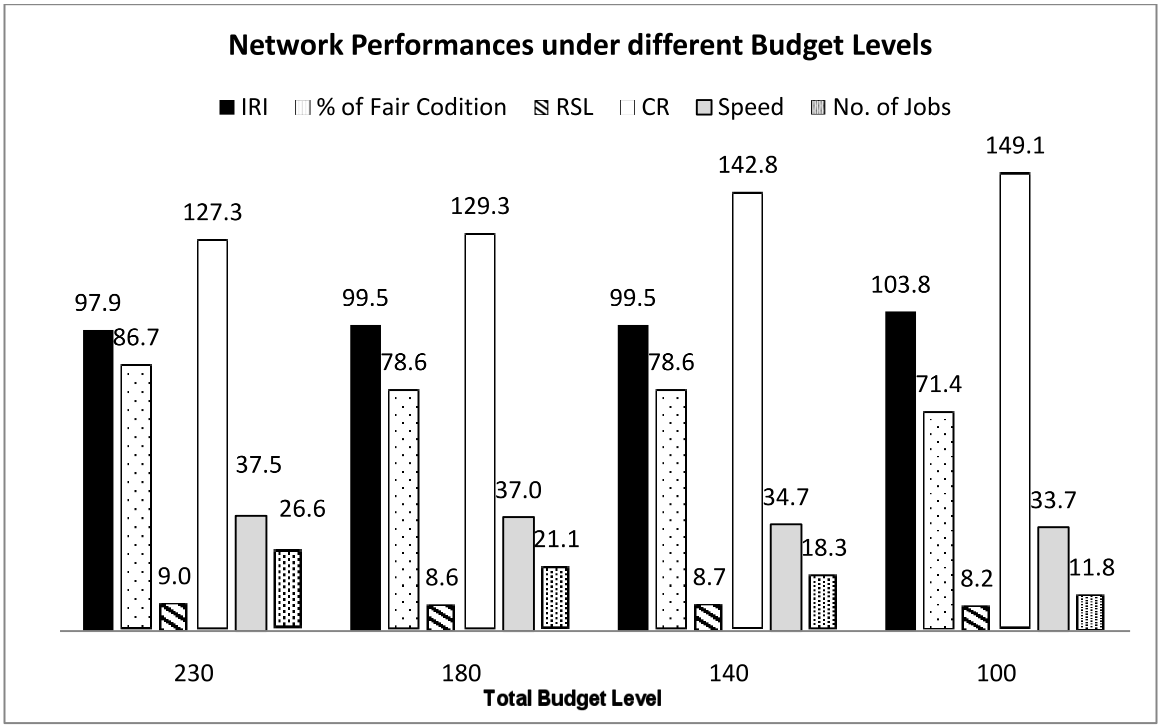


Figure 7.6: Tradeoff between Number of Jobs Created and Average Travel Speed

7.2.3 Tradeoff between Budget Level and Performance Measures

In this example, the cost for the implementation of all the projects is 222.6 million dollars. Figure 7.7 presents the network performance under different budget levels. In this figure, it can be observed that when the total budget decreases, all the performance measures are degraded considerably: average pavement condition decreases (that is, IRI increases), crash rate increases, average travel speed decreases, and total number of created jobs decreases.



Note:
IRI—Average Pavement Condition in units of International Roughness Index (inches/mile);
% of Fair condition —the percentage of bridges above fair condition (bridge condition rating ≥ 5);
RSL—Average Remaining service life (years); CR—Crash Rate (number of crashes per 100 million VMT);
Speed— Average travel speed (miles/hour); Nr. of Jobs— Total number of created jobs (in 100's).

Figure 7.7: Tradeoff Analysis between Budget Level and Performance Measures

7.2.4 Tradeoff Analysis between Sub-area Budgets

The effects of funds shifting can be reflected by network performance measures, especially the core performance measures of the funds shifting related sub-areas. The total budget in this example is \$135 M. Assume the combined budget for pavement and safety projects is \$60 M. Also, assume that the asset manager can shift this amount as desired between these two sub-areas. The fund shifts and the corresponding core performance measures are presented in Table 7.5.

