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Improving ITS Planning with Multicriteria Decision Analysis

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Improving ITS Planning with Multicriteria Decision Analysis

by

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Dissertation

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Doctor of Philosophy

The University of Texas at Austin

December 2005

Dedication

This work is dedicated with love and gratitude to my father, Zepei Wang, my mother Shaolan Deng and my wife Xiaoxia Gao

Acknowledgements

I wish to express my deepest appreciation to my dissertation supervisor, Dr. C. Michael Walton, for all of the support and mentorship that he has provided me during my time here at the University of Texas at Austin. It has been an honor, a pleasure, and a blessing to have the opportunity to work with him. I would like to thank my committee member Professors Randy B. Machemehl, Chandra R. Bhat, Leon S. Lasdon, and David R. Maidment for their insights and valuable suggestions to this work. The author also is very grateful to Brian Burk and the Texas Department of Transportation, and Daniel Yang and Capital Area Metropolitan Planning Organization for their provision of data and other support. My special thanks go to Nicolas E. Lownes for the precious friendship and for his sincere and generous support; to Vicki L. Simpson for all of the assistance she provided during these years. Last but not least, I am indebted to my wife Xiaoxia, my parents Zeipei and Shaolan, and my parents-in-law JinXuan and Weiyuan. Without their support and encouragement, I would never finish this work. I shall make it up to them during my lifetime.

IMPROVING ITS PLANNING WITH MULTICRITERIA DECISION ANALYSIS

Publication No._____________

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The University of Texas at Austin, 2005

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Intelligent Transportation Systems (ITS) planning is characterized by making decisions on various ITS strategies. Since the state-of-the-art in ITS planning still falls short of developing ITS plans in a systematic manner, research is needed to understand, formulate, and solve the two major problems identified in ITS planning. Specifically, at the "strategic" level, an innovative approach will be developed to screen the ITS market packages that best address local needs and local transportation problems. At the "executive" level, an appropriate approach will be developed to identify the ITS deployments that are most beneficial to the planning area.

In this dissertation, a multi-attribute utility theory (MAUT) model was first constructed and validated for ITS market package screening. ITS market packages were ranked using the values of aggregated utilities and sensitivity analyses were

conducted to examine how changes in performance measure weights affect the final ranking results. In addition, uncertainties that may influence the final outcomes were further investigated. A comparative study of an original MAUT model and a MAUT model integrating uncertainties indicates that uncertainties can affect the final rankings of the alternatives.

Secondly, an ELECTRE method was proposed to address problems resulting from comparing various ITS deployments. A modified ELECTRE-I method was developed to compare a number of ITS alternatives with respect to multiple objectives. By varying the weighting scheme to favor different criteria and performing a sensitivity analysis, the nondominated alternative was identified. A comparative study was conducted on the MAUT and ELECTRE methods. It was found that the MAUT approach and the ELECTRE method can both be applied to ITS deployment comparison problems. In some cases, the differences between them make one more suitable than the other in some cases. Based on the comparative study recommendations were made regarding the application of MAUT and ELECTRE to the decision analysis in ITS planning.

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Chapter 1 Introduction

1.1 RESEARCH MOTIVATION

As defined by the U.S. Department of Transportation (USDOT), Intelligent Transportation Systems (ITS) apply "well-established technologies in communications, control, electronics and computer hardware and software to improve surface transportation system performance". With the implementation of ITS technologies, the interfaces between drivers, vehicles, and roads will be improved so that transportation system will become safer, more efficient, more reliable, and more environmentally friendly.

Since the enactment of the Intermodal Surface Transportation Efficiency Act (ISTEA) in 1991, ITS have been widely supported by federal, state and local governments to alleviate current surface transportation problems. In the early stages of implementation in the 1990s, the interest in ITS program had been generally stimulated by federal funding, rather than through a systematic planning process. For example, in 1996, the USDOT chose the Phoenix, San Antonio, Seattle, and New York/New Jersey/Connecticut areas to lead a program to showcase deployments of ITS. This USDOT funded program, termed the Metropolitan Model Deployment Initiative (MMDI), marked a significant step in the development of ITS in the United States. With this approach, varieties of innovative ITS applications were generated in safety, traffic operations, transit operations, emergency management, and other transportation areas. However, due to the emphasis on the functionality of technological components and lack of a systematic planning approach at that time, the developments of these pilot or showcase programs somehow were not always clearly associated with local transportation problems or local user needs (USDOT, 1997).

Recognizing the importance of system planning, the Federal Highway Administration (FHWA) subsequently invested extensive effort and resources in ITS planning since mid-1990s. Various planning methods and tools have been proposed to create a basic understanding of the planning characteristics. Some planning frameworks (e.g., the National ITS Architecture and the FHWA ITS Planning Process) have been widely adopted by both public and private sectors in developing local and regional ITS plans.

These efforts have significantly improved ITS planning, from the strategic level to the more detailed executive level. However, many issues still remain unaddressed. For example, the FHWA ITS Planning Process only provides a conceptual framework to develop a strategic ITS plan. The approach to complete each task is not provided, which leaves not only substantial difficulties to ITS planners in practice, but also tremendous research opportunities for the modeling in ITS planning. Although some studies have been performed to solve these problems, the state-of-the-art still falls short of developing ITS solutions in a systematic manner, especially in the following two areas:

1) *Develop a strategic ITS market package plan based on local transportation problems and needs.*

A market package represents a group of ITS equipment capabilities that, when combined, deliver a specific transportation service. The National ITS Architecture defines the purpose of market packages in addressing specific services that might be required by traffic managers, transit operators, travelers, and other ITS stakeholders. In the ITS strategic planning process, selection of appropriate market packages is a central element. It serves as a bridge to link the high-level ITS user services identified through the visioning exercise with more detailed functional, operational, and organizational considerations necessary for successful ITS deployment.

To develop an ITS market package plan, planners usually complete market package screening by mapping the benefits of market packages with defined local ITS goals. The market packages that show high benefits in achieving the defined system goals are selected for implementation. Sadek et al. *(2001)* have introduced this heuristic approach in detail through a case study in a medium-sized area.

The advantage of this approach is that it makes market package screening straightforward and easy to follow. However, ITS planners may face challenges and difficulties from having multiple system goals and multiple options - a normal aspect of ITS planning. Given this situation, simply mapping the benefits of market packages may not yield the optimal ITS market package plan. The results provide no evidence to define ITS market package priority settings. The screening of ITS market packages has been more difficult to analyze than one may have desired. In addition, transportation investments are generally affected by budget limitations and a complex political environment (Khattak and Kanafani, 1996), as are ITS investments. An optimal ITS market package plan is desired in order to maximize the system benefits. Keeping in mind that ITS market packages screening is one of the initial steps in ITS system planning, as well as the foundation of the ITS implementation plan, the author believes that using innovative methods to identify the best market package plan will significantly enhance the positive impact of ITS investments.

2) *Identify the ITS deployments that are most beneficial to the planning area.*

Once an ITS market package plan is developed, local ITS agencies can then identify the ITS components that can be implemented to meet the local transportation needs and solve local transportation problems. However, identifying the ITS components to be implemented is not the final stage of ITS planning. ITS agencies must develop a deployment plan that translates the market package plan into "implementable" ITS deployments. The development of an ITS deployment plan includes providing the definition of ITS strategies and deployment locations. Various ITS deployments must be defined, evaluated, compared, and selected for implementation. To maximize the rewards of ITS investments, the most beneficial deployment that meets local objectives must be selected.

Cost-benefit analysis is the prevailing method to address this issue. Managers and analysts in transportation agencies are often required to provide analysis to support the resource allocation decisions within various transportation projects. During this planning stage, the costs and benefits of an ITS deployment are examined so that its cost-effectiveness can be determined. Given a limited budget, each ITS deployment chosen must have the largest possible value per dollar expended. Thus, in many situations, the ITS alternatives are ranked according to the measure of cost-benefit ratio allowing decisions to be made accordingly.

Cost-benefit analysis fits well into the decision-making process with respect to new initiatives, especially those that require legislative enactment prior to implementation. However, at the more detailed implementation level, decision makers may not be able to see an ITS deployment's operational performance from the cost-benefit ratio perspective. In other words, cost-benefit analysis may not provide decision makers enough information to compare various ITS deployments. It is possible that the alternative with highest cost-benefit ratio might not best fit the local objectives and needs. Given this predicament, it is necessary to evaluate the ITS deployments using multicriteria decision analysis approach. Through a thorough literature review, it was found that only a limited number of studies have been undertaken to assist decision makings in ITS deployment comparison. It would be beneficial to develop an innovative method to address this issue.

This research was principally motivated by the need to address the two aforementioned issues that have emerged in ITS planning. Challenges and difficulties in solving these two problems arise because of unclear impacts, lack of data, multiple objectives, tradeoffs between objectives, involvement of multiple stakeholders, and uncertainties resulting from the potential impact of ITS implementations. Using innovative approaches to address these issues would assist decision makers in planning appropriate ITS strategies for transportation improvements. A foreseeable benefit is that transportation agencies can make wiser investments of their resources on ITS and improve ITS deployments to better suit local transportation problems and user needs.

1.2 OBJECTIVE AND PROBLEM FORMULATION

The primary objective of this study is to understand, formulate, and solve the two major problems identified in ITS planning. Specifically, at the “strategic” level, an innovative approach will be developed to screen the ITS market packages that best address local needs and local transportation problems. At the “executive” level, an appropriate approach will be developed to identify the ITS deployments that are most beneficial to the planning area.

Although these two problems vary in planning details, objectives, planning horizons and alternatives, they share similar features: given a set of ITS alternatives, decision makers should assess each alternative with respect to a set of objectives or criteria. Then the best alternative or alternative set will be selected. They are typical multicriteria decision making problems. The mathematical representation of these ITS planning problems is shown as follows:

$$\begin{aligned} Maximize \quad Z(x_1,x_2,\ldots,x_n) =& [Z_1(x_1,x_2,\ldots,x_n), Z_2(x_1,x_2,\ldots,x_n), \\ & \ldots, Z_m(x_1,x_2,\ldots,x_n)] = Gx \end{aligned} \tag{1.2.1a}$$

subject to

$$x \in X = \{Ax \leq B; \quad x_j = 0 \quad or \quad 1, \quad j = 1,2,\ldots,n\} \tag{1.2.1b}$$

where Z(x) is the m dimensional ITS objective vector, G is the $m \times n$ matrix, in which its element G_{ij} represents the outcomes that ITS alternative x_j has achieved on objective Z_i ($i = 1, 2, \ldots, m; j = 1, 2, \ldots, n$); x is the n dimensional decision vector for n ITS alternatives, x_j=1 if x_j is selected, otherwise x_j =0; X is the ITS alternative set, which includes n alternatives. When the decision is resource constrained, a constraint set $Ax \leq B$ should be included, where A is the $l \times n$ matrix and it reveals the needed l resource amount for n alternatives; B is the resource constraint constants.

The two problems mentioned above can be formulated based on Model (1.2.1) and modified as necessary. To solve these problems, different approaches and algorithms can be applied. Each problem will be discussed in detail later in this document.

1.3 Dissertation Organization

This dissertation is organized in the following manner: Chapter 2 covers the necessary background information in ITS planning and presents a review of related work in previous studies. Chapter 3 introduces the general formulation of a deterministic multi-attribute utility theory (MAUT) model for ITS market package screening and a MAUT model that incorporates uncertainties in ITS market package plan development.

The ITS deployment comparison and selection problem is discussed in Chapter 4. A modified ELECTRE-I approach is presented to compare and rank various ITS alternatives. In addition, Chapter 4 provides a comparative study of the MAUT approach and the modified ELECTRE-I approach in ranking ITS alternatives. Chapter 5 summarizes the findings of this dissertation, provides conclusions, and makes recommendations for future research.

Chapter 2 Background Review

2.1 OVERVIEW OF NATIONAL ITS PROGRAM

2.1.1 The Policy Context of ITS

The national ITS program, originally termed the Intelligent Vehicle/Highway Systems (IVHS) in the early 1990s, is a program of the U.S. Department of Transportation (USDOT) to add information technology to transportation infrastructure and vehicles. It aims to manage vehicles, infrastructure, routes, and cargo to improve safety and to reduce congestion, delay, transportation-related negative environmental impacts, and fuel consumption.

In 1991, the national effort for ITS was inspired when the Intermodal Surface Transportation Efficiency Act (ISTEA) was enacted by the U.S. Congress. At that time, the focus was on encouraging the necessary planning of ITS on a national, regional and statewide basis; funding research on transportation technologies; and implementing and evaluating various ITS projects in selected locations.

Five years later, in 1996, the U.S. Secretary of Transportation announced a national initiative to install the Intelligent Transportation Infrastructure (ITI) in the 75 largest urban areas by 2006. Among these 75 largest urban areas, the Phoenix, San Antonio, Seattle, and New York/New Jersey/Connecticut areas were selected to lead a new program — Metropolitan Model Deployment Initiative (MMDI) — to showcase deployments of ITS and demonstrate the benefits of wide-scale deployment of integrated ITS.

In 1998, the successor transportation bill to ISTEA, the Transportation Equity Act for the 21st Century (TEA-21) was enacted. It continued the ITS program by funding $1.3 billion in authorizations. The renewed program continued to fund the research and development of ITS and grant incentives to states to foster integrated ITS deployment. Also, the National ITS Standards and the National ITS Architecture were established and consistency with them was required.

Since 2000 the national ITS program has undergone reassessment under the direction of USDOT in cooperation with ITS America. This re-evaluation coincides with a major new federal initiative to emphasize operation and management of the transportation system. The importance of systems management and ITS as a tool to manage the system has been emphasized, given the current political, fiscal, and quality of life realities that make delivery of new facilities less feasible.

In August 2005, the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU), was enacted. This legislation resulted in key changes in the national ITS program, including the development of a 5-year plan to specify goals, objectives, and milestones for the research and deployment of ITS; to specify the manner in which specific programs and projects will achieve the goals, objectives, and milestones; to identify activities that provide for the dynamic development, testing, and necessary revision of standards and protocols to promote and ensure interoperability in the implementation of ITS technologies; and to establish a cooperative process with state and local governments. Under the new legislation, ITS projects have to compete with other transportation improvement projects for funding opportunities, which makes ITS planning and the decision analysis on ITS projects more important.

2.1.2 ITS Goals and Objectives

Discussion of ITS planning is most productive when preceded by a recap of the underlying principles presented in a logical sequence. Because scope of ITS is wide, understanding the goals and objectives of ITS implementations is a good start to understand the characteristics of ITS planning. The goals of ITS implementation describe the intended purpose or outcome of ITS. The objectives identify what kinds of measurable changes might be achievable. These objectives are very important because they are a forerunner of the ITS planning that will be discussed in detail later.

2.1.2.1 ITS System Goals

The national ITS program goals provide guideposts to state and local transportation agencies in developing regional or local ITS plans. In practice, ITS system goals may vary with respect to the defined transportation problems and needs in a designated area.

The six goals of the national ITS program are shown as follows (ITS America, 1995):

- Increase operational efficiency and capacity of the transportation system;
- Enhance personal mobility and the convenience and comfort of the transportation system;
- Improve the safety of the nation's transportation system;
- Reduce energy consumption and environmental costs;

- Enhance the present and future economic productivity of individuals, organizations, and the economy as a whole; and
- Create an environment in which the development and deployment of ITS can flourish.

In the recently-published *National ITS Program Plan: A Ten Year Vision*, the benefit areas and associated goals of ITS implementations were updated (ITS America, 2002a). A new ITS system goal was added: *Improve Transportation System Security*. This goal is to maintain a transportation system that is well-protected against attacks and responds effectively to natural and man-made threats and disasters, enabling the continued movement of people and goods even in times of crisis.

2.1.2.2 ITS Deployment Objectives

ITS deployment objectives define specific and measurable improvements that are expected for each major ITS goal. These objectives lead to initial measurements that may be used to evaluate various ITS strategies or alternatives. They also define priority areas of ITS implementation, allowing transportation agencies to give higher priority to funding projects that could achieve these objectives. Table 2.1-1 illustrates the objectives for each ITS system goal defined by the national ITS program (ITS America, 1995; ITS America, 2002b).

Table 2.1-1a: ITS Deployment Objectives

Increase operational efficiency and capacity of the transportation system ▪ Increase operational efficiency ▪ Increase speeds and reduce stops ▪ Reduce delay at intermodal transfer points ▪ Reduce operating costs of the infrastructure ▪ Increase private vehicle occupancy and transit usage ▪ Reduce private vehicle and transit operating costs ▪ Facilitate fare collection and fare reduction/equity strategies ▪ Reduce freight operating costs and increase freight throughput consumed

Enhance personal mobility, convenience, and comfort of the transportation system
▪ Increase personal travel opportunities
▪ Decrease personal costs of travel
▪ Increase awareness, and ease of use of transit and ridesharing including:
    ▪ Travel time, travel time reliability, and travel cost
    ▪ Comfort, stress, fatigue, and confusion
    ▪ Safety and personal security
▪ Increase sense of control over one's own life from predictable system operation
▪ Decrease cost of freight movement to shippers, including:
    ▪ More reliable "just-in-time" delivery
    ▪ Travel time and cost
    ▪ Driver fatigue and stress
    ▪ Cargo security
    ▪ Safety (e.g., from tracking hazardous material)
    ▪ Transaction costs

Improve the safety of the nation's transportation system ▪ Increase personal security ▪ Reduce number and severity (cost) of accidents, and vehicle thefts ▪ Reduce fatalities
Reduce energy consumption and environmental costs ▪ Reduce vehicle emissions due to congestion and fuel consumption due to congestion ▪ Reduce noise pollution ▪ Reduce neighborhood traffic intrusiveness

Table 2.1-1b: ITS Deployment Objectives (Continued)

Enhance the present and future economic productivity of individuals, organizations, and the economy as a whole ▪ Increase sharing of incident/congestion information ▪ Reduce information-gathering costs ▪ Increase coordination/integration of network operation, management, and investment ▪ Improve ability to evolve with changes in system performance requirements and technology
Create an environment in which the development and deployment of ITS can flourish
Improve transportation system security ▪ Provide the security of freight and intermodal operations ▪ Improve public transportation security ▪ Provide the security of major transportation facilities ▪ Safeguard the security of ITS systems and data

2.2 AN OVERVIEW OF ITS PLANNING

The ITS planning process and implementation methods have evolved rapidly. With slightly longer than one decade of effort, many methodologies and resources are available for researchers and practitioners in various ITS planning scopes. The prevailing ITS planning methods and tools adopted by transportation agencies include the Federal Highway Administration (FHWA) ITS Planning Process, National ITS Architecture, and many others. A brief introduction of these methods and tools will be discussed in this section.

2.2.1 The National ITS Architecture

Extensive effort has been invested at the national level to provide a logical structure to ITS plan development and system design. This structure, named the National ITS Architecture, provides a "common framework for planning, defining, and integrating intelligent transportation systems. It is a mature product that reflects the contributions of a broad cross-section of the ITS community (transportation practitioners, systems engineers, system developers, technology specialists, consultants, etc." (USDOT, 2005a).

The National ITS Architecture is a common structure for the planning and design of ITS. It defines the functions of physical entities or subsystems where these functions reside, the interfaces and information flows between subsystems, and the communications requirements for the information flows in order to address identified user service requirements. It also describes the physical and logical interactions among ITS components, the surface transportation system, and users of both. Specifically, the National ITS Architecture defines the following components: user services, logical architecture, physical architecture, equipment packages, market packages, and standards. The interrelationships and data flows among these components are shown in Figure 2.2-1 (USDOT, 2005a).

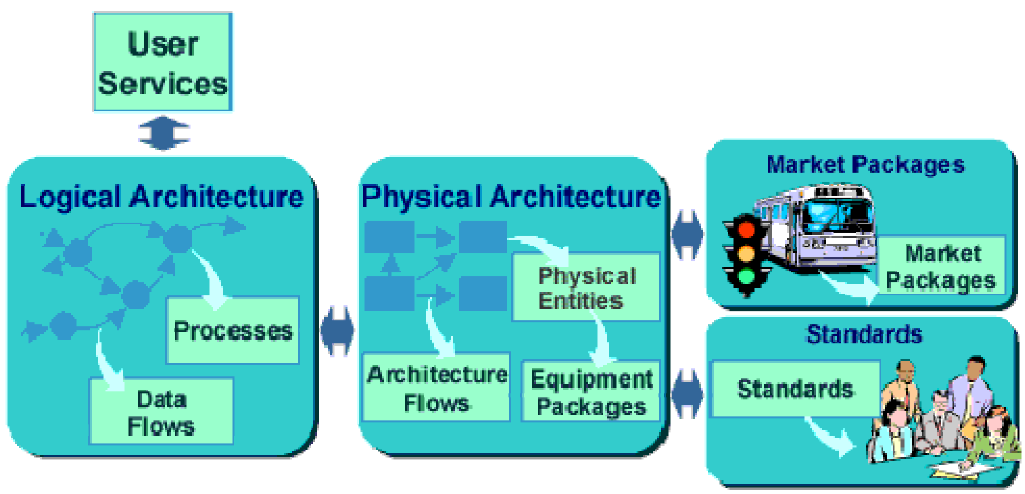

Figure 2.2-1: Interrelationships and Data Flows among National ITS Architecture Components

The newest version of this architecture is the National ITS Architecture Version 5.1. Containing documents that provide performance, cost, and benefits assessments, the National ITS Architecture provides very specific guidance for ITS planning and system design. At each stage of project development, it aids transportation agencies in determining how an ITS project fits into the regional context of transportation improvement. In summary, the National ITS Architecture defines the following three major aspects of an ITS system:

1) The functions that are required for ITS. For example, broadcast traffic information or detect incidents.
2) The physical entities or subsystems where these functions reside. For example, the field or the vehicle.
3) The information flows, or architecture flows, and data flows that connect these functions and physical subsystems together into an integrated system.