Table 7.5: Analysis of Shifting Funds between the Safety and Pavement Sub-areas

Pavement Budget ($M)	55	50	35	25
Safety Budget ($M)	5	10	25	35
Crash Rate (Crashes/100 million VMT)	97.87	99.46	101.87	103.82
Average IRI (inches/mile)	156.82	149.78	144.57	143.57

Table 7.5 provides the values of the core performance measures (crash rate and pavement condition) for different distributions of the budget across the two sub-areas. The relationship of crash rate and pavement condition is presented in Figure 7.8 with a regression equation.

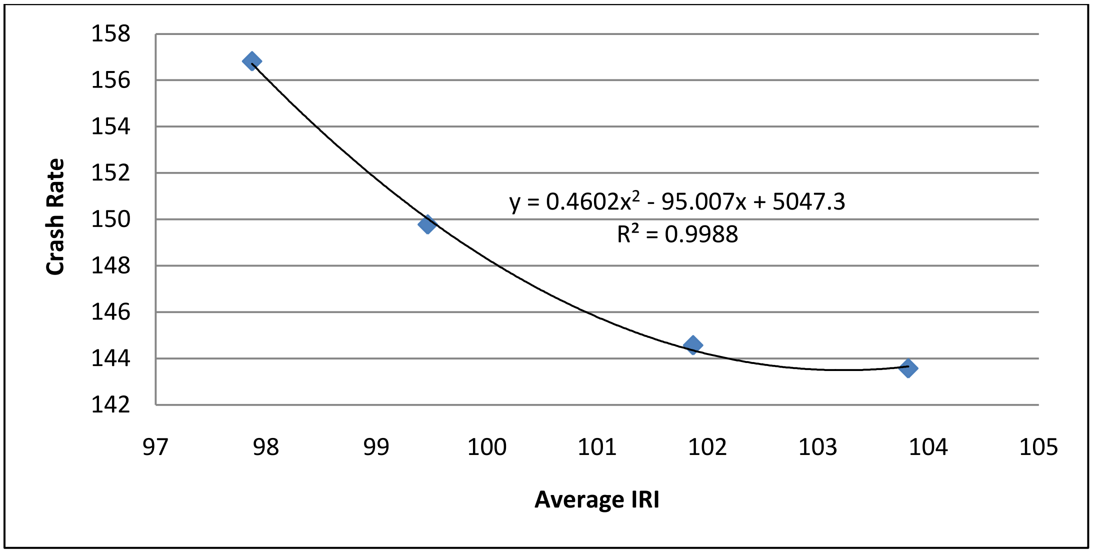


Figure 7.8: Shifting-Fund Analysis between Safety and Pavement Sub-areas

7.2.5 Tradeoff Analysis under Uncertainty

In the uncertainty situation, the distributions of performance measures need to be calibrated by historical data and then Monte Carlo simulation could be adopted to generate distribution for network performance measures. For the previous four types of tradeoff analyses, the deterministic value can be replaced by the mean value of each performance measure to conduct tradeoff analysis in uncertainty situation. Tradeoff analysis between benefit and risk can be conducted on the basis of the mean and variance of each network performance measure. Due to unavailability of data for calibrating the distribution of performance measure, the tradeoff analysis for these performance measures is not carried out for this case study. However, the methodologies developed in Chapter 6 are generally expected to work very well in practice for these performance measures.

7.3 Solution of the Multi-objective Optimization Problem

From the tradeoff analyses, the decision-maker acquires a general perspective of the possible optimal solutions, and might choose some solutions from the Pareto frontier and then determine the optimal solution from this set. This section presents a general optimization method that could be applied with or without tradeoff analyses. The basic idea is the same as that provided in Section 7.2.1. Also, the same utility functions in Section 7.2.1 are used to produce the final utility for each possible solution. Using GAMS software, the optimization problem was solved. The final network performance corresponding to the optimal solution is presented in Table 7.6. Furthermore, the optimization using the traditional method (Li and Sinha, 2004) is then conducted for comparison purposes. The network performance utility associated with the optimal solution for the traditional method is calculated by using the same formula as that used in the proposed method and by applying the network performance value from the results of the traditional method. The results are shown in Table 7.6.

Table 7.6: Network Performance Measures Comparison

Network performance Measure	**Network performance (proposed method)**	**Network performance (traditional method)**
Average IRI (inches/mile)	103.82	120.67
Percentage of BCR ≥ 5 (%)	71	71
Average RSL (years)	8.53	9.00
Crash Rate (crashes per 100 million VMT)	134.83	139.86
Average Speed (mph)	34.72	35.40
Total Jobs	1435.00	1278.00
Total utility	**0.677**	**0.654**
Number of selected projects	11	13
Actual Cost	132.32	133.31

Table 7.6 shows that the proposed method selects 11 projects while the traditional method selects 13 projects. The final utility of solution from proposed method exceeds that from the traditional method. Also, the results show that neither solution dominates each other in terms network performance measures. The total costs of two cases are almost same. Hence, it can be seen that by using the proposed method, the optimal solution is superior to that of the traditional method in terms of the overall network performance. This example is shown for a simple network. For larger highway networks, the benefits (difference in performance) could be far more significant.

In the uncertainty case, the objective function (Equation 6-2) should be used to balance the risk and benefit. Due to the data availability for calibrating the distribution of performance measure and time constraints in programming Monte Carlo simulation in multi-objective optimization problem, this case study does not provide an optimal solution that balances the risk and benefit. A future study could address this issue.

7.4 Chapter Summary

This chapter provides a case study based on hypothetical data to demonstrate the tradeoff analysis methodologies developed in previous chapters. Four types of tradeoff analyses were conducted and the results showed that these tradeoff methods can provide powerful tool to help decision-makers in the project selection process. The case study also showed that the new project selection framework based on network-level performance measure can produce an optimal selection that is superior to that of the traditional solution framework.

CHAPTER 8 OVERALL SUMMARY AND CONCLUSIONS

Due to ongoing developments in the transportation sector, such as increasing travel demand, aging highway facility, and shrinking transportation funding sources, transportation agencies seek to maximize the use of available resources while providing acceptable levels of service to the facility users. The complexity of this problem is exacerbated by the multiplicity of stakeholders and the specter of uncertainty regarding project outcomes. As such, there is a need for asset managers to consider uncertainty and multiple-criteria concepts in the decision-making process. As such, the asset management decision-making process has evolved into a complex multi-objective uncertainty-based optimization problem that involves the analysis of tradeoffs associated with the multiple performance measures.

Most of the traditional methods for multi-objective optimization for transportation use scalarization or utility theory to scale various performance measures to values with the same unit and then combine them together to form a single value that can represent the overall impact/benefit of each project. Then, on the basis of the single impact value of each project, the problem is treated as a single objective Knapsack problem and is solved by linear 0/1 programming. This research study shows that while this method is easy and straightforward, it loses some information during the scalarization process and does not always guarantee a truly optimal solution. This study provides a framework using the network-level performance measures as the final objectives, and transforms the classical problem to nonlinear 0/1 multi-objective optimization problem which avoids the shortcomings of the traditional methods.

Using the framework developed in earlier chapters of this report, various categories of tradeoff analyses were identified and established. The first step of tradeoff analysis is to find the Pareto solutions of the multi-objective optimization problem. In this study, Genetic Algorithm was adopted to generate Pareto solutions. The Pareto solutions were then visualized by plotting tradeoff curves for two dimension cases, tradeoff surface for three dimension cases, and scatterplot matrix for four or more dimension cases. On the basis of these visualization methods, four types of tradeoff analyses were developed: (1) tradeoff between projects; (2) tradeoff between performance measures; (3) tradeoff between budget level and performance measures; and (4) tradeoff between sub-area budgets. For the uncertainty situation, Monte Carlo simulation was applied to generate the distribution of objectives and expected values were adopted to conduct the above four types of tradeoff analysis. Also, a method was provided to conduct tradeoff analysis between risk and benefit and finally to determine the best solution that balances the risk and benefit.