The National ITS Architecture relates the goals, benefits, products, and services of ITS in a manner that allows users to understand how ITS can best meet stakeholder needs. Because of the broad range of ITS, understanding the relationships among goals, users services, service bundles, and market packages, etc. can be challenging. Figure 2.2-2 is an illustration from the National ITS Architecture documents that shows how ITS functions and stakeholders are interrelated (USDOT, 1997).

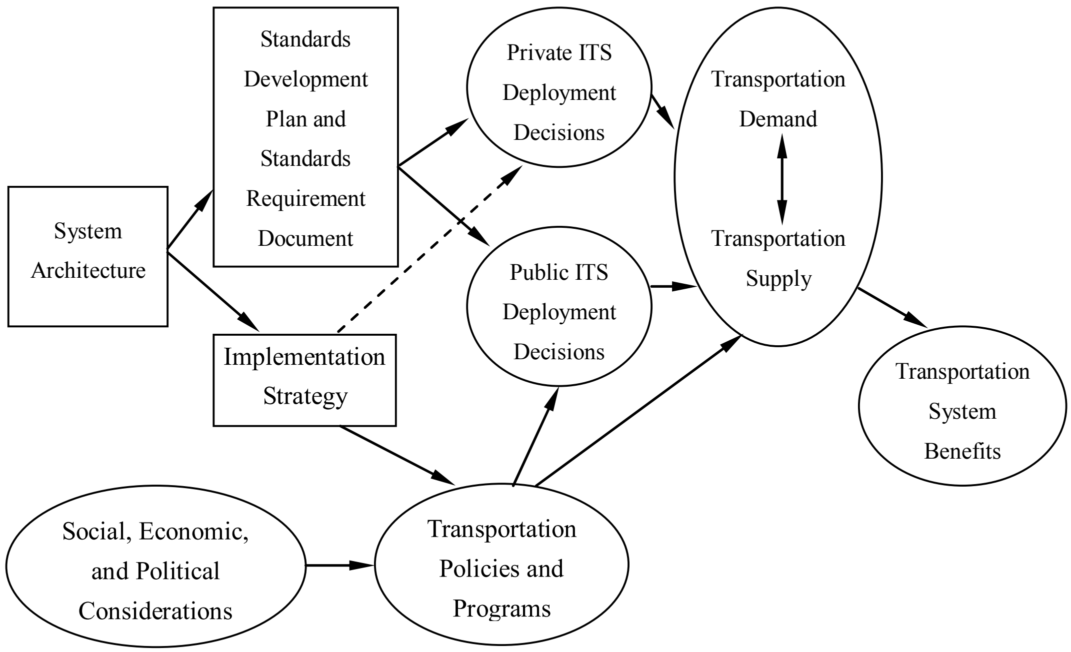

Figure 2.2-2: A Conceptual Framework for ITS System Development

2.2.1.1 User Services

User service is an important concept in the National ITS Architecture. It represents what the system will do from the perspective of the user, which might be either the public or a system operator.

The National ITS Architecture defines 33 user services, which are grouped into following eight categories:

1) Travel And Traffic Management
   - Pre-Trip Travel Information
   - En-Route Driver Information
   - Route Guidance

- Ride Matching And Reservation
- Traveler Services Information
- Traffic Control
- Incident Management
- Travel Demand Management
- Emissions Testing And Mitigation
- Highway-Rail Intersection

2) Public Transportation Management
    - Public Transportation Management
    - En-Route Transit Information
    - Personalized Public Transit
    - Public Travel Security

3) Electronic Payment
    - Electronic Payment Services

4) Commercial Vehicle Operations
    - Commercial Vehicle Electronic Clearance
    - Automated Roadside Safety Inspection
    - On-Board Safety and Security Monitoring
    - Commercial Vehicle Administrative Processes
    - Hazardous Material Security and Incident Response
    - Freight Mobility

5) Emergency Management
    - Emergency Notification And Personal Security
    - Emergency Vehicle Management

- Disaster Response and Evacuation

6) Advanced Vehicle Safety Systems
    - Longitudinal Collision Avoidance
    - Lateral Collision Avoidance
    - Intersection Collision Avoidance
    - Vision Enhancement For Crash Avoidance
    - Safety Readiness
    - Pre-Crash Restraint Deployment
    - Automated Vehicle Operation
7) Information Management
    - Archived Data Function
8) Maintenance and Construction Management
    - Maintenance and Construction Operations

Because ITS technologies evolve rapidly and ITS systems are open and expandable, the number of user services is increasing. Additionally, the user services can be customized according to local stakeholders' requirements and needs. For additional details regarding these user services, please refer to the National ITS Architecture documentation.

With the concept of user services, the ITS planners can start the process of system or project definition by considering what high level services should be provided to address identified problems and needs.

2.2.1.2 Logical Architecture

Logical architecture is another important concept in the National ITS Architecture. To accomplish a specific user service, specific requirements must be met. To reflect this, the concept of user requirements is introduced. User service requirements, also called functions, are more detailed functional statements about the user services. For example, the traffic control user service in the *Travel and Traffic Management* category is defined by more than 40 functions. These user requirements “can be used as a departure point for the development of project functional requirements and system specifications (USDOT, 2005a)”. A logical architecture, as shown in Figure 2.2-3, is used to aid in organizing complex entities and relationships in an ITS system (USDOT, 1997).

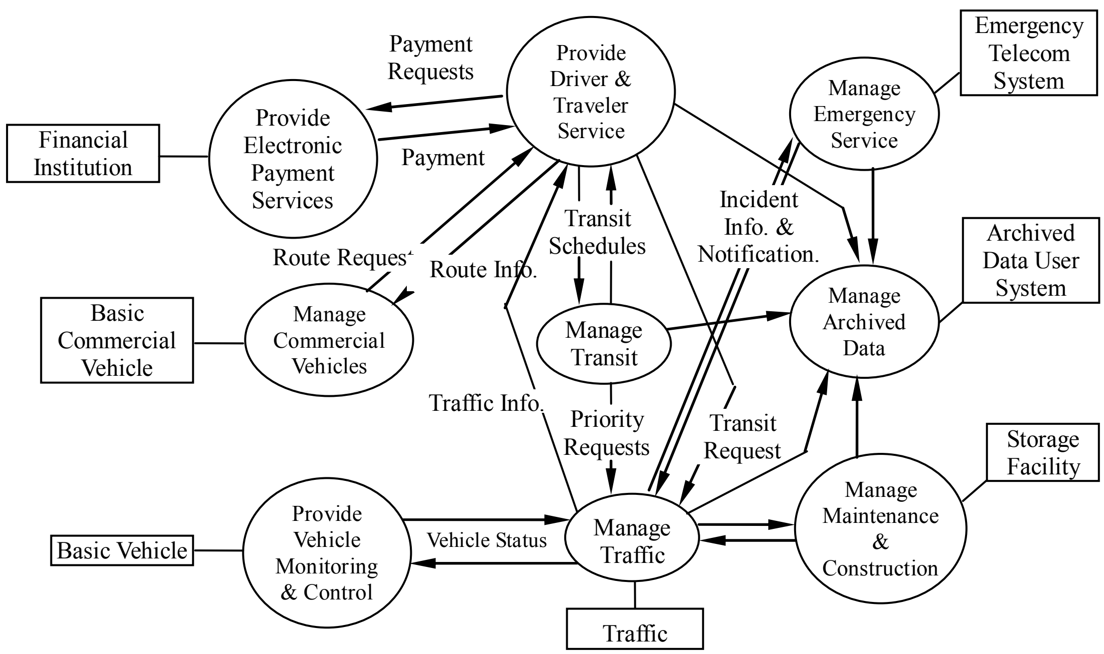

Figure 2.2-3: Complex Entities and Relationships in an ITS System

With the development of a logical architecture, system functions and information flows can be defined. Each function can be further broken down into subsystems or sub-functions. In addition, logical architecture provides guidance for the development of functional requirements for new systems and improvements. However, logical architecture does not define where or by whom functions are performed in the system, nor does it identify how functions are implemented.

2.2.1.3 Physical Architecture

Physical architecture provides agencies with a physical representation of how the ITS system should provide the required functionality. Figure 2.2-4 depicts the physical entities defined in the National ITS Architecture (USDOT, 1997). It also illustrates the interconnections among the physical subsystems.

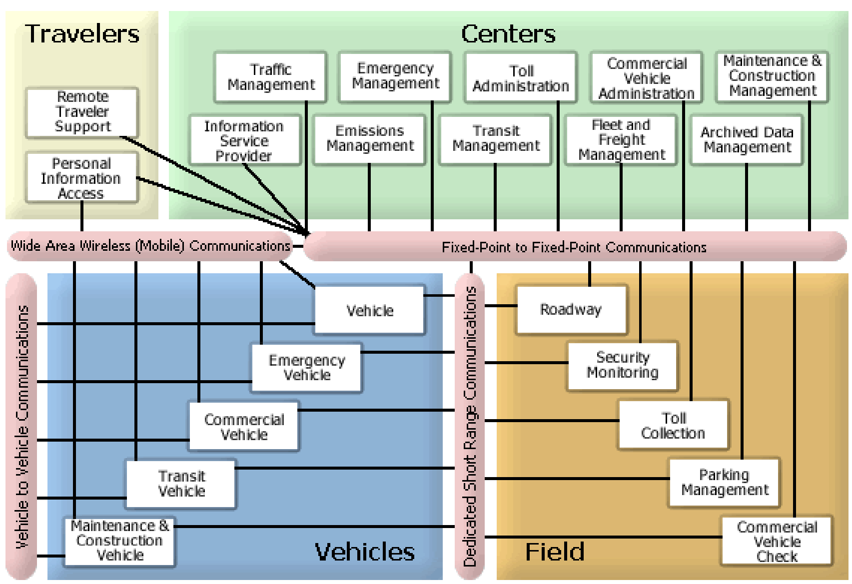

Figure 2.2-4: Physical Entities Defined in the National ITS Architecture

When developing a physical architecture, the processes identified in the logical architecture are assigned to physical entities or subsystems. In addition, the architecture flows are identified by grouping all data flows between any two subsystems. Namely, one architecture flow contains one or a group of data flows between two subsystems. Development of a physical architecture identifies the desired communications and interactions between different transportation management organizations/subsystems.

At this point, it can be seen that the physical architecture is comprised of two layers: the transportation layer and the communications layer. The transportation layer describes the relationships among subsystems while the communications layer shows all necessary communication services that connect the subsystems. The communications layer identifies the system interface where national ITS standards and communications protocols can be used.

2.2.1.4 Equipment Packages and Market Packages

With the development of logical and physical architectures, all essential architecture elements are identified so that desired user services can be provided. Thereafter, the equipment packages and market packages with respect to each architecture element must be screened for implementation.

The term “equipment package” is used to represent the “implementable” package of hardware and software capabilities for the identified functions of a particular subsystem. Equipment packages are associated closely with market packages and can be used as a basis for estimating deployment costs. The National ITS Architecture has defined a total of 198 equipment packages. However, this specific set of equipment packages is merely illustrative and does not represent a way to combine various functions within a subsystem. To address this issue, the concept of “market package” is introduced.

The original impetus for defining market package is that some of the user services are too broad in scope to be convenient for planning actual deployments. In the National ITS Architecture, market packages are defined from the original user services with a group of equipment packages that are required to work together to deliver a certain transportation service. In other words, a market package may contain multiple equipment packages in two or more subsystems.

The National ITS Architecture Version 5.1 defines 85 market packages that are grouped into eight bundles, as illustrated in Tables 2.2-1a, 2.2-1b, and 2.2-1c. With the rapid evolvement of technology, the number of market packages is still expanding. For more detailed information such as the description of each ITS market package’s functions and technical specifications, please refer to the National ITS Architecture documentation (USDOT, 2005a).

Table 2.2-1a: ITS Market Packages Bundles

Traffic Management	Network Surveillance Probe Surveillance Surface Street Control Freeway Control HOV Lane Management Traffic Information Dissemination Regional Traffic Control Traffic Incident Management System Traffic Forecast and Demand Management Electronic Toll Collection Emissions Monitoring and Management Virtual TMC and Smart Probe Data Standard Railroad Grade Crossing Advanced Railroad Grade Crossing Railroad Operations Coordination Parking Facility Management Regional Parking Management Reversible Lane Management Speed Monitoring Drawbridge Management Roadway Closure Management
Public Transportation	Transit Vehicle Tracking Transit Fixed-Route Operations Demand Response Transit Operations Transit Passenger and Fare Management Transit Security Transit Maintenance Multi-modal Coordination Transit Traveler Information
Traveler Information	Broadcast Traveler Information Interactive Traveler Information Autonomous Route Guidance Dynamic Route Guidance ISP Based Route Guidance Integrated Transportation Management/Route Guidance Yellow Pages and Reservation Dynamic Ridesharing In-Vehicle Signing

Table 2.2-1b: ITS Market Packages Bundles (Continued)

Advanced Safety Systems	Vehicle Safety Monitoring Driver Safety Monitoring Longitudinal Safety Warning Lateral Safety Warning Intersection Safety Warning Pre-Crash Restraint Deployment Driver Visibility Improvement Advanced Vehicle Longitudinal Control Advanced Vehicle Lateral Control Intersection Collision Avoidance Automated Highway System
Commercial Vehicle Operations	Fleet Administration Freight Administration Electronic Clearance CV Administrative Processes International Border Electronic Clearance Weigh-In-Motion Roadside CVO Safety On-Board CVO and Freight Safety and Security CVO Fleet Maintenance HAZMAT Management Roadside HAZMAT Security Detection and Mitigation CV Driver Security Authentication Freight Assignment Tracking
Emergency Management	Emergency Response Emergency Routing MAYDAY Support Roadway Service Patrols Transportation Infrastructure Protection Wide-Area Alert Early Warning System Disaster Response and Recovery Evacuation and Reentry Management Disaster Traveler Information

Table 2.2-1c: ITS Market Packages Bundles (Continued)

Archived Data Management	ITS Data Mart ITS Data Warehouse ITS Virtual Data Warehouse
Maintenance & Construction Operations	Maintenance & Construction Vehicle and Equipment Tracking Maintenance & Construction Vehicle Maintenance Road Weather Data Collection Weather Information Processing and Distribution Roadway Automated Treatment Winter Maintenance Roadway Maintenance and Construction Work Zone Management Work Zone Safety Monitoring Maintenance & Construction Activity Coordination

2.2.2 The FHWA ITS Planning Process

The FHWA ITS Planning Process was developed based on a system planning approach. It provides a flexible framework for the preliminary planning of the applications of ITS in a metropolitan area. The latest version is the FHWA ITS Planning Process Version 2.1. It is based on the FHWA ITS Planning Process Version 1.0 originally released in 1993 by the FHWA to aid local and regional agencies in developing ITS strategic plans. Figure 2.2-5 presents an overview of the planning framework.

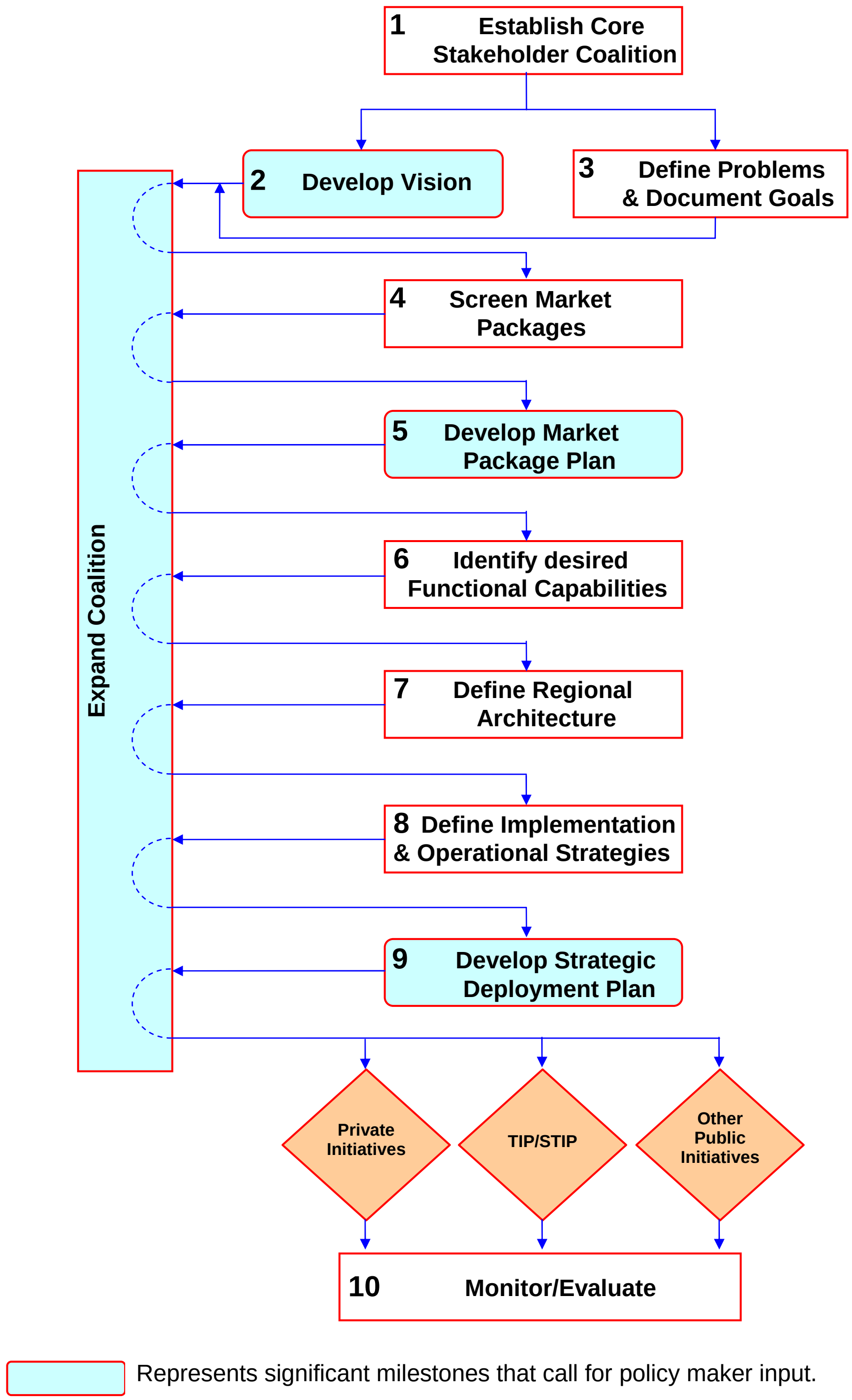

Figure 2.2-5: FHWA ITS Planning Process Version 2.1

As shown in Figure 2.2-5, the FHWA ITS Planning Process is comprised of a ten-task framework that commences with "establishing core stakeholder coalition" and ends with "monitoring/evaluating" the ITS project:

1) *Establish core stakeholder coalition*. This step establishes both technical and institutional panels for the ITS planning effort. An inventory of regional transportation organizations is developed to serve as the basis for a coalition to support the deployment of ITS.
2) *Develop vision*. With the establishment of a core stakeholder coalition, this step identifies and quantifies characteristics of the existing regional transportation system.
3) *Define problems and document goals*. This step involves defining existing surface transportation problems and short term, medium term, and long term goals of ITS implementation. A goal and need statement provides explanation to the public and decision makers as to why an ITS project is necessary and how proposed strategies can address the problem.
4) *Screen market packages*. This step identifies an inventory of the ITS market packages that address the problems and goals defined in Step 3.
5) *Develop market package plan*. This step documents the interconnections of the market packages identified in Step 4.
6) *Identify desired functional capabilities*. This step identifies the functions necessary to support the market packages. For example, communications, traveler interface, data processing, and surveillance are desired functional capabilities for the pre-trip traveler information user service.

7) *Define regional architecture*. This step groups the functions identified in Step 6 into related subsystems so that the overall system architecture is formed. The architecture defines how various market packages may be integrated to function as one integrated system.
8) *Define implementation and operational strategies*. In this step, the possible technologies that will meet the functional requirements of the system architecture are considered. However, this does not imply to technical design.
9) *Develop strategic deployment plan*. The strategic deployment plan provides guidance to the implementation of ITS projects that meet the needs and objectives documented in the market package plan.
10) *Monitor/Evaluate*. The purpose of this step is to monitor/evaluate the implementation of the plan to see if goals are achieved.

2.2.3 Supporting Tools for ITS Planning

The National ITS Architecture and the FHWA ITS Planning Process provide a foundation for ITS planning practice. To assist users in utilizing these resources, a number of computer programs and software packages have been developed with the support of FHWA. These tools include the Turbo ITS Architecture and several ITS simulation and evaluation programs such as ITS Deployment Analysis System (IDAS), Screening for ITS (SCRITS), DYNASMART-P, and others.

Turbo ITS Architecture is an interactive computer program that assists ITS planners and system integrators in developing regional and project architectures using the National ITS Architecture as a starting point. It allows users to create a regional architecture, to create one or more project architectures, to maintain consistency between the regional and project architectures, and to generate a variety of architecture reports and diagrams. The newest version of Turbo ITS Architecture is Version 3.0, released in April 2004.

IDAS is a computer program developed by FHWA to assist in planning ITS deployment. It is a sketch-planning tool for ITS impact analysis and cost-benefit analysis. Working with the output of existing transportation planning models, IDAS is capable of predicting costs and benefits for more than 60 types of ITS options. Using IDAS, users can compare and screen ITS deployment alternatives, estimate the impacts and traveler responses to ITS, develop inventories of ITS equipment needed for proposed deployments and identify cost sharing opportunities, estimate life-cycle costs (capital, operation, and maintenance costs for the public and private sectors), and provide documentation for transition into design and implementation.

SCRITS is a MS-Excel spreadsheet analysis tool for estimating user benefits of various ITS applications. SCRITS targets the need for simplified estimates in the early stages of ITS planning in the context of an either a focused ITS analysis, a corridor/subarea transportation study, or a regional planning analysis (SAIC, 1999). It is a sketch-level or screening-level analysis tool. Therefore, it is not suitable for detailed analysis. For situations requiring greater accuracy, users should use more sophisticated tools such as simulation models or the IDAS program.

DYNASMART-P, which was originally developed at the University of Texas at Austin under contract with FHWA and released from the University of Maryland in December 2004, is an ITS evaluation and planning tool that integrates traffic flow models, behavioral rules, and information supply strategies into a simulation-assignment framework (Mahmassani et al. 2004). DYNASMART-P is capable of modeling the evolution of traffic flows in a traffic network that result from the travel decisions of individual travelers affected by ITS deployments. By using dynamic traffic assignment algorithms, it overcomes many known limitations of traditional static traffic assignment models used in current practice and is suitable for ITS deployment evaluation and planning.

A big challenge in ITS planning is that resulting impacts and benefits are difficult to measure when an ITS system is not deployed on a real network. With the application of these supporting tools, decision makers have more detailed information with respect to the potential impact of ITS deployments. Through evaluation and comparison of various alternatives, decision makers can identify the optimal ITS solution for a designated planning area.

2.3 Decision Analysis in ITS Planning

2.3.1 Characteristics of ITS Planning

Being a relatively new area, ITS planning has only been studied since the mid-1990s. Various planning methods and processes have been proposed, and researchers have gained a basic understanding of planning characteristics.

First, ITS planning is financially constrained. Legislation usually requires transportation authorities at state and local levels to produce two documents in the planning process, one which indicates what transportation programs or projects will be implemented in the short-term and one which specifies long-term priorities. The projects on the short-term list are called the transportation improvement program, which must include a priority list of projects to be implemented over a two to three year period after its approval. Long-term priorities in the transportation plan usually cover the programs or projects to be implemented over a twenty year time period. Recent legislation such as ISTEA and TEA-21 has required that the metropolitan transportation plan and transportation improvement programs be financially constrained to reflect available funds that are reasonably anticipated over the time period they cover. Given this situation, using proper methodology to identify short-term programs, long-term programs, and priorities becomes extremely important in order to better utilize a limited budget.

Secondly, an ITS strategic plan is critical to ensure the success of ITS implementations. An ITS strategic plan is beneficial because: 1) it is an outcome of the multiple-agency discussion that incorporates their interests and concerns regarding ITS implementations; 2) during the ITS strategic plan development process, decision makers provide broad direction for ITS planning through the establishment of goals, objectives, and visions. It helps relate ITS solutions to specific transportation problems in a designated planning area; 3) more cost-effective ITS deployments over time could be identified through a comprehensive analysis; and 4) the desired ITS projects, usually with priority settings, can be defined to be funded and implemented in a logical and systematic manner. Developing a strategic ITS plan provides an opportunity to examine a certain type of ITS strategy or set of strategies so that better decisions can be made to support overall ITS planning objectives.

Third, ITS planning is a process that revolves around making decisions on various ITS strategies and applications. However, in the context of ITS planning, decisions are not easy to make. Multiple objectives, complicated alternatives, uncertainties residing in the potential impact of ITS alternatives, and decision maker's preferences make it hard to conduct. As discussed, there are many issues that should be addressed in ITS planning. In effect, that is the subject of this dissertation: using innovative approaches to identify implications of alternatives so that decision makers can wisely make investments of limited resources. Each chapter in this document contributes to the procedures and methods that support decision making in ITS planning.

2.3.2 Operational Framework for Decision Analysis in ITS Planning

2.3.2.1 Major Elements in Decision Analysis

Decision analysis is largely applied to solve the problem of allocating limited resources to a collection of activities in diverse application areas, such as inventory management, portfolio selection for capital investment, medical service, water-resource management, and transportation planning. There are a number of key elements in a general decision analysis structure found in several sources (Chadwick, 1978; Goicoechea et al., 1982; Chankong and Haimes, 1983; Gibson, 1989; Keeney and Raiffa, 1993; Skinner, 1999; Fitzgerald, 2002):

Define the problem. At this phase, a general statement of the problem and needs is prepared. In other words, the mission and vision are defined at this point.

Define broad goals and specific objectives. The goals and objectives indicate the desired state of the system under consideration. Reflecting the problems and needs stated above, the objectives should be specific and cover the main goals or needs. For example, in transportation, the objectives could be to reduce delay, reduce cost, and improve safety.

Define decision variables. Decision variables, also called attributes or measures of effectiveness, are defined to quantify the resulting performance of an alternative achieved in overall goals and specific objectives. The definition of decision variables is normally objective-oriented.

Formulate the problem with a mathematical representation. A decision analysis problem can be formulated with a mathematical model that incorporates the objectives, decision variables, and constraints. This phase always involves the formulation of objective functions and a constraint set. However, how to formulate the problem and how to solve it will depend on the nature of the problem. Literature suggests various methods such as mathematical programming, regression analysis, utility assessment, etc.

Develop an alternative or an alternative set. The alternatives are the objects decision makers want to evaluate or compare. The alternatives are either defined in the problem or developed by decision makers.

Quantify the alternatives. Once an alternative or a set of alternatives are developed, consequences can be measured in terms of how well stated objectives are met. After the quantification, each decision variable will be assigned a value for each alternative.

Identify the preferred or acceptable alternative(s). Based on the values of decision variables, the decision maker can be asked to subjectively assess the "utility" of the current solution. The decision maker will determine if the alternative is acceptable or preferred. If the solution is acceptable or preferred, it can be implemented. Otherwise, if the solution is not acceptable, the decision maker may need to relax his or her expectations, or invest more resource to relax the constraints, or develop new alternatives to address the problem.

Reach final decisions. If the solution is good enough, the decision will be made to implement that alternative solution. If the solution is not acceptable with respect to the decision maker's expectations and resources, no feasible plan will be available.

These elements largely represent a sequence of steps that can be found in various decision analysis scenarios. Figure 2.3-1, suggested by Goicoechea et al. (1982), presents an example of operational framework for decision analysis that is general enough to cover decision making in many areas.

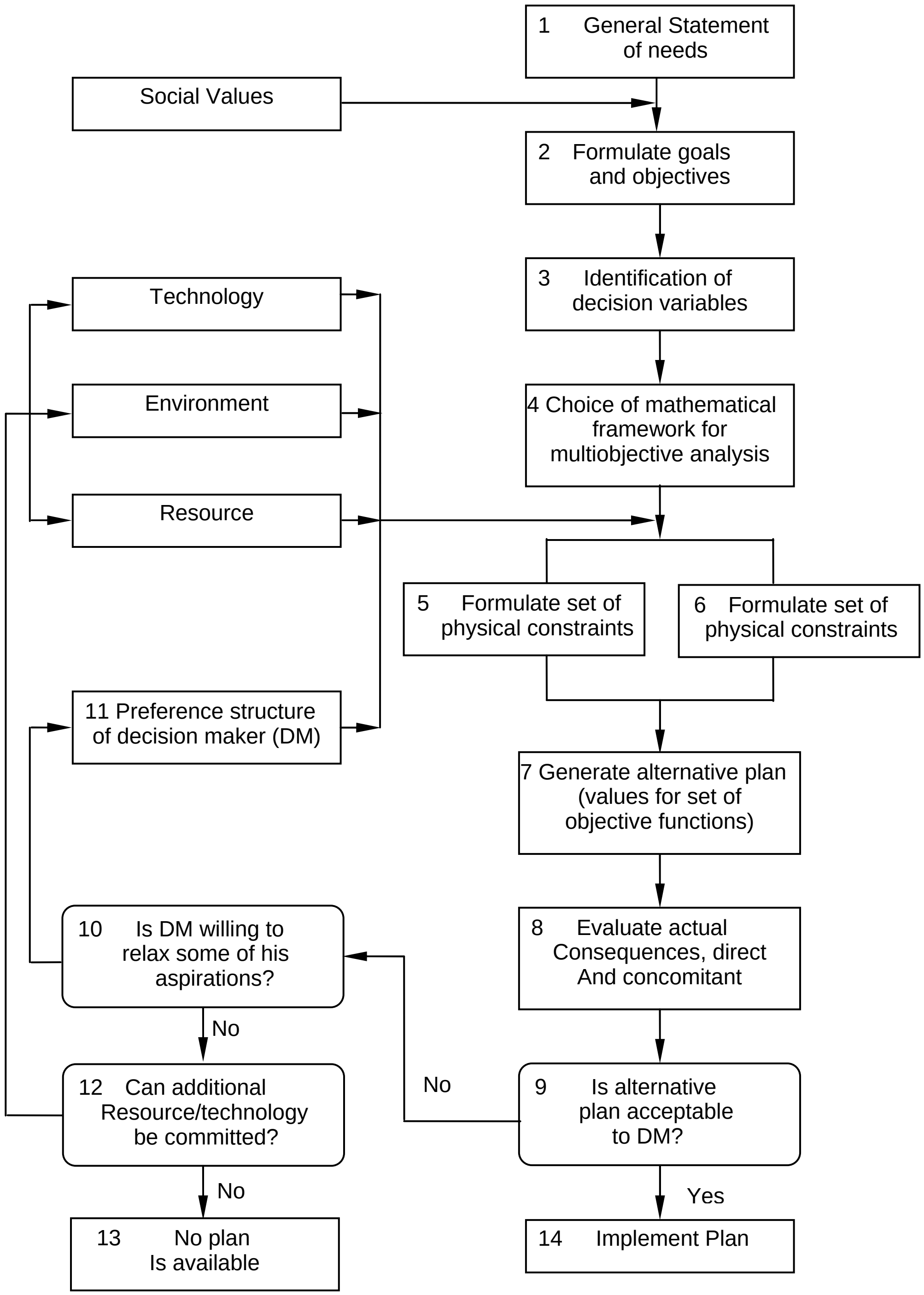

Figure 2.3-1: An Operational Framework for Decision Analysis

2.3.2.2 Strategic Planning for ITS

ITS planning is different than the planning of traditional highways or urban transportation systems. ITS covers a broad range of user services and functional areas and these user services and functional areas must be integrated into one system. Due to the rapidly-changing nature of technology, it is impossible to identify all existing ITS opportunities. User requirements are changing, and user services that can be delivered through ITS are expanding. It is important to plan for the orderly expansion and progress of an ITS system. Finally, resources are limited and the system to be established is large. It is not always feasible to deploy a complete ITS system in a short term due to budget constraints, which gives priority settings additional importance.

A strategic plan allows decision makers to be adaptable to the ever changing and increasingly complex environment that leads to priority-based resource allocation decisions. It also enables decision makers to check progress and reassess the validity of the plan and ensure the goals and objectives in the plan are both desirable and achievable. In general, there are five components in a strategic planning process (Johnson, 1987; Migliore, R.H., 1990; Rea and Kerzner, 1997; Kenny, 2005):

Environmental Scanning. Environmental scanning involves checking what other relevant work is being conducted in other communities, what new findings are available, and what strategies are being pursued. It provides planners with concrete examples of successes, failures, and potential solutions to the problems at hand. A review of the national ITS program, combined with state and local efforts in ITS strategic planning, will return substantial information in the environmental scanning process. Also, external factors such as regulatory, legislative, economic, social, political, technological, demographic, and other areas need to be checked. Attention to these factors will remarkably improve the successful implementation of the plan. The first task of the FHWA ITS Planning Process is similar to this type of analysis. These factors should be taken into account in building a coalition.

Mission and Vision. The development of a vision is an important characteristic of strategic planning. This step requires that the planning effort focus on the "big picture" - the desired outcome. The national ITS program has provided broad visions of ITS implementations that should be considered in regional or local strategic ITS plans (ITS America, 2002a): 1) future transportation systems will be managed and operated to provide seamless, end-to-end intermodal passenger travel regardless of age, disability, or location and efficient, seamless, end-to-end intermodal freight movement; 2) public policy and private sector decision makers will seize the opportunity to make ITS a vital driver in achieving the vision of the transportation system for the 21st century; and 3) future transportation systems will be secure, customer-oriented, performance-driven and institutionally innovative, enabled by information from a fully integrated spectrum of computing, communications and sensor technologies.

Goals and Objectives. This is a fundamental part of any system planning process. It is the third task of in the FHWA ITS Planning Process. Typical goals include improving safety, improving security, enhancing efficiency, enhancing mobility, and reducing negative environment.

Development of Alternatives. This component is found in all system planning processes, including ITS strategic planning. The alternatives are constrained to ITS market packages in the strategic planning process. This component covers Task 4 and Task 5 in the FHWA ITS Planning Process.

Develop Implementation Strategies. The strategic planning process concludes with the typical development and selection of alternatives. Implementation is the final step. The main objective of strategic planning is to develop a plan that will take into account all factors so that it functions well within those constraints and opportunities. The focus on implementation may be of benefit to the final product of the ITS planning process: the strategic deployment plan. This phase covers Task 8 and Task 9 in the FHWA ITS Planning Process.

2.3.3 ITS Performance and Benefit Evaluation

The performance and benefit evaluation provides decision makers intrinsic knowledge about the courses of ITS deployments and builds the foundation for decision analysis in ITS planning. Good planning depends on realistic evaluation of the benefits and costs, and advantages and disadvantages of potential courses of action. To predict critical performance factors in both engineering and marketing all ITS deployments should be carefully evaluated (Lee 2000a). In addition, properly evaluating ITS deployments as they are planned ensures the success of ITS projects.

There are various ways to predict the performance and benefits of ITS deployments. A literature review indicates that ITS performance and benefits evaluation approaches can be categorized into two types: the goal-oriented approach and the economic analysis approach. The goal-oriented approach employs a number of measures of effectiveness to evaluate ITS deployments. The measures of effectiveness are usually determined on the basis of the defined goals and objectives.

The impact of ITS deployments is determined by comparing the outcomes of performance measures with pre-defined goals or objectives. The economic analysis approach focuses on the cost effectiveness of the ITS deployments. Typical economic analysis practices include cost-benefit analysis and break-even analysis. In the following sections, selected studies are discussed in which ITS performance and benefits were evaluated using these two approaches.

2.3.3.1 Goal-Oriented Evaluation Approach

There are a significant number of studies that use the goal-oriented evaluation approach to evaluate the performance and benefits of ITS deployments. Brand (1994) outlines an ITS evaluation and planning process that is sensitive to the difference between ITS and traditional transportation improvements. The criteria and methods used to evaluate ITS plans and operational tests are discussed in this study. The author also presents a relatively complete set of evaluation criteria for ITS improvements, thereby avoiding double counting of benefits and highly correlated outcomes. In addition, the proposed criteria structure aids decision makers in reducing criteria sets to simplify ITS evaluations. Turner et al. (1998) propose an ITS benefits evaluation framework in order to assist the Texas Department of Transportation (TxDOT) in evaluating various statewide ITS deployments. The criteria set was developed based on national ITS program goals and objectives. Wunderlich et al. (2000) conducted an evaluation of ITS impacts in support of the metropolitan model deployment initiative evaluation program in the Seattle area. Various ITS deployments were evaluated using a simulation method. A simulation model, which is developed by Mitretek, Process for Regional Understanding and

Evaluation of Integrated ITS Networks (PRUEVIIN), is presented. The evaluation criteria include key traffic performance measures such as peak period delay reduction, travel time reliability, travel mode shift, corridor travel throughput, fuel consumption, and emission rates. Chu et al. (2004) present a micro-simulation method to evaluate the effectiveness of potential ITS solutions under non-recurrent congestion. The system efficiency measure (vehicle hours traveled) and the system reliability measure (the average standard deviation of trip time) are used to assess the network performance. The evaluation results show that all ITS strategies have positive effects on network performance.

Although efforts vary in study objectives and alternatives, they share the common features of a goal-oriented evaluation approach: a set of ITS alternatives or scenarios are evaluated with respect to a set of measures of effectiveness so that decision makers can compare these alternatives based on measured outcomes. The outcomes of performance measures are usually obtained through simulation or empirical judgments. Empirical judgments based on previous field test results will be discussed later on in this dissertation.

2.3.3.2 Economic Analysis Approach

There are a broad range of studies and analysis frameworks that stress use of an economic analysis on ITS deployments. Among them, the cost-benefit analysis is often used. Costs and benefits of ITS applications should be investigated in order to determine cost effectiveness at this stage of planning. Zavergiu (1996) presents an ITS cost-benefit analysis framework that can be used to predict benefits for three categories of beneficiaries: the first order beneficiary consists of travelers, the second order beneficiary consists of transportation agencies, and the third order beneficiary is comprised of external economy and environment. The classification of the beneficiaries in this study helps one better understand the true benefits of ITS in all aspects. Lee (2000b) presents a cost-benefit study on a traveler information system deployed in Washington State in which all internal benefits to travelers and external benefits to the environment and congestion were converted into dollar values. The value of time, dollar value of pollution cost, and the marginal cost of congestions were used in this cost-benefit analysis. In order to assist decision makers in such cost-benefit analysis, some computer programs were developed at the federal level. The most often used programs include IDAS (Cambridge Systematics, 2001) and SCRITS (SAIC, 1999), which were discussed and compared by Peng et al. (2000) along with other ITS evaluation programs. The application of these computer programs has remarkably enhanced the ITS benefits evaluation process (Sadek and Baah, 2003).

In cost-benefit analysis, there are three basic elements: cost, benefit and choice. The methodology itself is straightforward. With the total benefit and cost determined, conclusions can be drawn with respect to ITS deployments according to the benefit/cost ratio: the higher the benefit/cost ratio, the better the ITS deployment. However, to perform cost-benefit analysis on ITS deployments, there are a few challenges. For example, to obtain the benefit cost ratio, all aspects of ITS deployments must be translated into monetary terms. In this case, assumptions must be made with respect to the traveler's value of time, accident cost, pollution cost, vehicle operating cost, fuel cost, inflation rate, etc. Making reasonable assumptions is a challenge because these assumptions will significantly affect the final benefit cost ratio.

In effect, a true cost-benefit analysis cannot be conducted in the ITS planning context because the detailed “before” and “after” data resulting from the true performance of ITS deployment are not available. Given this situation, Peng and Beimborn (2001) present a break-even analysis approach to determine the minimum level of performance necessary for an ITS deployment to cover its costs. A break even analysis provides decision makers an opportunity to identify critical performance variables and to determine their relative magnitude for an acceptable benefit cost ratio. When a true cost-benefit analysis cannot be conducted, such an analysis is very useful because decision makers can judge the cost effectiveness of ITS deployment by ascertaining if the required improvements on critical performance variables are likely to be achieved.

2.3.3.3 Observed ITS Benefits

To better understand the true benefits of ITS deployments a variety of nationwide ITS deployments have been evaluated. Table 2.3-1 illustrates the evaluation results of the advanced traveler information system (ATIS). The observed benefits from these field tests were summarized in various documents and archived in a national ITS benefits database (Lockheed Martin Federal Systems, 1996; Turner et al., 1998; USDOT, 2001; Stockton et al., 2003; USDOT, 2005b).

Table 2.3-1: Observed Benefits of Advanced Traveler Information System

Study	Results/Findings
Ullman et al. 1996	A TTI study of 15 commuters in Houston who had access to travel time and incident information found that 8 changed trip patterns, and 5 changed routes.
Carter, 2000	Over a one-year period, a traveler using an in-vehicle navigation device could experience an 8.1% reduction in delay in the San Antonio area.
Wunderlich et al., 2000	Integrating arterial data into freeway ATIS may provide a 0.2% increase in vehicle throughput, 0.4% increase in VMT, 7% reduction in vehicle-hours of delay, 2.7% decrease in number of stops, and 2.1% reduction in travel time variation.
USDOT, 2001	Internet traveler information users saved 5.4% of travel time in San Antonio area.
Toppen et al., 2002	ATIS allows unfamiliar drivers to predict trip time with greater confidence and can significantly improve travel time reliability. ATIS users save about 5 minutes of total travel expenditure compared to non ATIS users, which is a 10% improvement.
Shah et al., 2003	ATIS users experienced a 56% reduction in early arrivals and a 52% reduction in late arrivals compared to nonusers. About 40% of OD pairs in the Washington, D.C. region could get an annual benefit more than 60 dollars (ATIS subscription fee) with 200 trips. The ATIS is beneficial from 7AM to 6:30PM.

Performance data collected from these post-project evaluations are very beneficial for ITS benefits predictions in similar deployment circumstances. For example, these observed benefits have been applied to case-based reasoning (CBR) ITS planning models. Khattak and Kanafani (1996, 1997) present a Planning and Analysis for Integrated Intelligent Transportation Systems (PLANiTS) model, a process-based computer program that assists transportation planning and facilitates ITS implementation. The PLANiTS uses CBR methodology to estimate the impact of transportation improvement programs, including ITS strategies. The model enables users to match a current ITS deployment with historical cases at various levels of stringency to rank the alternatives. Sadek et al. (1999) examine the potential of using CBR to overcome limitations of existing traffic management decision support systems. A prototype CBR routing system for a real-world network was developed and evaluated in this study. Instead of using observed results, cases for building the system's base were generated using a heuristic dynamic traffic assignment model specifically designed for the study area. In another study, Sadek et al. (2003) present a novel framework using a CBR approach for developing modeling tools for quantifying ITS deployments benefits. By comparing real-world network performance with results derived from the dynamic traffic assignment model, the feasibility of CBR approach was demonstrated. Karim and Adeli (2003) present a CBR model for freeway work zone traffic management. The model characterizes a work zone with layout, traffic demand, work characteristics, traffic control measures, and mobility impacts. A four-set case base schema or domain theory was then developed to represent the cases based on the aforementioned characteristics. When integrated into an intelligent decision-support tool, this CBR model is used to assist traffic agencies in the development of work zone traffic control plans and to better design and manage work zones for increased mobility and safety.

These CBR models take advantage of observed ITS performance data. Evaluations of ITS deployments are significantly enhanced at the planning stage. However, there are limitations in CBR models. A common limitation is that it becomes increasingly difficult for the CBR model to find similar historical cases or simulated cases as the level of stringency increases.