Finally, a case study was developed to demonstrate the tradeoff methods proposed in this study. The result showed that these tradeoff methods can provide powerful tool for decision-makers to conduct analysis during the project selection process. The results also demonstrated that the new framework provides a solution that is superior to that of the traditional method.

REFERENCES

AASHTO (1997). 21st Century Asset Management. American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO (1999). Asset Management Peer Exchange: Using Past Experience to Shape Future Practice, Executive Workshop Proceedings, Scottsdale, AZ.

AASHTO (2006). Measuring Performance Among State DOTs. Washington, D.C.

AASHTO (2002). Transportation Asset Management Guide. American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO and FHWA (2007). U.S. Domestic Scan Program: Best Practices in Transportation Asset Management, SCAN-TOUR REPORT. Transportation Research Board, Washington, D.C.

Amekudzi, A. (1999). Uncertainty Analysis of National Highway Performance Measures in the Context of Evolving Analysis Models and Data. Ph.D. Dissertation, Carnegie Mellon University, Pittsburgh, PA.

APCC (2001). Asset Management. Australian Procurement and Construction Council, Australia.

Arakawa, M., H. Nakayama, I. Hagiwara, and H. Yamakawa(1998). Multi-objective Optimization using Adaptive Range Genetic Algorithms with Data Envelopment Analysis, in: A Collection of Technical Papers on Seventh Symposium on Multidisciplinary Analysis and Optimization (TP98- 4970), AIAA, Vol. 3, pp. 2074-2082.

ASCE (2009). 2009 Report Card for America's Infrastructure. American Society of Civil Engineers. Reston, VA.

Austroads (1997). Strategy for Improving Asset Management Practice, Sydney. (http://www.austroads.com.au/asset/mgmtstrategy.html) . Accessed September 18, 2009.

Bai, Q., S. Labi, and Z. Li (2009) Trade-Off Analysis Methodology for Asset Management. Technical Report, Joint Transportation Research Program, Purdue University. West Lafayette, IN.

Bernardin,V. , and P. Durango-Cohen (2006). Transportation Asset Management for Local Government Agencies: Threshold Levels and Best Practice Guide, Midwest Regional University Transportation Center, Madison, WI.

Branke, J., K. Deb, K. Miettinen, and R. Słowi´nski (2008). Multi-objective Optimization: Interactive and Evolutionary Approaches. Springer,Verlag Berlin Heidelberg, Germany.

Cambridge Systematics (2000). A Guide Book for Performance-Based Transportation Planning. NCHRP Report 446. National Academy Press, Washington, D.C.

Cambridge Systematics, Inc., PB Consult, Inc., and Texas Transportation Institute (2006). NCHRP Report 551: Performance Measures and Targets for Transportation Asset Management. Transportation Research Board, Washington, D.C.

Carnahan, J. V., W. J. Davis, M. Y. Shahin, P. L. Keane, and M. I. Wu (1987). Optimal Maintenance Decisions for Pavement Management. ASCE Journal of Transportation Engineering, 113(5), 554-572.

De Jong, K. A. (1975). An Analysis of the Behavior of a Class of Genetic Adaptive Systems. Ph.D. Thesis, University of Michigan, Ann Arbor, MI.

Deb, K., A. Pratap, S. Agarwal, and T. Meyarivan (2000). A Fast and Elitist Multi-Objective Genetic Algorithm: NSGA-II. Technical Report 200001, Indian Institute of Technology, Kanpur Genetic Algorithms Laboratory (KanGAL), Kanpur, India.