2.3.4 Mathematical Frameworks for Decision Analysis

Transportation is one of the traditional fields that have extensive decision analysis applications. Various mathematical decision analysis approaches have been developed and applied in transportation planning, infrastructure design, public transportation planning, and investment analyses. These mathematical models include mathematical programming models, utility assessment models, analytic hierarchy processes, ELECTRE methods, and others. A brief review is provided for each approach in the following sections.

2.3.4.1 Mathematical Programming

Mathematical programming - a term often used in operations research - is a procedure used to locate the maximum or minimum of a function subject to a set of constraints. It is a very useful and flexible framework for multi-objective analysis when the objectives and constraints are expressed as functions of decision variables (Goicoechea et al., 1982). This framework allows decision analysts to identify the optimal solution based on reasonable assumptions about available resources, costs, and quantification of decision variables. The earliest mathematical programming exploration was conducted by Dantzig (1951) and Charnes and Cooper (1961) with the development of linear programming, which is now being applied in various engineering and management scenarios. Based on the fundamentals of linear programming, factors such as hierarchy of importance among goals, uncertainties, and nonlinearities are incorporated and a range of mathematical formulations are proposed along with solution algorithms. The general form of a mathematical programming model is shown as follows:

$$\begin{aligned} \max imize \quad & f(x) \\ subject \quad to \quad & g(x) < 0 \\ & h(x) = 0 \\ & x \in X \end{aligned} \qquad (2.3.1)$$

Where X is a subset of R^n and is in the domain of the real-valued functions f, g and h. The relations, *g(x) < 0* and *h(x) = 0*, are called constraints, and *f* is called the objective function.

Mathematical programming models have been widely applied in transportation-related decision making. Wilson and Gonzales (1985) present a study using the mathematical programming models to analyze highway construction projects. The objective is to find the best plan; the decision variables include the highway distance, cost, travel time for travelers, etc. This study provides a good example of using mathematical programming model for transportation investment analysis. In another study, Czyzk and Zak (1995) present a multi-objective, mixed integer linear fractional programming (MOMILFP) model to solve a public transportation mode choice problem. The conflicting objectives of passengers and operators are considered in this study. Teng and Tzeng (1996) developed a multi-objective programming approach that compared alternatives consisting of non-independent transportation investments. The authors present a method that uses a heuristic algorithm that attempts to maximize objectives subject to resource constraints. The benefit of using this method is that the near-optimal solution can be attained, and the sensitivity analysis can easily be performed. Shen (1997) presents a mathematical programming model that incorporates trip distribution, equilibrium network assignment, and residential location choice. Wardrop's user equilibrium principle and the random utility theory are applied to formulate travelers' route choice behavior and residential location choice behavior, respectively. Ciancimino et al. (1999) present a deterministic linear programming model and a probabilistic nonlinear programming model for railway passenger seat inventory management. In this problem, the railway transport revenue is maximized subject to constraints such as capacity, demand, and train frequency. This is a typical operations research problem. Chowdhury and Tan (2005) present a multi-objective programming model to aid in the transportation infrastructure investment decision-makings. The most desirable options are identified based on the assessments of all options with respect to objectives and constraints. The authors recommend this model to public agencies for infrastructure planning as an alternative to traditional economic analysis tools.

Based on the literature review, it can be seen that the mathematical programming method is characterized first by formulating the problem with a set of objectives and constraints and then a search for the optimal solution using proper algorithms. This method best suits problems in which the objectives can be explicitly expressed by decision variables and a convex feasible solution area for the decision variables exists. In these problems, the alternatives, or feasible plans, can be finite or infinite. If a finite set of alternatives or feasible plans are considered, the utility assessment framework and other multicriteria decision analysis approaches can also be used to solve the problem. This will be discussed later in this dissertation.

2.3.4.2 Utility Assessment Approach

The original efforts of utility theory can be found in the work of Jeremy Bentham, a 19th century British philosopher (Bentham, 1948). However, it is the work of Pareto (1971) that provides a foundation for utility theory's contemporary developments in welfare economics.

Utility theory assumes that an individual can choose among available alternatives in such a way that his/her satisfaction is maximized. An individual's utility function, which is normally defined over a number of attributes, is used to capture all information pertaining to the various levels of objectives. It is a mapping of the values in the range of an attribute, i.e. an objective, into a cardinal worth scale. The attribute domain may contain one or more attributes. If there is only one attribute, the utility function is called a single-utility function (SUF). If there are multiple attributes, which is seen in many cases, the utility function is called a multi-attribute utility function (MUF) or multivariate utility function.

The MUF assessment is one of the most popular multicriteria decision analysis techniques currently used. It has been applied to decision analysis in various transportation issues. For example, Mohan and Bushnak (1985) applied the multi-attribute utility theory to pavement rehabilitation decision making. The authors point out that the strength of the utility theory is that some unquantifiable factors or attributes (e.g., safety and level of service) can be converted into terms of utility on a zero-to-one scale. Tzeng et al. (1989) present a study using multiattribute utility theory to evaluate a traveler's route choice behavior through pairwise comparison. Van-Dam and Thurston (1994) present a multiattribute utility analysis model for pavement alternative comparison. According to the authors, this approach is more rigorous than the two traditional approaches, life cycle costing, and weighting methods. Reed et al. (1994) applied the multiattribute utility theory (MAUT) to the public transportation system design. It was found that the MAUT model provides tools for systematically evaluating, priority ranking, and integrating desired transit functionalities and APTS capabilities. Schwartz and Eichhorn (1997) propose a multiattribute utility analysis approach in which stakeholders are involved in a collaborative process to solve transportation issues. The advantages of this approach, as indicated by the authors, include inexpensiveness to execute, the fostering of problem solving, and a high probability of a defensible, and implementable decision. Li and Sinha (2004) present a multicriteria decision analysis approach for highway asset management. The authors developed systemwide MUFs for individual asset management programs to form the basis of trade-off analyses.

The ample utility theory applications in the area of transportation have verified that the utility assessment approach is valuable to the transportation decision making process. In summary, the utility assessment approach allows decision makers to think in terms of consequences rather than form, freeing them from cognitive biases. However, difficulties with utility assessment exist in the absence of an objective model capable of dealing with multiple criteria. In other words, decision makers must state preferences between criteria or alternatives. Additionally, when there are multiple decision makers or stakeholders involved in the planning process, individual preferences must be aggregated into a single group preference. If group members have conflicting objectives, which is very likely in many situations, only conditioned compromises are likely to appear. Group members must make concessions to reach a final preference statement. This may lead to a situation where decision making group members refuse to accept solutions in which only some, but not all, members' concerns are considered and the group will possibly end up selecting a nondominated but best compromised solution.

2.3.4.3 Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) (Saaty, 1980), is a major competitor to the utility assessment approach for ranking alternatives. Developed by Thomas Saaty, it is sometimes referred to as the Saaty method. The primary objective of AHP is to identify an alternative out of a set of alternatives that best satisfies a set of criteria. The criteria can be divided into subcriteria, thus forming a hierarchical decision tree. In this manner, objectives and alternatives are compared in a natural and pairwise manner. Individual preferences are converted into ratio-scale weights that are combined into linear additive weights for associated alternatives. Decision makers can then use the resultant weights to rank alternatives or forecast an outcome.

A broad range of studies have been performed using the AHP for multicriteria decision analysis in the area of transportation. Ababutain and Bullen (2003) present a study using multicriteria decision analysis to select build-operate-transfer (BOT) toll road proposals. The approach proposed in this study is based on AHP and is validated by a case study in California in which major criteria and variables related to toll roads are identified. In addition, an integrated decision-making process was developed as a framework to help the public sector make quality decisions on BOT toll roads. Bhasin (2005) recommends a multi-criteria analysis such as AHP over traditional cost-benefit analysis for infrastructure appraisal. The author indicates that although the traditional cost-benefit analysis evaluates the cost effectiveness of alternatives, it excludes effects that are difficult to value in monetary terms. Hu and

Shi (2002) present an AHP framework for ITS deployments evaluation. With this approach, various ITS deployments can be compared and ranked. Khasnabis et al. (2002) present a comparative study using AHP and Goal Achievement Techniques (GAT) to evaluate public transit service. The authors conclude that both AHP and GAT are viable tools for conducting a transit performance assessment by using a wide range of performance data and developing a composite performance index for each transit agency. However, the authors prefer AHP as a multicriteria assessment tool due to its stronger mathematical foundation, ability to gauge judgment consistency, and flexibility in choice of ranges at the sub-criteria level. Cafiso et al. (2002) present an AHP decision making framework for pavement maintenance management that incorporates factors such as social benefits, environmental effects, safety impact, and strategic importance of roads. It was found that the prioritization based on this AHP model distributes the available budget more evenly than the prioritization based on economic criteria, which tends to favor roads with high volumes of traffic. Mattingly et al. (2000) developed a methodology that integrates two existing techniques, the MAUT model and AHP model, for evaluating transportation projects. An innovative linear scaling proxy is used to measure the priorities of the alternatives. Guegan et al. (2000) propose an AHP model to prioritize traffic calming projects. Compared to the existing point scoring systems, the AHP model apparently produces similar rankings when applied to local streets that have problems resulting from speeding vehicles. However, the AHP model produces different rankings when complex issues and qualitative factors need to considered. The authors recommend the AHP model for cases in which some factors cannot be quantified.

These studies have shown that AHP is a very effective and flexible framework for multicriteria decision analysis. In general, there are three major steps in using AHP to assist decision makers: (1) Given $i = 1, 2, \ldots, m$ criteria, determine their respective weights w_i; (2) for each criterion i, compare the $j = 1, 2, \ldots, n$ alternatives and determine their weights w_{ij} with respect to each criterion i; and (3) determine the final alternative weights W_j with respect to all the criteria by $W_j = w_{1j}w_1 + w_{2j}w_2 + \cdots + w_{mj}w_m$. The alternatives are then ordered by the W_j , with the most preferred alternative having the largest W_j. However, unlike the utility assessment models, AHP utilizes ratio scales for even the lowest level of the hierarchy. Pairwise comparisons are employed to derive ratio-scale measures that can be interpreted as final ranking priorities or weights. Thus, the resulting priorities for the alternatives in an AHP model will be ratio-scale measures rather than "utility" measures. Another significant difference between an AHP model and a MAUT model is that the latter requires the transitivity property while the former admits intransitive relationships.

2.3.4.4 The ELECTRE Method

ELECTRE, standing for elimination and (et) choice translating algorithm, was originally proposed by Benayoun, Roy and Sussman (1966) and has been continuously improved (Roy, 1971; Figueira and Roy, 2002). It is a multicriteria decision analysis approach used to identify nondominated solutions in an alternative comparison problem. Similar to the MAUT and AHP approaches, ELECTRE particularly suits problems with a limited number of alternatives. The ELECTRE method has evolved through a number of versions (I through IV); all are based on the same fundamental principals but are operationally different. ELECTRE method has several unique features not found in other solution methods, including the concepts of outranking, indifference, and preference thresholds.

ELECTRE is a proven method for alternative ranking in many decision making cases. For example, using an ELECTRE-III method, Beccali et al. (2003) assessed an action plan for the diffusion of renewable energy technologies, such as wind energy, solar energy, hydraulic energy and others on a regional scale. The authors concluded that this method enables decision makers to modify and test priority frameworks. It also allows a "robustness" test of actions, according to the priorities scenarios. Applications of the ELECTRE method are also found in waste management (Morrisseya and Browneb, 2004; Chenga et al., 2003) and environment and water resource management (Rogers and Bruen, 1998a; Rogers and Bruen, 1998b; Arondel and Girardin, 2000).

Transportation is another traditional area in which ELECTRE applications can be found. For example, Roy and Hugonnard (1982) developed an ELECTRE-IV method to rank 12 suburban line extension projects for the Paris metro system. Teodorovic et al. (1983) presented an ELECTRE application that ranked the priorities of new airport construction. Teng and Tzeng (1994) applied an ELECTRE-III method to rank transportation management policies that could be adopted to improve the air quality. Rogers and Bruen (2000) proposed a practical application of the ELECTRE method to choose a new motorway route.

These studies show that the ELECTRE method provides decision analysts with a powerful tool to rank a set of alternatives. Although these studies cover a variety of areas, they share several common features. First, there are a discrete number of alternatives in the decision making cases. Unlike the mathematical programming method, the ELECTRE method can only solve problems with a limited number of alternatives. Second, pairwise comparisons are used in the ELECTRE method to construct the outranking relationships. Concordance indices and discord indices should be calculated in this process. Third, the flexibility of the outranking relation (i.e., the preference threshold) is used to identify the nondominated solution set. These features of the ELECTRE method enable analysts to rank the alternatives based on a realistic evaluation. The ELECTRE method offers decision analysts a good option to rank a discrete number of choices.

2.3.4.5 Other Mathematical Frameworks for Decision Analysis

The mathematical frameworks discussed above are often called multiobjective decision analysis models or multicriteria/multiattribute decision analysis models, depending on the specific formulation of the problems. In addition to these methods, there are also several mathematical frameworks that can be applied in decision analysis. Input-output analysis and tricotyledon set theory is often found in multi-objective decision analysis cases.

The input-output analysis model is based on a fundamental identity that equates supply and demand. It gains advantages in analyzing how all parts of a system are affected by a change in one part of that system. Therefore, it best suits the decision analysis in the areas of agriculture, industrial, commercial, government, energy, and freight transportation. Leontief (1966) pioneered in using a linear input-output model to model the flow of goods in and out of a sector to other sectors in an economy system. In the transportation area, applications of an input-output model, single-region or multiple-region, show that the input-output model is extremely beneficial to modeling commodity inflows/outflows and land use (Sikow et al., 1994; Braslau and Johns, 1998; Vilain et al., 1999; Seetharaman et al., 2003; Liu and Vilain, 2004; Zhao and Kockelman, 2004). However, ITS planning is generally a multi-objective decision-making process that aims to identify a set of candidates from a set of alternatives. The input-output analysis does not suit the ITS planning objectives well and can be replaced by mathematical programming or multicriteria decision analysis approaches.

The tricotyledon theory, originally proposed by Wymore (1976), is a specific mathematical system theory with which an interdisciplinary group conducts the system planning. It is a general approach comprised of five steps (Duckstein et al., 1975; Goicoechea et al., 1982): 1) Generate an input-output specification where inputs are assigned parameters or external factors and outputs are goals, criteria and decisions; 2) Define an ordering or ranking α over the set of feasible systems that satisfies input-output specifications using a set of figures of merits or performances indices; 3) List resources available and necessary to implement alternative systems and define a resource ordering β using a set of resource indices; 4) Resolve conflicts between orderings α and β, which are of the type "System I performs better than System II but uses more resources"; define a trade-off ordering γ; and 5) Design a test plan to ensure that the system performs as designed—this includes acceptance criteria, monitoring network, and tolerance levels.

This general tricotyledon approach has many applications in industrial system design. However, in the transportation area, use of this approach for transportation planning and project design is very limited. One reason is that for transportation planning or project design, it is difficult to determine input-output specifications. Another reason is that most decision analysis in transportation planning and project design is goal oriented and can be better solved using methods such as mathematical programming or multicriteria decision analysis. For ITS planning problem, MAUT, AHP, or ELECTRE models are better options. The best opportunity for the tricotyledon method in ITS planning probably lies in the hardware and software development in ITS system design.

2.4 SUMMARY

In the context of public policy ITS has been widely supported by federal, state, and local governments to solve current surface transportation problems. In the planning context, ITS is a complicated system embracing a broad range of technologies and providing numerous user services. During the past decade of implementation, it has gradually become clear that the success of ITS not only depends on the quality of technological components, but depends on the capability of the system to function as an integrated system to address local transportation problems and user needs. A complex system with cutting-edge technology will not be a good choice if it does not solve pressing transportation problems. It would be extremely beneficial if the ITS user services were better connected with local problems and user needs through a systematic planning process.

ITS planning is characterized by making decisions on ITS strategies and implementations. The publication of the National ITS Architecture, the FHWA ITS Planning Process, and various support tools have greatly improved regional and local ITS planning. However, based on a thorough understanding of current ITS planning procedure and a thorough literature review, it was found that the decision-makings process could be enhanced using appropriate mathematical decision analysis frameworks.

One opportunity exists in developing an ITS market package plan. Screening ITS market packages is the initial step and one of the fundamental tasks in ITS planning. The method currently used is a goal-oriented approach. Namely, by mapping benefits of market packages and defined system goals, the market packages that showing high benefits in achieving these goals are selected. A limitation of this method is that when there are multiple goals, the identified ITS market packages combinations may not be optimal. In addition, since ITS planning is typically finically constrained, decision makers must find a plan that maximizes system benefits using limited resource.

The other opportunity exists in ITS deployment plan development, which requires alternative comparison and priority ranking. A literature review shows that state-of-the-art ITS deployment ranking still falls short of comparing alternatives in a systematic manner. Goal-oriented approaches, cost-benefit analysis, and empirical methods were applied to evaluate ITS deployments. However, these methods often fail to provide decision makers enough information and convincing results to make decisions when there are multiple choices.

To address these issues and aid in decision makings in the ITS planning process, a variety of decision analysis approaches can be used. Based on a thorough review of decision analysis approaches, it was found that the multicriteria decision analysis approaches best suit the characteristics of ITS planning. MAUT, AHP and ELECTRE are three most often applied multicriteria decision analysis approaches.

They are proven methods that solve decision analysis problems in public policy, environment management, water resource management, energy planning, financial analysis, and of course, transportation. Applying these approaches into ITS planning is feasible. The AHP approach has been applied in ITS project development and meaningful results have been reported (Hu and Shi, 2002). However, it is difficult to find studies in which MAUT and ELECTRE are applied in ITS planning.

Based on the understanding of ITS planning problems and a thorough literature review, two studies are proposed in this research: one study is to develop a MAUT model for ITS market package screening; the other is to develop an ELECTRE method for ITS deployments comparison. No effort has been found of using these approaches to address these issues. The benefits of these studies are foreseeable. In the next two chapters, the applications of these methods in ITS planning will be discussed in detail.

Chapter 3 A Multi-Attribute Utility Theory Approach for ITS Market Package Plan Development

3.1 INTRODUCTION

Screening ITS market packages—a process that identifies the ITS technology bundles that will work together to deliver specific transportation services to address local transportation problems—is a fundamental task and central element in the ITS strategic planning.

The National ITS Architecture documentation provides definitions of a variety of ITS market packages. The benefits of each market package in achieving certain ITS system goals were evaluated through field tests and post-project assessments. The qualitative benefits of each market package in achieving certain ITS system goals were then summarized based on evaluation results (USDOT, 2005a). To develop an ITS market package plan or an ITS master plan, ITS planners usually complete market package screening by mapping the benefits of market packages with defined local ITS goals. The market packages that show high benefits in achieving the defined system goals would be included in the market package plan and recommended for implementation. For example, given the goal of improving safety, it is found that *Speed Monitoring*, *Intersection Safety Warning*, *Weather Information Processing and Distribution*, and many other ITS market packages show high benefits in improving safety. Therefore, these ITS market packages are recommended to be included in the ITS market package plan.

The advantage of this heuristic approach is that it makes market package screening straightforward and easy to follow. However, planners may face challenges and difficulties from having multiple system goals and multiple options, a normal aspect of ITS planning. Given this situation, simply mapping the benefits of market packages with system goals may not return the optimal ITS market package plan. On the other hand, since ITS implementation is financially constrained, it is not feasible to deploy all ITS market packages that show high benefits in achieving the goals. Priority settings must be provided in terms of short term, mid term, and long term plans. With the current method, this is not feasible. ITS market packages are more difficult to analyze in advance than one might anticipate. ITS market package screening is one of the initial steps in ITS system planning and is the foundation of the deployment plan. An optimal ITS market package plan is desired to maximize system benefits. Using innovative methods to identify the best market package plan will enhance the positive impact of ITS investments.

3.2 THE MULTI-ATTRIBUTE UTILITY THEORY APPROACH

ITS market package plan development revolves around making decisions on ITS market packages. The challenges and difficulties are rooted in issues such as unclear impacts, multi-objectives, and involvement of multiple stakeholders. In general, limited applications of decision analysis were found in ITS planning literature. The state-of-the-art still falls short of developing ITS market package plans in a systematic manner. There is a tremendous opportunity to improve ITS planning through the application of proper decision analysis techniques. The characteristics of ITS planning, as mentioned in the literature review section, make it suitable for applying multiple criteria decision analysis, especially the multi-attribute utility theory (MAUT) approach (Keeney and Raifa, 1993). No previous effort has been found using the MAUT approach for ITS market package plan development. Using this approach, the decision process in ITS planning can be improved and the chance for the success of ITS implementation enhanced.

The MAUT approach embraces both a large body of mathematical theory for utility models and a wide range of practical assessment techniques that together assist decision makers with regard to ranking alternatives, making a selection, or clarifying a decision situation. The MAUT approach is usually applied when a decision maker is to select among a discrete number of alternatives that are evaluated using two or more measures. The alternatives may involve uncertainties and may require sequential actions at different times. It is assumed that the decision maker will maximize a utility function that depends on the objectives as well as the relative importance of each objective. Sensitivity analysis is included in the assessment and selection processes in order to evaluate the effects on the results of changes in measure levels or preferences.

When a utility function is used to represent an individual's preferences, certain conditions must be satisfied. As originally proposed by Markowitz (1959) and summarized by Goicoechea et al. (1982), four axioms must be conformed so that an individual's preferences can be expressed by a utility function for both certain and uncertain outcomes:

1) For two alternatives, A_1 and A_2, one of the following must be true: the individual prefers A_1 to A_2, prefers A_2 to A_1, or is indifferent between them.

2) The individual's evaluation of alternatives is transitive: if he prefers A_1 to A_2 and A_2 to A_3, the he prefers A_1 to A_3.
3) Assuming that A_1 is preferred to A_2 and A_2 to A_3, then there exists some probability p, $0<p<1$, that the individual is indifferent between outcome A_2 with certainty or getting A_1 with probability p and A_3 with probability $(1-p)$. In other words, there exists a certainty equivalent to any gamble.
4) Assuming an individual is indifferent between two choices, A_1 and A_2, and if A_3 is any third alternative, then he will be indifferent between the following two gambles: Gamble 1 offers a probability p of receiving A_1 and a probability $(1-p)$ of receiving A_3, and Gamble 2 offers a probability p of receiving A_2 and a probability of $(1-p)$ of receiving A_3.

Utility function has been widely applied in economics and decision-making problems. When there are multiple objectives in a decision-making problem, a multiattribute utility function (MUF) $u(x) = u(x_1, x_2, \ldots, x_m)$ can be used to assess the decision maker's total utility, where $x_i = x_i(a)$ is the ith objective function evaluated at point a.

According to MAUT, the overall utility $u(x)$ of an alternative or an object x is defined as a weighted addition of its utility with respect to its relevant value dimensions (i.e. performance measures) (Winterfeld and Edwards, 1986). The overall utility is defined by the following overall utility function:

$$u(x) = \sum_{i=1}^{n} w_i u_i(x) \qquad (3.2.1)$$

or

$$1 + ku(x_1, x_2, \ldots, x_n) = \prod_{i=1}^{n} [1 + kk_i u_i(x_i)] \tag{3.2.2}$$

Where $u_i(x)$ is the utility of the alternative or object on the i-th sub-goal or performance measure; n is the number of different sub-goals or performance measures; w_i is the weight that determines the impact of the i-th sub-goal or performance measure on the overall utility, i.e. the relative importance of i-th sub-goal or performance where

$$\sum_{i=1}^{n} w_i = 1 \tag{3.2.3}$$

The k_i's are scaling constants with $0 < k_i < 1$. The function (3.2.1) is usually referred to as the additive form, which assumes individual's preferences satisfy certain independence conditions. The function (3.2.2) is usually referred to as the multiplicative utility function, which assumes that an individual's preferences are correlated.

For each sub-goal or performance measure, the utility function $u_i(x)$ is defined as the utility of relevant attributes:

$$u_i(x) = \sum_{a \in A_i} w_{ai} u_{ai}(l(a)) \tag{3.2.4}$$

Where A_i is the set of all attributes relevant to the i-th sub-goal or performance measure; $u_{ai}(l(a))$ is the utility of the actual level $l(a)$ of attribute a on the i-th sub-goal or performance measure; w_{ai} is the weight that determines the impact of the utility of attribute a on the i-th sub-goal or performance measure. w_{ai} is also called the relative importance of attribute a for the sub-goal or performance measure. For all sub-goals and performance measures

$$\sum_{a \in A_i} w_{ai} = 1 \tag{3.2.5}$$

3.3 A MAUT MODEL FOR ITS MARKET PACKAGE PLAN DEVELOPMENT

In order to better understand the MAUT model and its application in ITS market package plan development, the MAUT model was carefully constructed based on ITS planning objectives and available data resources. A case study in Austin, Texas was performed to validate the approach.

Austin is a pilot area in the nation with strong interest in seeking ITS solutions to solve local transportation problems. The Texas Department of Transportation (TxDOT) Austin District Office is responsible for planning and implementing ITS projects in the Austin metropolitan area. In order to integrate existing and planned ITS deployments, the Combined Traffic and Emergency Communications Center (CTECC) was constructed.

3.3.1 Construction of the MAUT Model

3.3.1.1 Problem Formulation

Developing an ITS market package plan requires decision makers to choose ITS market packages that best meet local goals. Given a set of alternatives $\{O_1, O_2, \ldots, O_m\}$ which are ITS market packages defined in the National ITS Architecture, a set of measures to evaluate the outcomes of these alternatives $\{x_1, x_2, \ldots, x_n\}$, and a set of relative importance of each measure $\{k_1, k_2, \ldots, k_n\}$, a general form of the additive utility function are used to solve the ITS market package screening problem, assuming the decision maker's preferences are consistent with certain independence conditions. The mathematical representation of this MAUT model is as follows:

$$u(x_1, x_2, \ldots, x_n) = \sum_{i=1}^{n} k_i u_i(x_i) \qquad (3.3.1)$$

Where i = attribute of interest, $u(x_1, x_2, \ldots x_n)$ is the total utility for a given ITS market package with respect to the performance measure set, x_i = the i-th performance measure, $u_i(\cdot)$ is a single-attribute utility function over measure i that scaled from 0 to 1, and k_i is the weight, i.e. the relative importance, of measure i where

$$\sum_{i=1}^{n} k_i = 1 \tag{3.3.2}$$

If the decision maker's preferences are not consistent with the additive model, Dyer et al.*(1998)* suggest that a multiplicative model, which is based on a weaker independence condition, might be appropriate. The multiplicative model is as follows:

$$1 + ku(x_1, x_2, \ldots, x_n) = \prod_{i=1}^{n} [1 + kk_i u_i(x_i)] \tag{3.3.3}$$

In this expression, $u_i(\cdot)$ is still a single-attribute utility function over measure i that scaled from 0 to 1, k_i is positive scaling constant satisfying $0 \leq k_i \leq 1$, and k is an additional constant that measures the interactions of different measures on preferences. The value of k can be determined by an additional question similar to the question used to determine the performance weighting scheme. When $\sum k_i = 1$, the multiplicative model collapses to the additive model.

3.3.1.2 The Alternatives

The purpose of developing an ITS market package plan is to identify market packages most suitable to solve local transportation problems. The alternatives for consideration are the ITS market packages. A complete list of ITS market packages defined in the National ITS Architecture are shown in Tables 2.2-1a through 2.2-1c, which are grouped into eight bundles:

- Traffic Management
- Public Transportation
- Traveler Information
- Advanced Vehicle Safety
- Commercial Vehicle Operations
- Emergency Management
- Achieved Data Management
- Maintenance and Construction Operations

Since ITS technologies evolve rapidly and ITS systems are open and expandable, the number of market packages is also expanding. For additional details regarding these market packages, their descriptions, functions, and interrelationships, please refer to the National ITS Architecture documentation (USDOT, 2005a).

3.3.1.3 The Objectives and Performance Measures

Similar to many other transportation improvement programs, the overall objective of ITS implementation is to improve the transportation system and make it more effective, efficient, and safe. To aid users in developing ITS plans, the FHWA has recommended the following six objectives (USDOT, 1996a; USDOT, 1996b; USDOT, 1997):

- Increase operational efficiency and capacity of the transportation system.

- Enhance personal mobility, convenience, and comfort of the transportation system.
- Improve the safety of the nation's transportation system.
- Reduce energy consumption and environmental costs.
- Enhance the present and future economic productivity of individuals, organizations, and the economy as a whole.
- Create an environment in which the development of ITS can flourish.

These objectives represent a wide range of concerns from various stakeholders from the public sector, private sector, and traveling public. Corresponding measures can be defined to meet these ITS system objectives. Specifically, six ITS system goals, which can also be used as performance measures, are recommended by FHWA (USDOT, 1996a; USDOT, 1996b; USDOT, 1997):

- *Increase Transportation System Efficiency.* This goal is most applicable to outlying urban areas and suburbs, where congestion is a significant problem and road capacity increases are the desired solution (e.g., alternative modes are not present or do not provide a viable alternative to private vehicles).
- *Improve Mobility*. This goal applies to congested areas that wish to influence both demand and capacity to improve mobility for individuals.
- *Improve Safety*. This goal has universal importance but is especially significant in rural areas, where a disproportionate number of serious accidents occur.

- *Reduce Fuel Consumption and Environmental Costs*. This goal is of particular importance to areas that are not compliant to federal air quality standards.
- *Increase Economic Productivity*. This goal has universal importance.
- *Create an Environment for an ITS Market*. This goal directly affects the characteristics of the physical architecture and its deployment. It is proposed to assess the ability of the architecture to create a market for ITS products and services.

These goals and measures reflect the FHWA's concerns with respect to ITS implementations. Many ITS research and development efforts have been conducted targeting these goals. In this study FHWA goals are followed using the goal hierarchy for ITS market packages screening shown in Figure 3.3-1. Different ITS deployment agencies in the nation may have different concerns due to disparities in regional characteristics and constituent interests. However, these six goals and measures cover most concerns anticipated as a result of ITS deployments.

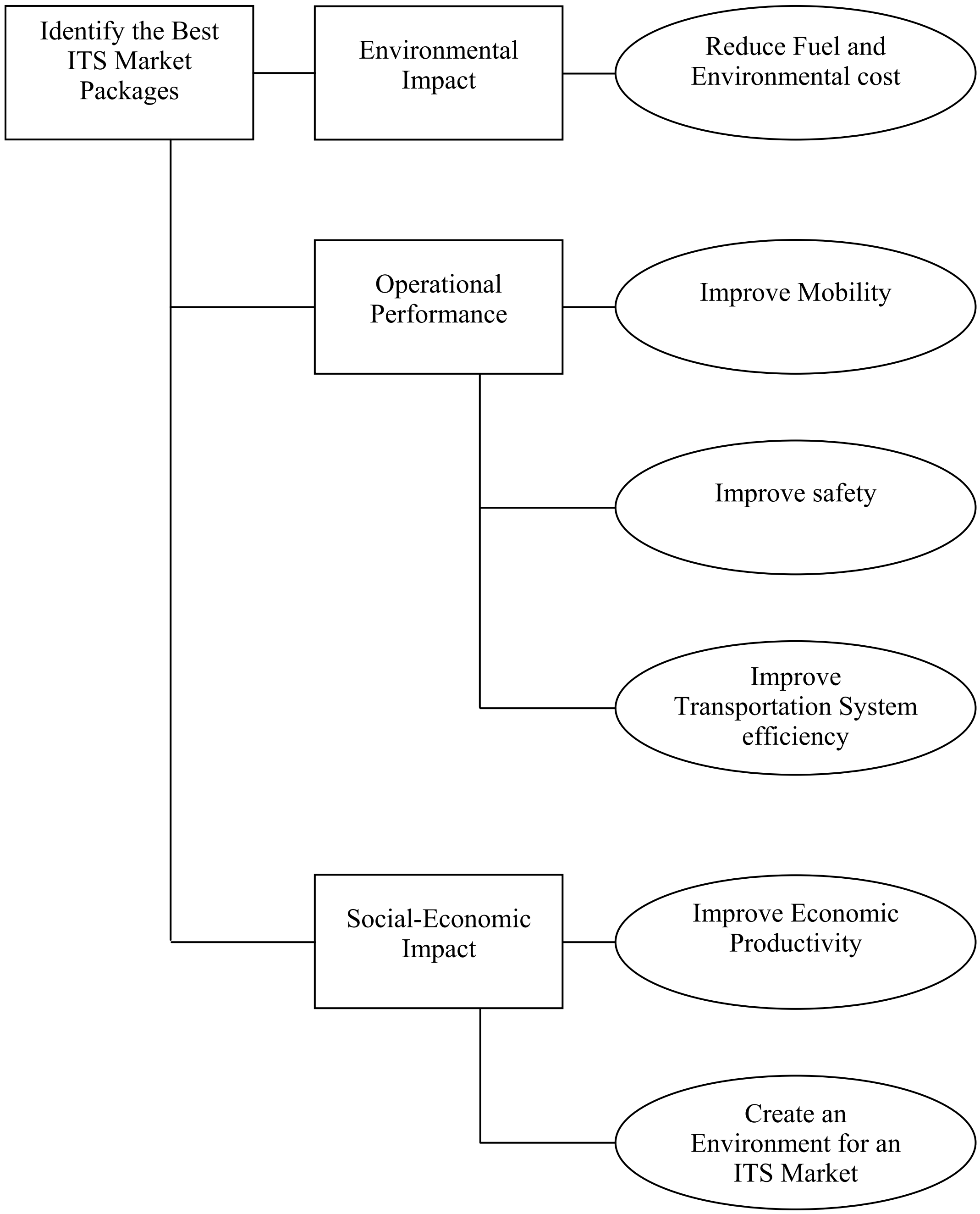

Figure 3.3-1: Goal Hierarchy and Measures for ITS Market Package Plan Development

3.3.1.4 Quantification of Performance Measures

Evaluating ITS benefits is difficult. The difficulties are rooted in the complexity of the transportation system, which includes extensive uncertainties. In the past decade, many field tests have been performed and many ITS projects assessed. Based on these studies a qualitative assessment was summarized for ITS market packages. Since ITS market package plan development is a strategic planning action, a qualitative level assessment is appropriate. However, it is recommended that more detailed ITS designs, deployment plan development, and ITS technology selections be evaluated both qualitatively and quantitatively.

The National ITS Architecture documentation presents qualitative judgments of benefits that can be expected from each market package. Tables 3.3-1a through 3.3-1g illustrate the benefits of each ITS market package in achieving a certain ITS system goal from a qualitative perspective. The projected benefits are aligned with specific needs of a deploying agency, which includes those in both the public and private sectors, to select the right market packages for deployment for a designated area. To perform the MAUT decision analysis, qualitative evaluation results provided in the National ITS Architecture documentation were used to quantify the utilities.

For additional details regarding the evaluation of these ITS market packages, see the ITS Performance and Benefit Study report (USDOT, 1996b and USDOT, 2005a).

Table 3.3-1a: Benefits of ITS Market Packages

	Market Package Name	Increase Transportation System Efficiency	Enhance Mobility	Improve Safety	Reduce Fuel Consumption and Environmental Cost	Increase Economic Productivity	Create an Environment for an ITS Market
Advanced Data Management	ITS Data Mart	**	**	**	**	**	***
	ITS Data Warehouse	**	**	**	**	**	***
	ITS Virtual Data Warehouse	**	**	**	**	**	***
Public Transportation	Transit Vehicle Tracking	*	**		*	*	*
	Transit Fixed-Route Operations	*	**		*	*	*
	Demand Response Transit Operations	*	**		*	*	*
	Transit Passenger and Fare Management					**	*
	Transit Security			**			*
	Transit Maintenance					*	*
	Multi-modal Coordination	*	*			*	
	Transit Traveler Information	*	**	*		*	*

Key: * — low benefit, ** — moderate benefit, ***— high benefit

(Source: USDOT, 2005a)

Table 3.3-1b: Benefits of ITS Market Packages (Continued)

	Market Package Name	Increase Transportation System Efficiency	Enhance Mobility	Improve Safety	Reduce Fuel Consumption and Environmental Cost	Increase Economic Productivity	Create an Environment for an ITS Market
Traffic Management	Network Surveillance	*	*		*		*
	Probe Surveillance	*	*		*		**
	Surface Street Control	**	***	**	**		*
	Freeway Control	**	***	*	**		*
	HOV Lane Management	*	**		*		*
	Traffic Information Dissemination	**	*		*		*
	Regional Traffic Control	***	***	**	***		*
	Traffic Incident Management System	**	**	**	***		*
	Traffic Forecast and Demand Management	**	**				*
	Electronic Toll Collection					**	*
	Emissions Monitoring and Management				***		**
	Virtual TMC and Smart Probe Data	*	*		*	*	*
	Standard Railroad Grade Crossing			***			*
	Advanced Railroad Grade Crossing			***			*
	Railroad Operations Coordination	*	*		*		*
	Parking Facility Management	**			*	*	
	Regional Parking Management	**	*		*		
	Reversible Lane Management	**	*		*		
	Speed Monitoring	**	*	***			*
	Drawbridge Management	**	**	*		*	
	Roadway Closure Management	*	**		*		*

Key: * — low benefit, ** — moderate benefit, ***— high benefit

(Source: USDOT, 2005a)

Table 3.3-1c: Benefits of ITS Market Packages (Continued)

	Market Package Name	Increase Transportation System Efficiency	Enhance Mobility	Improve Safety	Reduce Fuel Consumption and Environmental Cost	Increase Economic Productivity	Create an Environment for an ITS Market
Traveler Information	Broadcast Traveler Information	*	**		*		***
	Interactive Traveler Information	**	***		*		***
	Autonomous Route Guidance	**	***				***
	Dynamic Route Guidance	**	***	*	*		***
	ISP Based Trip Planning and Route Guidance	**	***	*	*		***
	Integrated Transportation Management/Route Guidance	***	***	*	**		**
	Yellow Pages and Reservation	*					**
	Dynamic Ridesharing	**	*		*		*
	In Vehicle Signing		*	*			***

Key: * — low benefit, ** — moderate benefit, ***— high benefit

(Source: USDOT, 2005a)

Table 3.3-1d: Benefits of ITS Market Packages (Continued)

	Market Package Name	Increase Transportation System Efficiency	Enhance Mobility	Improve Safety	Reduce Fuel Consumption and Environmental Cost	Increase Economic Productivity	Create an Environment for an ITS Market
Vehicle Safety	Vehicle Safety Monitoring			***			***
	Driver Safety Monitoring			***			***
	Longitudinal Safety Warning			***			***
	Lateral Safety Warning			***			***
	Intersection Safety Warning			***			***
	Pre-Crash Restraint Deployment			***			***
	Driver Visibility Improvement			***			***
	Advanced Vehicle Longitudinal Control	**	*	***			***
	Advanced Vehicle Lateral Control	**	*	***			***
	Intersection Collision Avoidance			***			***
	Automated Highway System	***	***	***			***

Key: * — low benefit, ** — moderate benefit, ***— high benefit

(Source: USDOT, 2005a)

Table 3.3-1e: Benefits of ITS Market Packages (Continued)

	Market Package Name	Increase Transportation System Efficiency	Enhance Mobility	Improve Safety	Reduce Fuel Consumption and Environmental Cost	Increase Economic Productivity	Create an Environment for an ITS Market
Commercial Vehicle Operations	Fleet Administration		***	*		***	**
	Freight Administration		***			***	**
	Electronic Clearance	**	***			***	**
	CV Administrative Processes					**	*
	International Border Electronic Clearance	**	***			***	**
	Weigh-In-Motion	**	***			***	**
	Roadside CVO Safety	*	**	**		**	**
	On-board CVO and Freight Safety & Security			***		**	**
	CVO Fleet Maintenance	*		**		**	*
	HAZMAT Management	*		**		**	*
	Roadside HAZMAT Security Detection and Mitigation			*			*
	CV Driver Security Authentication			*			*
	Freight Assignment Tracking			*			*

Key: * — low benefit, ** — moderate benefit, ***— high benefit

(Source: USDOT, 2005a)

Table 3.3-1f: Benefits of ITS Market Packages (Continued)

	Market Package Name	**Increase Transportation System Efficiency**	**Enhance Mobility**	**Improve Safety**	**Reduce Fuel Consumption and Environmental Cost**	**Increase Economic Productivity**	**Create an Environment for an ITS Market**
Emergency Management	Emergency Call-Taking and Dispatch	*		***	*	**	*
	Emergency Routing	*		***	*	**	*
	Mayday and Alarms Support			***		*	**
	Roadway Service Patrols	*		***	*	**	*
	Transportation Infrastructure Protection			*			*
	Wide-Area Alert			*			*
	Early Warning System			*			*
	Disaster Response and Recovery	*		*	*		
	Evacuation and Reentry Management	*	*				
	Disaster Traveler Information	*	*				

Key: * — low benefit, ** — moderate benefit, ***— high benefit

(Source: USDOT, 2005a)

Table 3.3-1g: Benefits of ITS Market Packages (Continued)

	Market Package Name	Increase Transportation System Efficiency	Enhance Mobility	Improve Safety	Reduce Fuel Consumption and Environmental Cost	Increase Economic Productivity	Create an Environment for an ITS Market
Maintenance & Construction Management	Maintenance and Construction Vehicle and Equipment Tracking		*	**		**	*
	Maintenance and Construction Vehicle Maintenance			**	*	**	
	Road Weather Data Collection	**	*	***		**	*
	Weather Information Processing and Distribution	**	*	***		**	**
	Roadway Automated Treatment	*	*	***			*
	Winter Maintenance	**	***	***	*	**	
	Roadway Maintenance and Construction	*	*	*	*		
	Work Zone Management	*			*	*	
	Work Zone Safety Monitoring	*		***	*	*	**
	Maintenance and Construction Activity Coordination	*	*		*	*	

Key: * — low benefit, ** — moderate benefit, ***— high benefit

(Source: USDOT, 2005a)

3.3.1.5 Performance Measure Weights

To compute utilities for alternatives, each goal and measure must be assigned a weight that reflects the relative importance of that measure. Due to disparities in regional characteristics and constituent interests, it is expected that ITS deploying agencies will have different goals and weighting schemes. However, if weights and potential trade-offs are assessed, each agency should be able to identify the market packages most suitable to solve the problems in their respective areas.

Rather than seeking for new expert judgments regarding weights and trade-offs between measures for each agency or location, existing findings can be used to develop weights and reasonable tradeoffs. For example, Levine and Underwood (1996) investigated the preferences of different groups of stakeholders. The results from that study are very beneficial for assessing weights and trade-offs in the ITS market packages screening process.

A questionnaire, which can be found in the appendix, was designed for interviewing ITS planners in TxDOT's District Office in Austin. The purpose of this questionnaire is to investigate the ITS agency's concerns with respect to ITS planning. Questions regarding ITS planning procedure, ITS vision and goals, performance measures, and relative importance of each goal are included. The interviewee was asked to assign a score of 0 through 10 to each goal/measure to represent his or her valuation of the measure's relative importance. A goal/measure receives a score of 10 if the interviewee deems it extremely important and a score of 0 if the interviewee finds its importance negligible. Ratio scales are then calculated to represent the weights for those measures. The weight assigned to a sub-goal is derived from the global weights of the measures under that sub-goal. Table 3.3-2 illustrates the weighting scheme in Austin, TX based on TxDOT's concerns. The valuation of the ITS goals from stakeholders such as the private transportation sector, citizens groups, and the ITS business sector are not included in this study for two reasons. First, the main research objective was to help the district office identify the ITS market packages that can address the local transportation problems, thereby representing TxDOT's interests and concerns. Second, and most importantly, sensitivity analysis was performed to examine how changes in goal/measure weights will affect final rankings of alternatives. Sensitivity analysis can be an effective tool to investigate the outcomes of potential valuation conflicts between various stakeholders.