FHWA (1999). Asset Management Primer. FHWA-IF-00-010, U.S. Department of Transportation, Federal Highway Administration, Office of Asset Management, Washington, D.C.

FHWA (2000). Primer: GASB 34. FHWA, Office of Asset Management, Washington, D.C.

FHWA (2005). Transportation Asset Management in Australia, Canada, England, and New Zealand, FHWA-PL-05-019. Federal Highway Administration, Washington, D.C.

FHWA and AASHTO (1996). Asset Management: Advancing the State of the Art into the 21st Century Through Public-Private Dialogue. Federal Highway Administration and the American Association of State Highway and Transportation Officials, Washington, D.C.

Feighan, K. J., M. Y. Shahin, K. C. Sinha, and T. D. White (1988). An Application of Dynamic Programming and Other Mathematical Techniques to Pavement Management Systems. Transportation Research Record 1200, pp. 90-98.

Fonseca, C.M. and P. J. Fleming (1993). Genetic Algorithm For Multi-objective Optimization, Formulation, Discussion and Generalization, in: Proceedings of the 5th International Conference: Genetic Algorithms, pp. 416–423.

Gabriel, S.A., J. F.Ordóñez, and J. A. Faria (2006). Contingency Planning in Project Selection Using Multiobjective Optimization and Chance Constraints. Journal of Infrastructure Systems, Vol. 12, pp. 113-120

Haimes, Y. Y., and W. A. Hall (1974). Multi-objectives in Water Resource Systems Analysis: The Surrogate Worth Trade off Method. Water Resources Research, Vol. 4, pp.615-623.

Hening, M.I., and J.T. Buchanan (1997). Tradeoff Directions in Multi-objective Optimization Problems. Mathematical Programming, Vol. 78, pp. 357-374.

Holland, J. H. (1975). Adaptation in Natural and Artificial Systems. University of Michigan Press, Ann Arbor, MI.

Holland, J. H. (1992). Adaptation in Natural and Artificial Systems: An Introductory Analysis with Applications to Biology, Control, and Artificial Intelligence (Reprint Edition), MIT Press, Cambridge, MA.

Ingram, D. R. (1971). The Concept of Accessibility: A Search for an Operational Form. Regional Studies, Vol. 5, pp. 101–107.

Keeney, R. L., and H. Raiffa (1976). Decisions with Multiple Objectives: Preferences and Value Trade-Offs. Cambridge University Press, Cambridge, UK.

Lambert, J.H., K.D. Peterson, S.M. Wadie, and M.W. Farrington (2005). Development of a Methodology to Coordinate and Prioritize Multimodal Investment Networks, Tech. Rep. FHWA/VTRC 05-CR14, VTRC, Charlottesville, VA.

Li, Z., and K. C. Sinha (2009). Application of Shackle's Model and System Optimization for Highway Investment Decision Making under Uncertainty. ASCE Journal of Transportation Engineering, Vol. 135, No. 3, pp.129–139.

Li, Z., and K. C. Sinha (2004). Methodology for Multicriteria Decision Making in Highway Asset Management. Transportation Research Record 1885, pp. 79–87.

Li, Z., and K. C. Sinha (2004). Multicriteria Highway Programming Incorporating Risk And Uncertainty: A Methodology for Highway Asset Management System. Joint Transportation Research Program, Purdue University, West Lafayette, IN.

Li, Z., and M. Puyan (2006). A Stochastic Optimization Model for Highway Project Selection and Programming under Budget Uncertainty. Proceedings of the 9th International Conference on Applications of Advanced Technology in Transportation. Chicago, IL.

Meisel, W.S. (1973). Tradeoff decision in multiple criteria decision making. In: Cochrane, J., Zeleny, M. (eds.) Multiple Criteria Decision Making. University of South Carolina Press, Columbia. SC. pp. 461–476

Mrawira, D., and L. Amador (2009). Cross-Assets Trade-off Analysis: Why are we still talking about it? Proceedings, 88th annual meeting of the Transportation Research Board, Washington, D.C.