Table 3.3-2: Weighting Scheme for MAUT Analysis on ITS Market Packages in Austin, Texas

Sub-Goal	Objectives	Weight	Total
Operational Performance	Increase Transportation System Efficiency	0.265	0.715
	Improve Mobility	0.238	
	Improve Safety	0.212	
Energy and Environmental Impact	Reduce Fuel Consumption and Environmental Cost	0.185	0.185
Social-Economic Impact	Increase Economic Productivity	0.05	0.1
	Create an Environment for an ITS Market	0.05	

When there are multiple stakeholders involved in ITS market plan development, the weight assessment process becomes more complicated. Stakeholders may have varying degrees of knowledge and experience. Their opinions and valuations of ITS goals may be taken into consideration using different weights. An average of the weights based on each stakeholder or interest group's valuation may not well reflect the reality. In many cases, the valuations may be counted differently based on the credentials of the stakeholders. Given this situation, an AHP method (Levine and Underwood, 1996) is recommended.

3.3.2 Evaluation of the Alternatives

Once a MAUT model is constructed, ITS market packages can then be evaluated. Single utility function values are aggregated with the following three assumptions:

1) Decision maker's preferences are consistent with the additive model;
2) Single utility functions are linear; and
3) Weights for measures are directly assessed.

During aggregation, weights reflect the relative importance of measures and are multiplied by corresponding single utility values. The evaluation results of ITS market packages, presented with a stack bar graph, are shown in Figure 3.3-2. At this point, the relative strength and weakness of each ITS market package can be investigated in more detail. The stack bar graph provides a visual display of the aggregated strength of the market packages on each of the performance measures. Figure 3.3-3 reflects the relative contributions of individual sub-objectives to the overall utility for each alternative. In this graph, each segment represents the utility value of each market package on each sub-goal using the additive utility function.

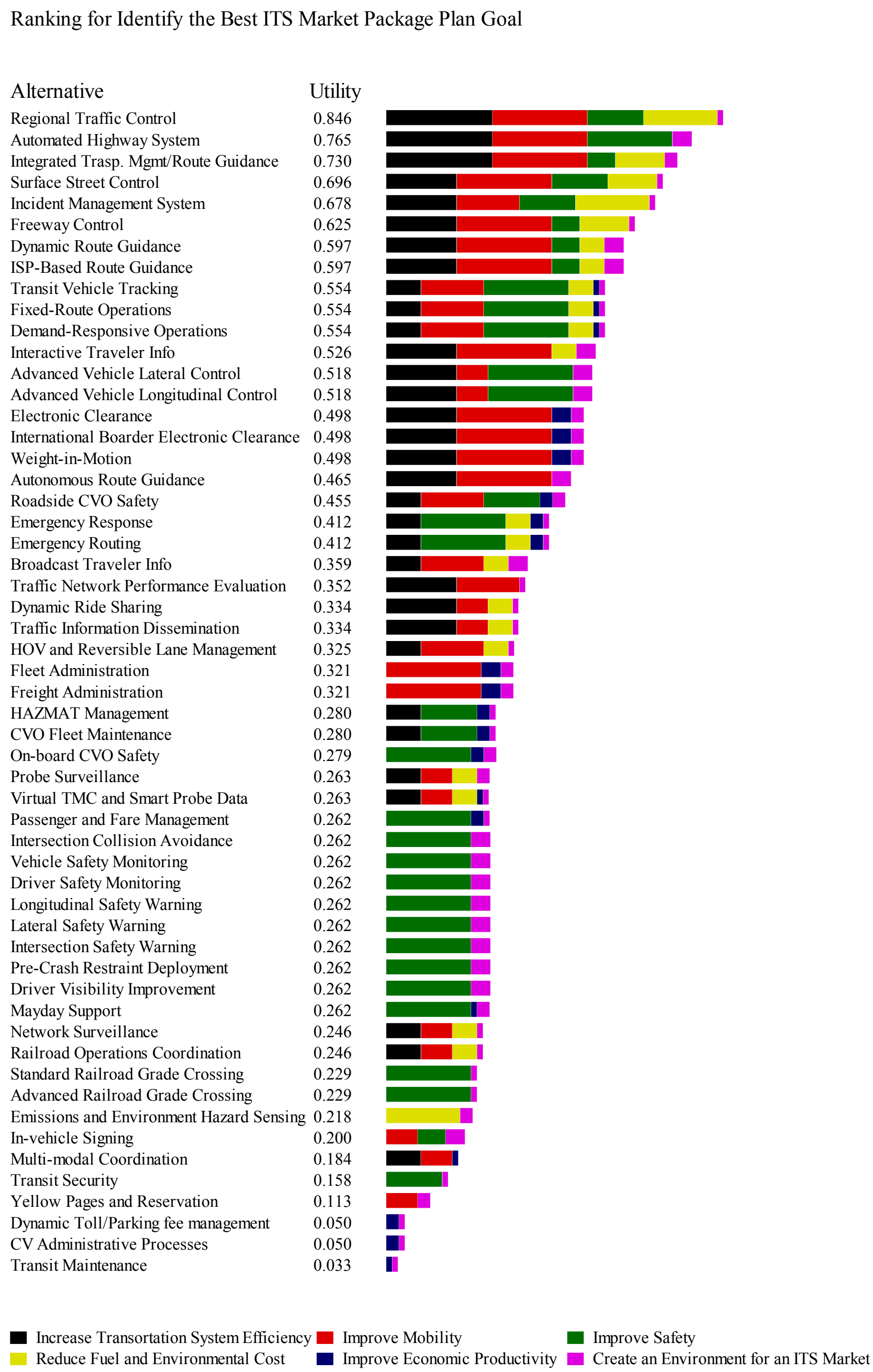

Figure 3.3-2: Contributions of Performance Measures to Overall Utility

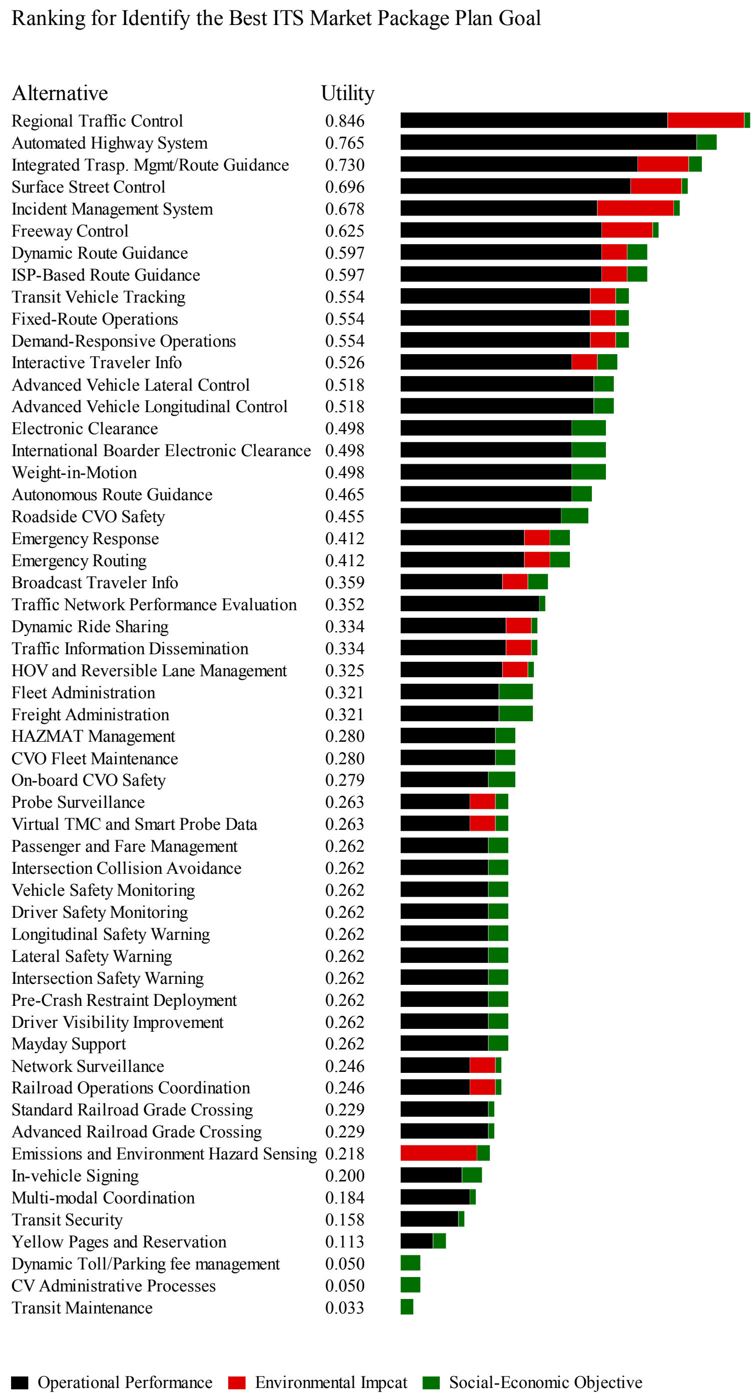

Figure 3.3-3: Contributions of Sub-Objectives to Overall Utility

Given the weighting scheme shown in Table 3.3-2, the MAUT ranking analysis shows that the following ten market packages, with descriptions provided in the National ITS Architecture (USDOT, 2005a), have the highest aggregated utilities:

1) *Regional Traffic Control*. This market package provides for the sharing of traffic information and control among traffic management centers to support a regional control strategy. It advances the Surface Street Control and Freeway Control Market Packages by adding the communications links and integrated control strategies that enable integrated inter-jurisdictional traffic control.
2) *Automated Highway System*. This market package enables "hands-off" operation of the vehicle on the automated portion of the highway system. Implementation requires lateral lane holding, vehicle speed and steering control, and *Automated Highway System* check-in and checkout. This market package currently supports a balance in intelligence allocation between infrastructure and the vehicle pending selection of a single operational concept by the AHS consortium. However, it is still a number of years away from practical deployment.
3) *Integrated Transportation Management/Route Guidance*. This market package will provide advanced route planning and guidance which is responsive to current conditions and supports collection of near-real time information on intended routes for a proportion of the vehicles in the network.
4) *Surface Street Control*. This market package provides the central control and monitoring equipment, communication links, and the signal control

equipment that support local surface street control and/or arterial traffic management. It is generally an intra-jurisdictional package that does not rely on real-time communications between separate control systems to achieve area-wide traffic signal coordination and is consistent with typical urban traffic signal control systems.

5) *Incident Management System.* This market package manages both unexpected incidents and planned events so that the impact to the transportation network and traveler safety is minimized. It includes incident detection capabilities through roadside surveillance devices (e.g. CCTV) and through regional coordination with other traffic management, maintenance and construction management, and emergency management centers as well as rail operations and event promoters.

6) *Freeway Control*. This market package provides central monitoring and control, communications, and field equipment that support freeway management. It supports a range of freeway management control strategies including ramp metering, interchange metering, mainline lane controls, mainline metering, and other strategies including variable speed controls.

7) *Dynamic Route Guidance*. This market package offers advanced route planning and guidance that is responsive to current conditions. It combines the autonomous route guidance user equipment with a digital receiver capable of receiving real-time traffic, transit, and road condition information, which is considered by the user equipment in provision of route guidance.

8) *ISP-Based Route Guidance*. This market package offers the user trip planning and en-route guidance services. It generates a trip plan, including a multimodal route and associated service information (e.g., parking information), based on traveler preferences and constraints. Routes may be based on static information or reflect real time network conditions.

9) *Transit Vehicle Tracking*. This market package monitors current transit vehicle location using an Automated Vehicle Location (AVL) system. The location data may be used to determine real time schedule adherence and update the transit system's schedule in real-time. Vehicle position may be determined either by the vehicle (e.g., through GPS) and relayed to the infrastructure or may be determined directly by the communications infrastructure.

10) Fixed Route Operation. This market package performs transit vehicle routing and scheduling, as well as automatic operator assignment and system monitoring for fixed-route and flexible-route transit services. This service determines current schedule performance using AVL data and provides information displays at the Transit Management Subsystem. Static and real time transit data is exchanged with Information Service Providers where it is integrated with that from other transportation modes (e.g. rail, ferry, air) to provide the public with integrated and personalized dynamic schedules.

The number of ITS market packages recommended for deployment is not limited to ten. Having a higher utility means that a particular ITS market package would have more potential to meet local objectives compared to other alternatives. The rankings provide ITS deployment agencies with a prioritization strategy for ITS project implementation. Based on the rankings of these market packages, the ITS market package plan can be defined. However, some factors must be considered: the maturity of a given ITS package and the potential funding availability for these market packages. For example, according to the ranking results, *Automated Highway System* was given a very high utility that made it the second most desirable market package. However, an *Automated Highway System* is still a number of years away from practical deployment. It may not be included in a short-term plan, or even a long-term plan.

Based on the ranking results and consideration of the factors such as maturity, the ITS market packages with high rankings that fit local needs will be recommended. The number of market packages that will be included in the Austin area ITS strategic plan depends on the vision for ITS, local transportation problems, and funding availability. Compared to the conventional ITS market packages screening method, the MAUT approach advances by providing decision makers with more detail to better understand which options are better suited to address the local transportation problems. The conventional ITS market package screening method is unable to provide ITS planners such rankings based on a systematic evaluation.

3.3.3 Sensitivity Analysis

Sensitivity analysis is a procedure to determine the sensitivity of the outcomes of an alternative to changes in its parameters. If a small change in a parameter results in relatively large changes in outcomes, the outcomes are said to be sensitive to that parameter. Weight assessment is a critical part in applying MAUT approach to ITS market package screening as it could directly affect the ranking of alternatives. However, weights are generally determined by decision maker's preferences. Therefore, subjectivities are inevitably involved. In addition, conflicts could exist between various stakeholders when assigning weights. Given this situation, sensitivity analysis should be performed to enable ITS planners to examine the effects of subjectivity and possible weight assessment conflicts between various stakeholders.

To examine how changes in measure weight or preference levels affect the evaluation results, sensitivity analyses were performed on the sub-goals and measures in the Austin case. When a sensitivity analysis is performed on a selected sub-goal or measure, the change in its weight is assigned to other sub-goals or measures proportionally according to their original weights.

There are three sub-goals that contain six FHWA ITS system planning measures. Figures 3.3-4, 3.3-5, 3.3-6 present graphical sensitivity analysis results on the weights of "*Operational Performance Goal*", "*Environmental Impact Goal*", and "*Socio-Economic Impact Goal*", respectively. Figures 3.3-7 through 3.3-11 present sensitivity analysis results on the weights of performance measures under the sub-goals.

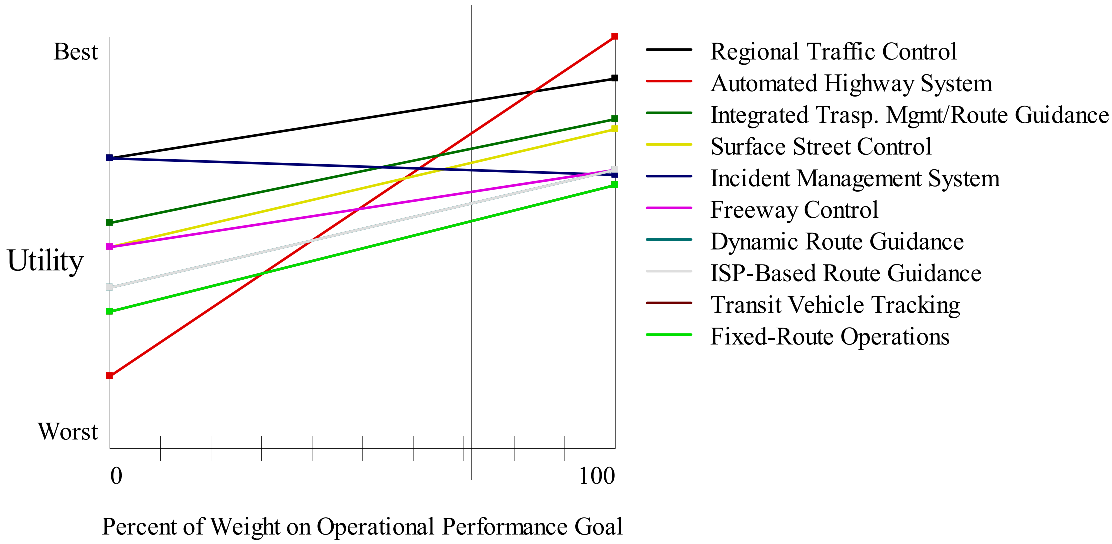

Figure 3.3-4: Sensitivity Analysis on *Operational Performance* Goal

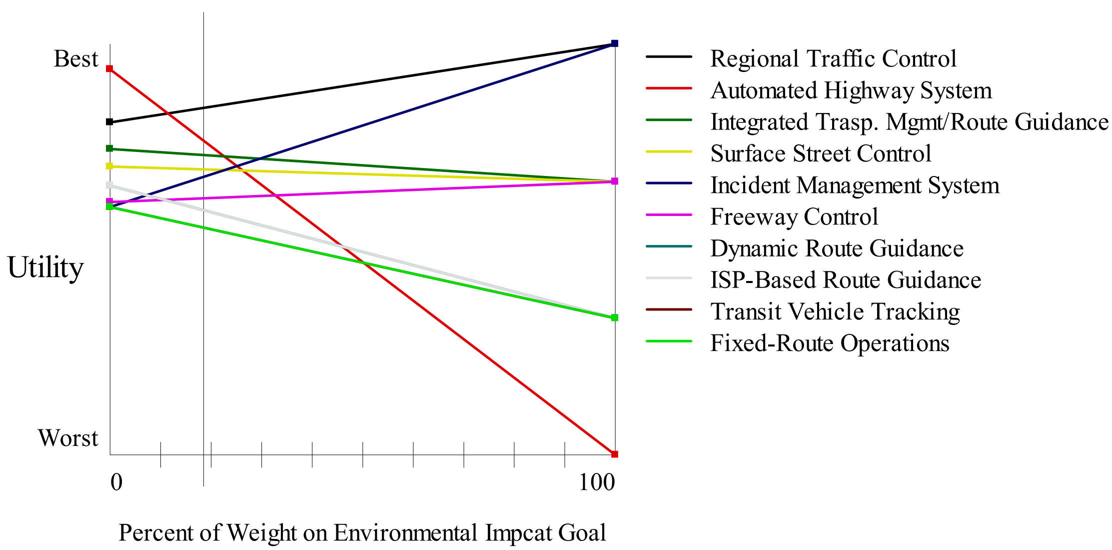

Figure 3.3-5: Sensitivity Analysis on *Environmental Impact* Goal

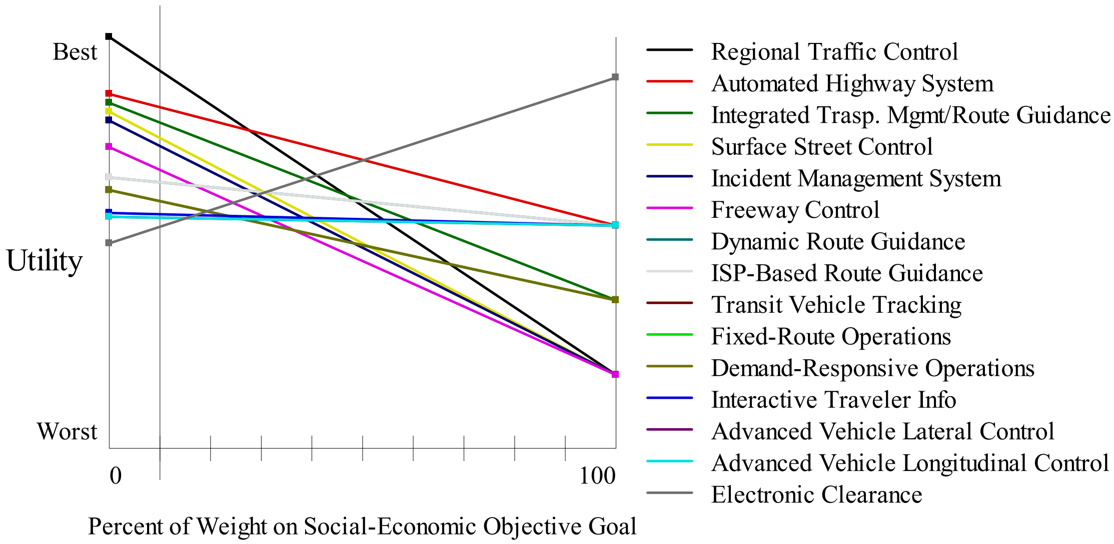

Figure 3.3-6: Sensitivity Analysis on *Socio-Economic Impact* Goal

The sensitivity graph in Figure 3.3-4 depicts that changing the weight assigned to the *Operational Performance* sub-goal will slightly affect the rankings of top ten market packages. A vertical line, which indicates the weight on the operational performance goal, is used to show the ranking status of the alternatives. As shown in Figure 3.3-4, when the weight on the *Operational Performance* sub-goal increases, foremost top-ranked market packages will sustain higher total utilities, with the exception of the *Incident Management System* package. The *Automated Highway System* package has the most significant increase and will eventually dominate other market packages when the weight on the *Operational Performance* sub-goal is more than 0.84. This occurs because the *Automated Highway System* shows high benefits with respect to increasing transportation system efficiency and mobility, which are decisive factors for operational performance. Except for the *Automated Highway System* package, the rankings of packages with high overall utilities will not significantly change. Accordingly, as the weight on the *Operational Performance* sub-goal decreases, most top-ranked packages will result in lower utilities, with the exception of Incident Management System. The ranking of the *Incident Management System* continuously rises as the weight on the *Operational Performance* sub-goal declines. When the weight on the *Operational Performance* goal is less than 0.55, the *Incident Management System* will become the second highest ranked market package. Eventually, the *Incident Management System* package will be dominated by other packages when the weight on the *Operational Performance* sub-goal is less than 0.3. Through sensitivity analysis, it is clear that among the ten top tanked packages, the rankings of *Automated Highway System* and *Incident Management System* are most sensitive to the weight on the *Operational Performance* sub-goal.

Figure 3.3-5 illustrates how the weight assigned to the *Environmental Impact* goal will change the overall utilities and rankings of top ranked packages. Unlike the operational performance sub-goal, changing the weight on environmental impact sub-goal will significantly affects the rankings of the alternatives. As that weight increases, the overall utilities of these alternatives change yielding different trends and different magnitudes. The *Automated Highway System* package drops most sharply in overall ranking and will eventually be dominated by other market packages as the weight on environmental impact sub-goal increases to more than 0.48. *Incident Management System* also shows a notable change in its ranking. Its ranking will continuously increase and will eventually reach the second highest position as the weight on environmental impact sub-goal increases to more than 0.3. On the other hand, the *Automated Highway System* package has the sharpest increase in overall utility and ranking as the weight on environmental impact sub-goal increases. It will eventually dominate all other market packages, including *Regional Traffic Control*, when the weight on environmental impact sub-goal is less than 0.1. The ranking of *Incident Management System* will decrease remarkably and eventually fall to the bottom as the weight on environmental impact sub-goal decreases. Generally, the moving trends of the overall utilities of these top-ranked packages show significant variations. Weight changes in the environmental impact sub-goal/measure will significantly affect the overall utilities of these ITS market packages because they show significant disparities in energy and environmental benefits.

Figure 3.3-6 explains how the weight on the *Social-Economic Impact* goal will affect the overall utilities and rankings of top-ranked packages. Because the weight assigned to this goal is relatively low in the initial assessment, fifteen top-ranked market packages, rather than ten top-ranked ranked packages, are included in the sensitivity analysis. The sensitivity graph shows that the packages, which include *Regional Traffic Control*, *Freeway Control*, *Incident Management*, *Surface Street Control*, and *Integrated Transportation Management/Route Guidance*, drop significantly in overall utility and ranking. When the weight on *Social-Economic Impact Goal* increases to more than 0.3, the rankings of the top-ranked packages will change dramatically. Electronic Clearance has the most significant increase in both overall utility and ranking. In the initial assessment, the *Electronic Clearance* package is ranked the lowest. However, its ranking continues to rise as the weight on the *Social-Economic Impact* goal increases. It will eventually dominate all other packages when the weight on the *Social-Economic Impact* goal increases to more than 0.5.

In order to better understand how the weight on each performance measure affects alternatives' overall utilities and rankings, sensitivity analyses were performed on each measure's weight. Because *Reduce Fuel Consumption and Environmental Cost* is the only measure under the *Environmental Impact* goal, its sensitivity graph is identical to the sensitivity graph of *Environmental Impact Goal,* which is already shown in Figure 3.3-5. Figures 3.3-7 through 3.3-11 present the sensitivity analysis results on the weights assigned to "*Increase Transportation System Efficiency*", "*Improve Safety*", "*Improve Mobility*", "*Increase Economic Productivity*", and "*Create an Environment for an ITS Market*", respectively.

These sensitivity graphs provide ITS planners with sufficient information to identify the packages that are sensitive to the weights of evaluation measures. In addition, these sensitivity graphs help ITS planners predict potential outcomes of conflicting weight assessment between various stakeholders or interest groups.

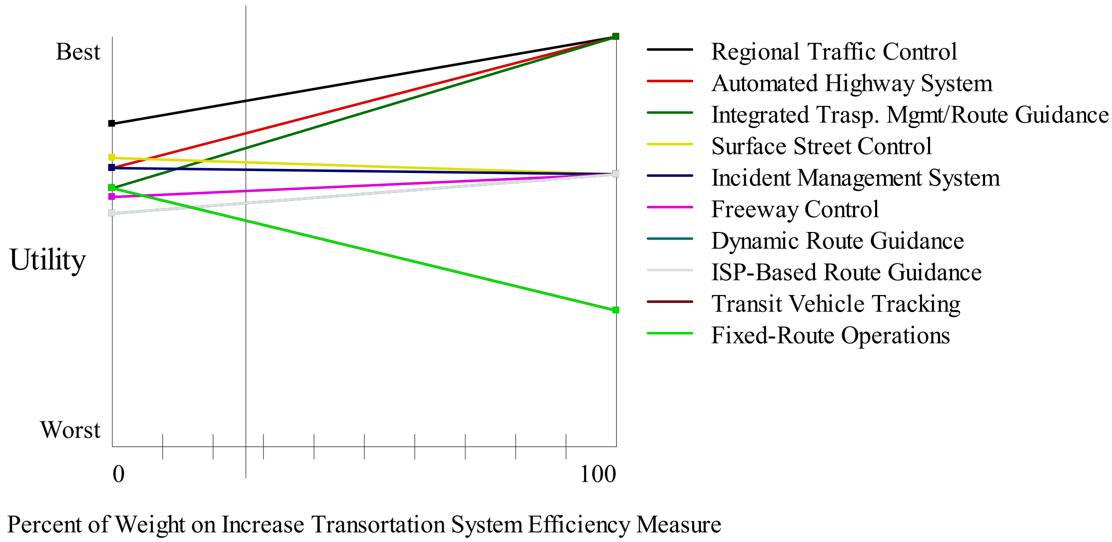

Figure 3.3-7: Sensitivity Analysis on *Increase Transportation System Efficiency* Measure

Figure 3.3-7 illustrates how the weight assigned to the *Increase Transportation System Efficiency* measure will affect the overall utilities and rankings of the top ranked packages. It can be seen that the rankings of the top ten packages will not change as the weight on the efficiency measure increases from the current point of 0.265. Among the top-ranked packages, *Regional Traffic Control*, *Automated Highway System*, and *Integrated Transportation Management/Route Guidance* have the highest benefits with respect to improving the system efficiency. On the other hand, as the weight on the *Increase Transportation System Efficiency* measure decreases, the rankings of *Fixed-Route Operations* and *Transit Vehicle Tracking* will rise and the rankings of *Integrated Transportation Management/Route Guidance* and *Automated Highway System* will fall. These four packages are sensitive to the weight on *Increase Transportation System Efficiency* measure.

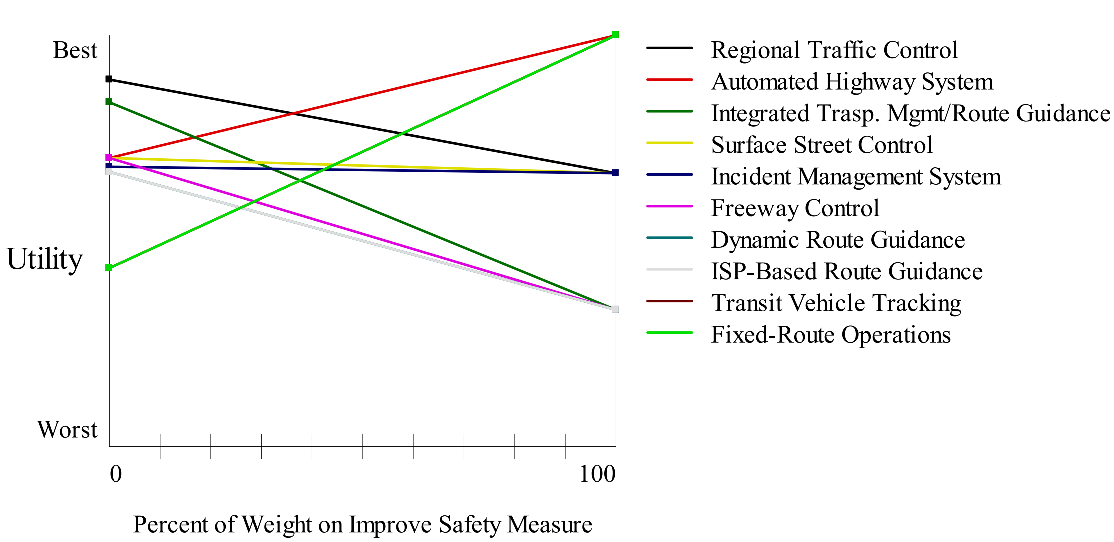

Figure 3.3-8: Sensitivity Analysis on *Improve Safety* Measure

Figure 3.3-8 illustrates how the weight assigned to the *Improve Safety* measure will affect the overall utilities and rankings of the top-ranked packages. It can be seen that *Automated Highway System*, *Fixed-Route Operations*, and *Integrated Transp. Mgmt/Route Guidance* are most sensitive to the weight on safety measure because both of them show high benefits in achieving the safety goal. The overall utilities and rankings of *Automated Highway System* and *Fixed-Route Operations* will rise as the weight on safety measure increases and will decrease as the weight on the *Improve Safety* measure decreases. If the weight assigned to the safety measure increases from current 0.212 to 0.59 or more, *Automated Highway System* and *Fixed-Route Operations* will become the two highest ranked packages. The *Integrated Transp. Mgmt/Route Guidance* package will have the most significant decrease in overall utility and ranking as the weight on safety measure increases.

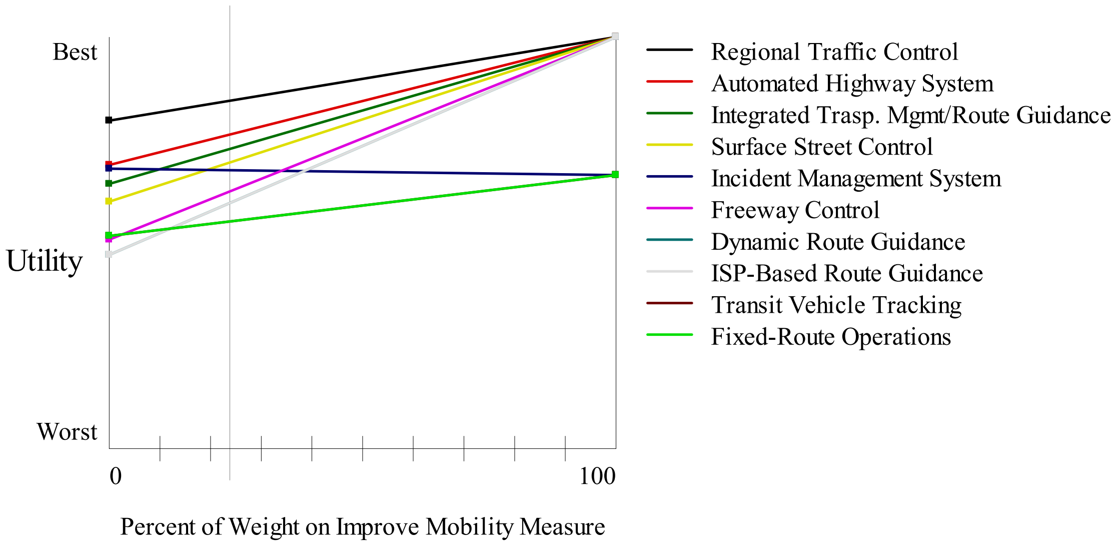

Figure 3.3-9: Sensitivity Analysis on *Improve Mobility* Measure

Figure 3.3-9 illustrates how the weight assigned to the *Improve Mobility* measure will affect the overall utilities and rankings of the top-ranked packages. It can be seen that *Incident Management System* is the most affected package in overall rankings. Its ranking continues to decrease at the points of 0.32 and 0.37 as the weight on mobility measure increases. On the other hand, all packages except *Incident Management System* result in increasing utilities as the weight on mobility measure increases. This implies that *Incident Management System* has the lowest benefits with respect to improving mobility among the top ranked packages. With the exception of *Incident Management System*, the rankings of other packages are not affected significantly.

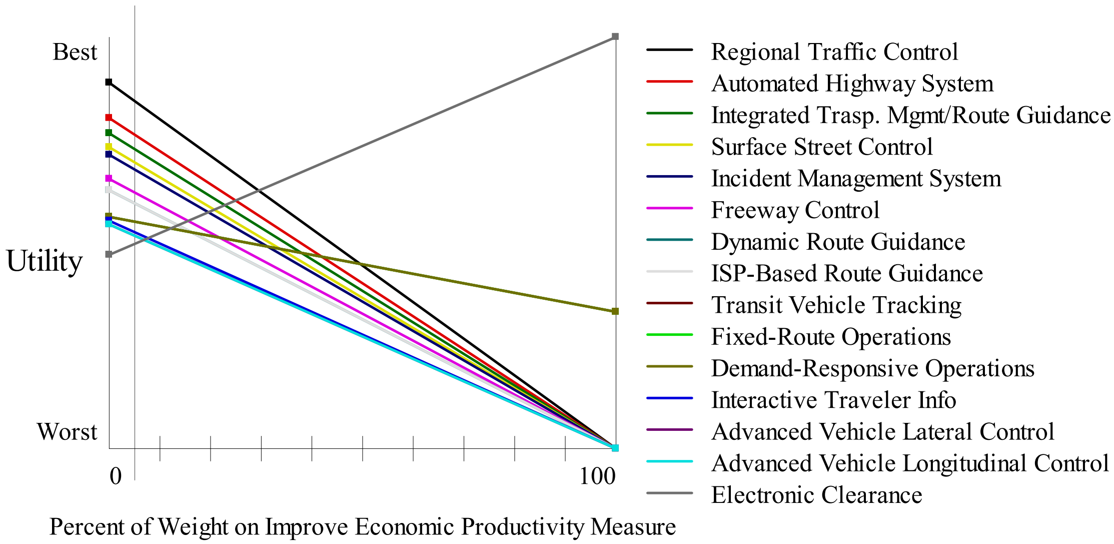

Figure 3.3-10: Sensitivity Analysis on *Improve Economic Productivity* Measure

Figure 3.3-10 illustrates how the weight assigned to the *Improve Economic Productivity* measure affects the overall utilities and rankings of the top-ranked packages. It can be seen that, among the top ranked packages, *Demand-Responsive Operations* and *Electronic Clearance* have the most significant changes in rankings. As the weight on the *Improve Economic Productivity* measure increases, all packages but *Electronic Clearance* obtain decreasing overall utilities because *Electronic Clearance* shows the most significant benefits with respect to the *Improving Economic Productivity* measure. As the weight on the *Improve Economic Productivity* measure increases to more than 0.3, the *Electronic Clearance* package jumps from last place to first place in rankings. *Demand-Responsive Operations* becomes the second best package when the weight increases to more than 0.5. Therefore, it can be said that Electronic Clearance and Demand-Responsive

Operations are most sensitive to the weight on *Improve Economic Productivity* measure.

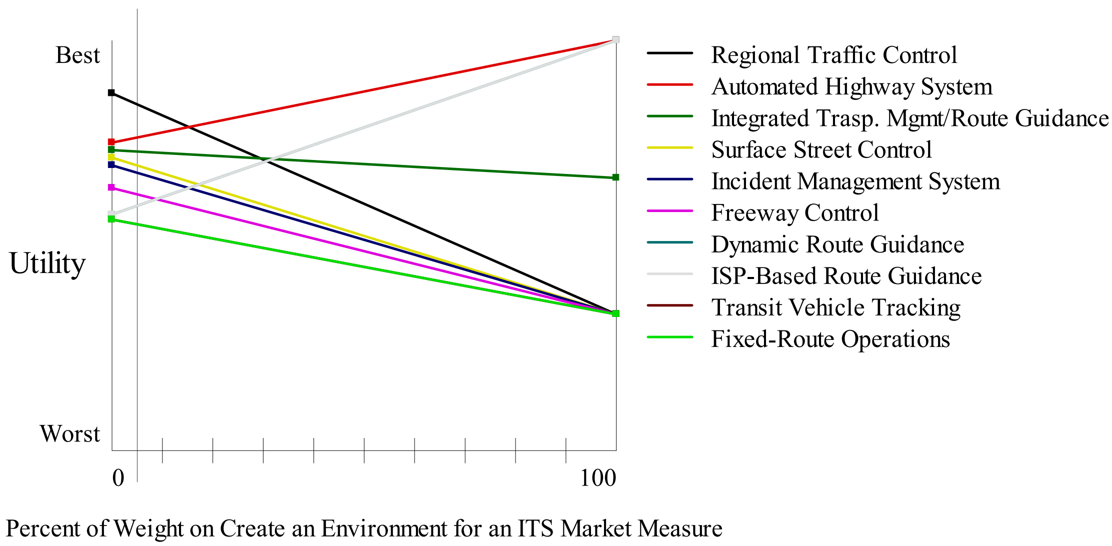

Figure 3.3-11: Sensitivity Analysis on *Create an Environment for an ITS Market* Measure

The *Create an Environment for an ITS Market* measure could be a concern of ITS industry that supplies various ITS products. Figure 3.3-11 illustrates how its weight affects the overall utilities and rankings of the top-ranked packages. It can be seen that *Regional Traffic Control*, *Dynamic Route Guidance*, and *ISP-Based Route Guidance* are most sensitive to this parameter. As the weight assigned to the *Create an Environment for an ITS Market* measure increases from its current value, the overall utility and ranking of the *Regional Traffic Control* package will drop and the overall utilities and rankings of the *Dynamic Route Guidance* and *ISP-Based Route Guidance* packages will continue to rise. From the sensitivity graph, it can be seen that the most effective packages that can create an environment for the ITS market are *Automated Highway System*, *Dynamic Route Guidance*, and *ISP-Based Route Guidance*.

3.4 A MAUT MODEL WITH UNCERTAINTIES FOR ITS MARKET PACKAGE PLAN DEVELOPMENT

Currently, uncertainties are rarely considered in the ITS planning process. In fact, no effort has been found in previous studies to identify and address uncertainty issues in ITS planning. However, uncertainties do exist and may be a significant factor affecting final outcomes. For example, in ITS market package plan development, performance measures are quantified based on empirical data. Many field tests and post-project evaluations were conducted and the results from these studies were summarized to assess each market package's potential in achieving certain ITS system goals. Because the empirical data is very limited and the sample size is small, conclusions drawn on these market packages may not be certain. As shown in Tables 3.3-1a through 3.3-1g, the evaluations of market packages are based on limited data. The deterministic assessments of these ITS packages may not reflect the dynamic nature of transportation system, even though they were developed and distributed by FHWA and have been widely applied to ITS market package screening. In this case, uncertainties should be integrated into the screening process and examined.

3.4.1 Problem Formulation

The MAUT model is capable of incorporating uncertainties into decision analysis. In situations with uncertainties, the expected value of the utility is the appropriate guide for decision making. Namely, alternatives with the highest expected utility value will be ranked accordingly. Assuming that the decision maker's preference is consistent with the linear additive condition, the mathematical representation of this MAUT model with uncertainties is as follows:

$$\bar{u}(x_1, x_2, \ldots, x_n) = \sum_{i=1}^{n} k_i \bar{u}_i(x_i) \tag{3.4.1}$$

Where i = attribute of interest, $\bar{u}\,(x_1, x_2, \ldots x_n)$ is the expected total utility for a given ITS market package with respect to the performance measure set, x_i = the i-th performance measure, $\bar{u}_i(\cdot)$ is a single-attribute expected utility function over measure i that scaled from 0 to 1, and k_i is the weight, i.e. the relative importance, of measure i where

$$\sum_{i=1}^{n} k_i = 1 \tag{3.4.2}$$

The alternatives, objectives, performance measures, and weighting scheme are identical to those in the original deterministic MAUT model. However, the quantifications of performance are different. The impact matrices shown in Tables 3.3-1a through 3.3-1g are still used. However, uncertainties are considered. The benefit of each ITS market package is no longer assessed in a deterministic manner – it is assessed with a probability. For example, the *Freeway Control* package is deterministically assessed to have low benefits in achieving the *Improve Safety* goal. This conclusion is drawn based on observed outcomes of freeway control deployments: it was reported that crash reductions of 5 to 50 percent resulted from freeway control deployments in Seattle, Denver, Portland, Detroit, and Minneapolis (Cambridge Systematics Inc., 2001; USDOT, 2001; USDOT, 2005a). With such few cases and a range of 5 to 50 percent crash reduction, it is difficult to conclude that

Freeway Control yields low benefit to improving safety. In addition, there are enormous uncertainties in traffic operations. An ITS deployment may not achieve identical outcomes given different circumstances. Therefore, it is more meaningful to assess ITS market packages based on several levels of performance, assessing a probability to each level. For example, in achieving the *Improve Safety* goal, *Freeway Control* is projected to yield low benefit with a probability of 0.7, moderate benefit with a probability of 0.25, and high benefit with a probability of 0.05.

These discrete probabilities should be defined based on empirical data. However, since ITS deployment only has been in existence for a short time, current ITS benefit databases are too small to develop reasonable probability levels for each ITS market package. As more ITS projects are implemented and subsequently evaluated, it will be feasible in the future. In this study, assumptions are made on these probabilities to evaluate ITS market packages.

3.4.2 Evaluation of ITS Market Packages under Uncertainty

Instead of using deterministic assessments, the benefits of an ITS package in achieving a certain goal are assumed to be assessed in the following manner:

> ***High Benefit***: In Tables 3.3-1a through 3.3-1g, if an ITS market package is evaluated as having a *High* benefit in achieving a goal, it is assumed that it has a high probability of generating a high benefits, a relatively low probability of generating a moderate benefit, and a very low probability of generating a low benefits. For example, in Table 3.3-1b, the *Freeway Control* package is found to have a *High* benefit with respect to enhancing

mobility. Therefore, it is stated to have a 70% chance to obtain a high benefit, a 25% chance to obtain a moderate benefit, and a 5% chance to obtain a low benefit.

***Moderate Benefit*:** In Tables 3.3-1a through 3.3-1g, if an ITS market package is evaluated as having a *Moderate* benefit with respect to achieving a goal, it is assumed that it has a high probability of generating moderate benefits and, equivalently, a relatively low probability of generating a high or low benefits. For example, in Table 3.3-1b, the *Freeway Control* package is evaluated to have a moderate benefit of increasing transportation efficiency. Therefore, it is assumed that it would have a 15% chance to obtain a high benefit, a 70% chance to obtain a moderate benefit, and a 15% chance to obtain a low benefit.