Nakayama, H., M. Yoon, and Y. Yun (2009). Sequential Approximate Multi-objective Optimization Using Computational Intelligence. Springer,Verlag Berlin Heidelberg, Germany.

OECD (2001). Asset Management for the Road Sector. Organization for Economic Co-Operation and Development, Paris, France.

Pagano, A. M., S. McNeil, and E. Ogard (2005). Linking Asset Management to Strategic Planning Processes: Best Practices from state departments of transportation. Transportation Research Record, 1924, pp.184-191.

Pareto, V. (1906). Manuale di Economia Politica. Societa Editrice Libraria, Milano, Translated into English by A. S. Schwier, Manual of Political Economy. Macmillan, NY.

Patidar,V., S. Labi, and K.C. Sinha (2007) Multi-Objective Optimization for Bridge Management Systems. NCHRP Report 590. Transportation Research Board, Washington, D.C.

Pryke, A., S. Mostaghim, and A. Nazemi (2007). Heatmap Visualization of Population Based Multi Objective Algorithms. In: Obayashi, S., Deb, K., Poloni, C., Hiroyasu, T., Murata, T. (eds.) EMO. LNCS, Vol. 4403, pp. 361–375. Springer, Heidelberg, Germany.

Saito, M., and K.C. Sinha (1989). The Development of Optimal Strategies for Maintenance, Rehabilitation and Replacement of Highway Bridges, Final Report Vol. 5: Priority Ranking Method, Joint Highway Research Project, W. Lafayette, IN.

Sakawa, M, and H. Yano (1990). Trade-Off Rates in the Hyperplane Method for Multi-objective Optimization Problems. European Journal of Operational Research. Vol.1, pp. 105-118.

Shaw, T. (2003). Performance Measures of operational effectiveness for highway segments and systems: A Synthesis of Highway Practice. NCHRP Synthesis 311. Washtington, D.C.

Speicher, D., M. Schwartz, and T. Mar (2000). Prioritizing Major Transportation Improvement Projects – Comparison of Evaluation Criteria, Transportation Research Record 1706, Washington, D.C., pp. 38-45.

Trinkaus, H. L., and T. Hanne (2005). Knowcube: A Visual and Interactive Support for Multicriteria Decision Making. Computers and Operations Research 32, pp.1289–1309.

Tsamboulas, D., G.S. Yiotis, and K.D. Panou (1999). Use of Multicriteria Methods for Assessment of Transport Projects. ASCE Journal of Transportation Engineering , Vol 125, pp. 407-414.

Tsao, H. J., and R.W. Hall (1997). Safety and Efficiency Tradeoff Analysis for Automated Highway System. Part 3, Longitudinal Separation on AHS: A Trade-Off Between Collision Probability/Severity and Capacity. Partners for Advanced Transit and Highways. Caltrons, Sacramento. CA.

Turner, S. M., M. E. Best, and D. L. Shrank (1996). Measures of Effectiveness for Major Investment Studies, Tech. Rep. SWUTC/96/467106-1, Southwest Region University Transportation Center, Texas Transportation Institute, College Station, TX.

Young, R.A. (2001). Uncertainty and the Environment: Implications for Decision Making and Environmental Policy. Edward Elgar, Cheltenham. UK.

Younger, K. (1994).Multimodal Project Evaluation: A Common Framework, Different Methods, Transportation Research Record 1429, pp. 24-29.

Yun, Y.B., H. Nakayama,T. Tanino, and M. Arakawa (2001). Generation of Efficient Frontiers in Multi-Objective Optimization Problems by Generalized Data Envelopment Analysis. European Journal of Operational Research 129(3):586–595.

Webster (2009).Webster's Online Dictionary. http://www.websters-online-dictionary.org. Accessed September 28, 2009

Winston, W.L., M. Venkataramanan, and J.B. Goldberg (2002). Introduction to Mathematical Programming. Books/Cole-Thomson Learning, Pacific Grove, CA.