***Low Benefit*:** In Tables 3.3-1a through 3.3-1g, if an ITS market package is evaluated as having a *Low* benefit with respect to achieving a goal, it is assumed that it has a very low probability of generating high benefits, a relatively low probability of generating moderate benefits, and a very high probability of generating low benefits. For example, in Table 3.3-1b, the *Freeway Control* package is ascertained to have low benefits with respect to increasing safety. It is then assumed to have a 5% chance to obtain high benefits, a 25% chance to obtain moderate benefits, and a 70% chance to obtain low benefits.

Theoretically, these assumptions should be carefully made based on the characteristics of the planning area and empirical data. The practice of assessing probabilities to benefit levels of ITS market packages is comparable to that of case-matching analysis in the case-based reasoning (CBR) models (Khattak and Kanafani, 1996; Khattak and Kanafani, 1997; Karim and Adeli, 2003). However, these two practices are fundamentally different. In CBR models, if current ITS application and implementation environment match a historical case closely, the potential outcomes of the current case is predicted to be that of the similar historical case. However, as the stringency level increases, it may be difficult to find a suitably matched historical case. Decision makers may face a dilemma when using CBR models because simply lowering the stringency level may not yield good estimations. At this point, assigning probabilities to the benefit levels of ITS market packages provides decision makers more flexibility with reasonable accuracy in ITS strategic planning.

Based on the original MAUT model developed in Section 3.3, the single-attribute expected utility function values and the overall expected utilities are computed incorporating uncertainty assumptions. The overall rankings of the alternatives are shown in Figure 3.4-1. The contributions of each performance measure are presented with a stack bar graph and shown in Figure 3.4-2. The relative contributions of individual sub-objectives to the overall expected utility for each alternative are presented in Figure 3.4-3. At this point, the relative strength and weakness of each ITS market package can be investigated in more detail. The stack bar graph provides a visual display of the expected aggregated utility of the market packages on each of the performance measures or sub-goals.

An uncertainty summary is provided in Figure 3.4-4. Statistics such as mean, standard deviation, minimum value, and maximum value of the expected overall utility are provided for each ITS market package. The risk of choosing one market package over another can be assessed based on these statistics. Decision makers can compare any pair or any group of market packages and then make rational decisions accordingly.

Ranking for Identify the Best ITS Market Package Plan Goal

Alternative	Utility
Regional Traffic Control	0.772
Integrated Trasp. Mgmt/Route Guidance	0.696
Automated Highway System	0.676
Surface Street Control	0.674
Incident Management System	0.663
Freeway Control	0.628
Dynamic Route Guidance	0.617
ISP-Based Route Guidance	0.610
Transit Vehicle Tracking	0.593
Fixed-Route Operations	0.593
Demand-Responsive Operations	0.593
Advanced Vehicle Lateral Control	0.515
Advanced Vehicle Longitudinal Control	0.515
Interactive Traveler Info	0.514
Roadside CVO Safety	0.486
Electronic Clearance	0.464
International Boarder Electronic Clearance	0.464
Weight-in-Motion	0.464
Emergency Response	0.446
Emergency Routing	0.446
Autonomous Route Guidance	0.431
Broadcast Traveler Info	0.405
Dynamic Ride Sharing	0.390
Traffic Information Dissemination	0.390
HOV and Reversible Lane Management	0.384
Traffic Network Performance Evaluation	0.358
Virtual TMC and Smart Probe Data	0.355
Probe Surveillance	0.343
Network Surveillance	0.332
Railroad Operations Coordination	0.332
HAZMAT Management	0.316
CVO Fleet Maintenance	0.316
Fleet Administration	0.288
Freight Administration	0.288
On-board CVO Safety	0.254
Vehicle Safety Monitoring	0.249
Driver Safety Monitoring	0.249
Multi-modal Coordination	0.249
In-vehicle Signing	0.247
Mayday Support	0.243
Passenger and Fare Management	0.243
Longitudinal Safety Warning	0.242
Lateral Safety Warning	0.242
Intersection Safety Warning	0.238
Intersection Collision Avoidance	0.231
Pre-Crash Restraint Deployment	0.231
Driver Visibility Improvement	0.231
Standard Railroad Grade Crossing	0.210
Advanced Railroad Grade Crossing	0.210
Emissions and Environment Hazard Sensing	0.197
Transit Security	0.164
Yellow Pages and Reservation	0.140
Dynamic Toll/Parking fee management	0.056
CV Administrative Processes	0.056
Transit Maintenance	0.045

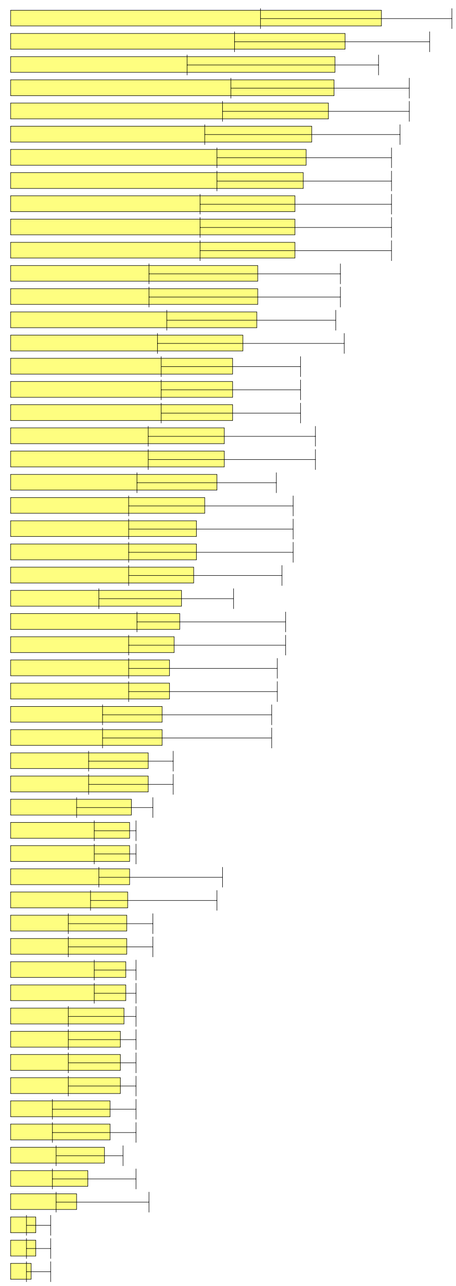

Figure 3.4-1: Rankings of ITS Market Packages with Uncertainty (1)

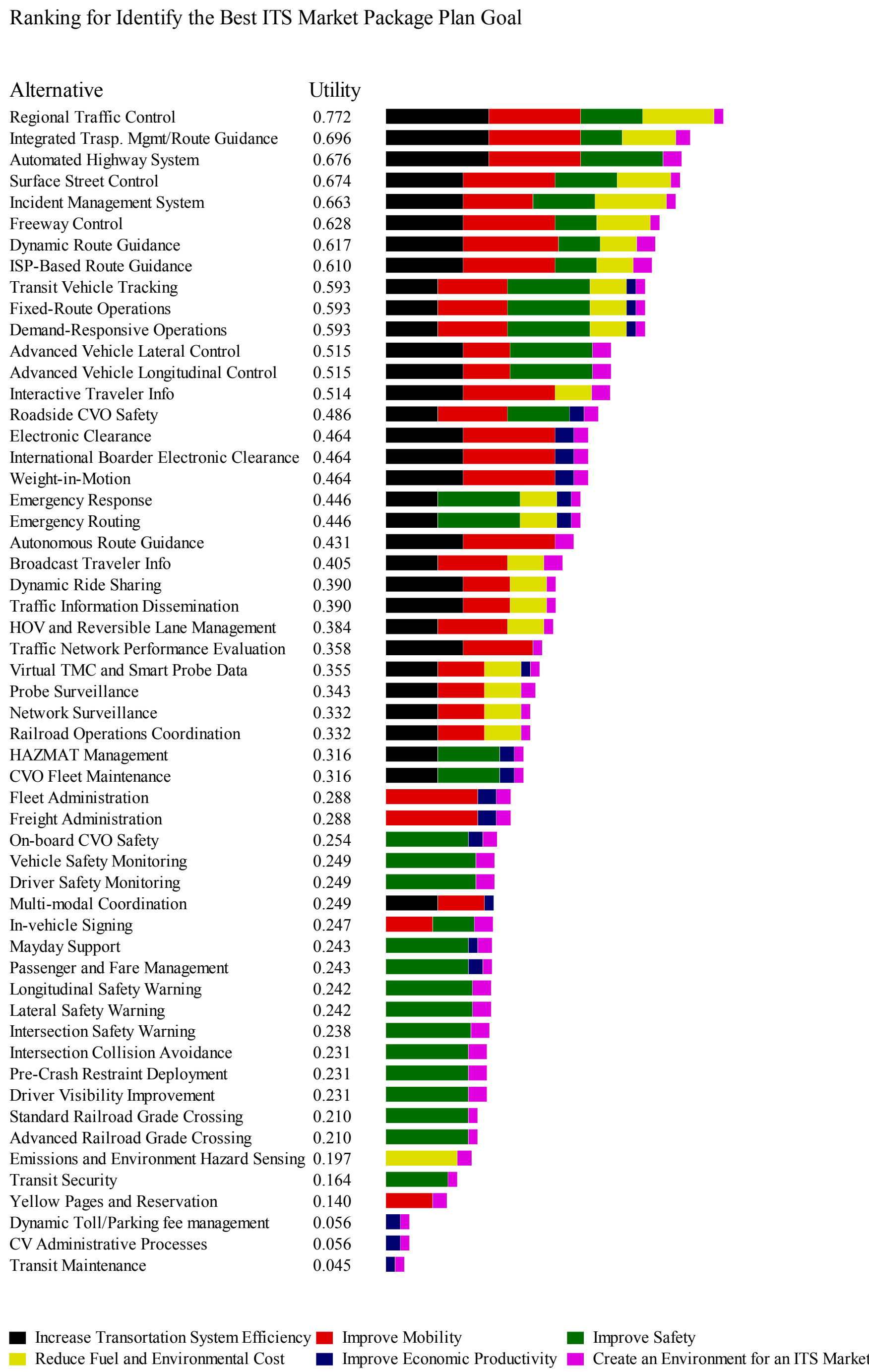

Figure 3.4-2: Contributions of Measures to the Overall Utility with Uncertainty

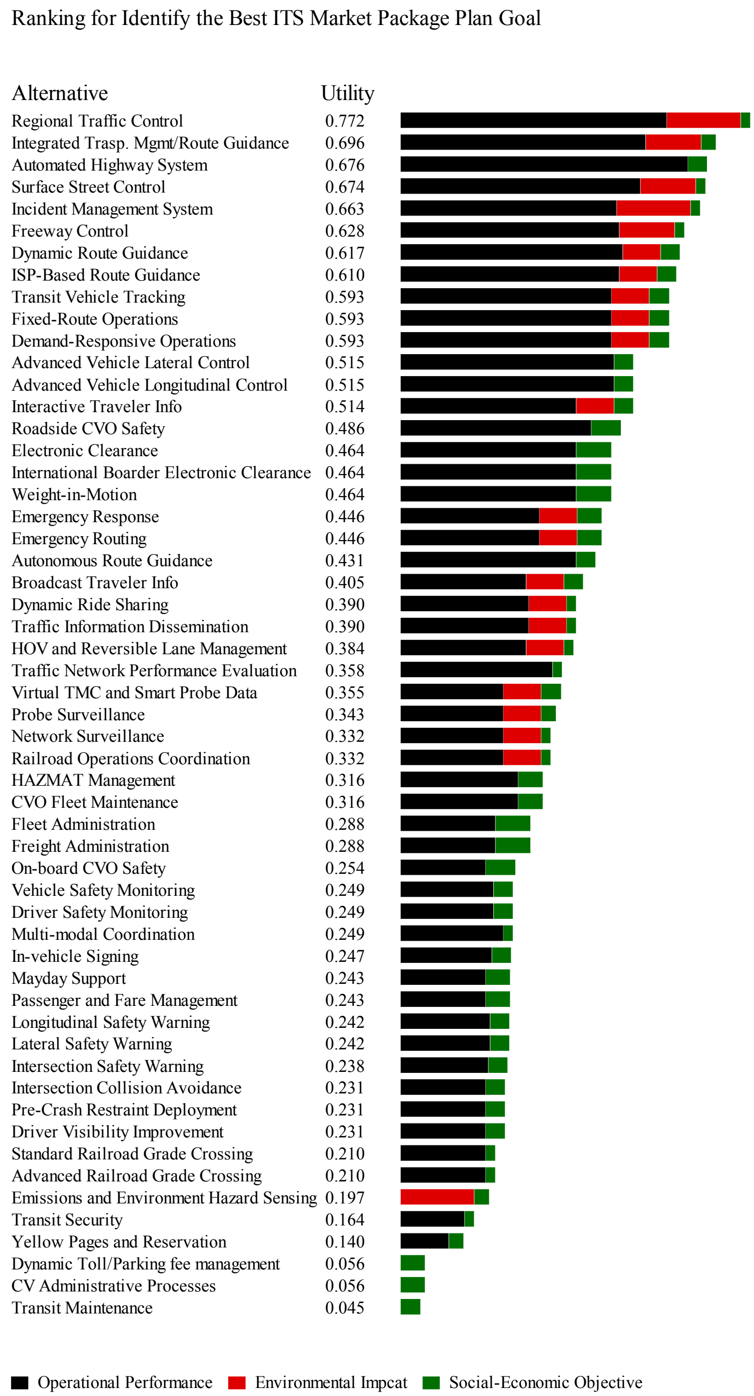

Figure 3.4-3: Contributions of Sub-Objectives to the Overall Utility with Uncertainty

Utility uncertainty summary for Identify the Best ITS Market Package Plan Goal

Alternative	Mean	Std. Dev.	Median	Min.	5%P	95%P	Max.
Advanced Railroad Grade Crossing	0.212	0.039	0.229	0.087	0.158	0.262	0.262
Advanced Vehicle Lateral Control	0.523	0.081	0.518	0.288	0.413	0.677	0.686
Advanced Vehicle Longitudinal Control	0.523	0.081	0.518	0.288	0.413	0.677	0.686
Automated Highway System	0.683	0.078	0.686	0.368	0.572	0.765	0.765
Autonomous Route Guidance	0.431	0.063	0.448	0.264	0.306	0.553	0.553
Broadcast Traveler Info	0.402	0.083	0.420	0.246	0.279	0.535	0.588
CV Administrative Processes	0.057	0.013	0.050	0.033	0.033	0.083	0.083
CVO Fleet Maintenance	0.319	0.067	0.296	0.192	0.226	0.455	0.544
Demand-Responsive Operations	0.592	0.093	0.587	0.395	0.475	0.754	0.792
Driver Safety Monitoring	0.251	0.021	0.262	0.175	0.191	0.262	0.262
Driver Visibility Improvement	0.234	0.039	0.262	0.121	0.175	0.262	0.262
Dynamic Ride Sharing	0.393	0.078	0.396	0.246	0.246	0.519	0.588
Dynamic Route Guidance	0.614	0.078	0.597	0.429	0.492	0.747	0.791
Dynamic Toll/Parking fee management	0.057	0.013	0.050	0.033	0.033	0.083	0.083
Electronic Clearance	0.466	0.063	0.498	0.314	0.339	0.586	0.603
Emergency Response	0.451	0.077	0.430	0.287	0.341	0.595	0.634
Emergency Routing	0.451	0.077	0.430	0.287	0.341	0.595	0.634
Emissions and Environment Hazard Sensing	0.193	0.039	0.218	0.095	0.112	0.235	0.235
Fixed-Route Operations	0.592	0.093	0.587	0.395	0.475	0.754	0.792
Fleet Administration	0.290	0.048	0.321	0.163	0.179	0.338	0.338
Freeway Control	0.624	0.078	0.625	0.405	0.484	0.758	0.809
Freight Administration	0.290	0.048	0.321	0.163	0.179	0.338	0.338
HAZMAT Management	0.319	0.067	0.296	0.192	0.226	0.455	0.544
HOV and Reversible Lane Management	0.379	0.083	0.387	0.246	0.246	0.519	0.564
ISP-Based Route Guidance	0.607	0.083	0.597	0.429	0.491	0.747	0.791
In-vehicle Signing	0.252	0.067	0.254	0.167	0.183	0.413	0.429
Incident Management System	0.649	0.086	0.669	0.440	0.511	0.783	0.828
Integrated Trasp. Mgmt/Route Guidance	0.698	0.086	0.714	0.467	0.555	0.818	0.872
Interactive Traveler Info	0.513	0.074	0.526	0.325	0.368	0.650	0.676
International Boarder Electronic Clearance	0.466	0.063	0.498	0.314	0.339	0.586	0.603
Intersection Collision Avoidance	0.234	0.039	0.262	0.121	0.175	0.262	0.262
Intersection Safety Warning	0.241	0.035	0.262	0.121	0.175	0.262	0.262
Lateral Safety Warning	0.244	0.029	0.262	0.175	0.191	0.262	0.262
Longitudinal Safety Warning	0.244	0.029	0.262	0.175	0.191	0.262	0.262
Mayday Support	0.247	0.039	0.262	0.121	0.191	0.279	0.295
Multi-modal Coordination	0.259	0.072	0.264	0.184	0.184	0.376	0.440
Network Surveillance	0.340	0.084	0.334	0.246	0.246	0.502	0.555
On-board CVO Safety	0.258	0.038	0.279	0.137	0.191	0.295	0.295
Passenger and Fare Management	0.246	0.038	0.262	0.121	0.191	0.295	0.295
Pre-Crash Restraint Deployment	0.234	0.039	0.262	0.121	0.175	0.262	0.262
Probe Surveillance	0.351	0.084	0.351	0.246	0.246	0.510	0.571
Railroad Operations Coordination	0.340	0.084	0.334	0.246	0.246	0.502	0.555
Regional Traffic Control	0.769	0.091	0.767	0.519	0.617	0.917	0.917
Roadside CVO Safety	0.482	0.083	0.472	0.305	0.376	0.632	0.693
Standard Railroad Grade Crossing	0.212	0.039	0.229	0.087	0.158	0.262	0.262
Surface Street Control	0.668	0.079	0.696	0.458	0.546	0.784	0.828
Traffic Information Dissemination	0.393	0.078	0.396	0.246	0.246	0.519	0.588
Traffic Network Performance Evaluation	0.351	0.066	0.352	0.184	0.264	0.448	0.465
Transit Maintenance	0.046	0.014	0.050	0.033	0.033	0.083	0.083
Transit Security	0.161	0.038	0.158	0.087	0.087	0.229	0.262
Transit Vehicle Tracking	0.592	0.093	0.587	0.395	0.475	0.754	0.792
Vehicle Safety Monitoring	0.251	0.021	0.262	0.175	0.191	0.262	0.262
Virtual TMC and Smart Probe Data	0.363	0.083	0.359	0.263	0.263	0.519	0.571
Weight-in-Motion	0.466	0.063	0.498	0.314	0.339	0.586	0.603
Yellow Pages and Reservation	0.146	0.052	0.113	0.096	0.096	0.271	0.288

Figure 3.4-4: Uncertainty Summary of ITS Market Packages

A comparative study was performed to examine outcomes resulting from the original MAUT model and the MAUT model incorporating uncertainties. There are two major benefits to performing this comparative study. First, the study enables decision makers to examine the impact of uncertainty on the final rankings of ITS market packages; second, it allows decision makers to assess the risk of using top-ranked market packages to achieve defined ITS goals. If the ranking of an ITS package significantly changes when uncertainty is considered, the risk level of selecting this package could be high. Risk analysis could also be performed based on the uncertainty summary.

Table 3.4-1 presents a comparison of the rankings and utilities of top-ranked ITS market packages with and without uncertainty. It depicts that the incorporation of uncertainty slightly affects the overall rankings of the top twenty ITS market packages. The market packages that have different rankings are highlighted in bold in the table. Among the top ten ranked market packages, only three which include *Integrated Trasp. Mgmt/Route Guidance*, *Automated Highway System,* and *ISP-Based Route Guidance*, are ranked differently in the two scenarios. However, the ranking difference is not significant, as these packages move up or down by one ranking space. The market packages ranked between 11 and 20 show more variations in rankings. When uncertainties in the benefits of ITS market packages are considered, *Interactive Traveler Info* and *Roadside CVO Safety* gain more than one spot in the overall rankings. On the other hand, *International Border Electronic Clearance* and *Weight in Motion* fall more than one spot in rankings.

Table 3.4-1 Rankings and Utilities of ITS Packages with and without Uncertainty

ITS Market Package	Ranking (Utility) with Uncertainty	Ranking (Utility) w/o Uncertainty
Regional Traffic Control	1 (0.772)	1 (0.846)
Integrated Trasp. Mgmt/Route Guidance	**2 (0.696)**	**3 (0.730)**
Automated Highway System	**3 (0.676)**	**2 (0.765)**
Surface Street Control	4 (0.674)	4 (0.696)
Incident Management System	5 (0.663)	5 (0.678)
Freeway Control	6 (0.628)	6 (0.625)
Dynamic Route Guidance	7 (0.617)	7 (0.597)
ISP-Based Route Guidance	**8 (0.610)**	**7 (0.597)**
Transit Vehicle Tracking	9 (0.593)	9 (0.554)
Fixed-Route Operations	9 (0.593)	9 (0.554)
Demand Responsive Operations	9 (0.593)	9 (0.554)
Advanced Vehicle Lateral Control	**12 (0.515)**	**13 (0.518)**
Advanced Vehicle Longitudinal Control	13 (0.515)	13 (0.518)
Interactive Traveler Info	**14 (0.514)**	**12 (0.526)**
Roadside CVO Safety	**15 (0.486)**	**19 (0.455)**
Electronic Clearance	**16 (0.464)**	**15 (0.498)**
International Border Electronic Clearance	**17 (0.464)**	**15 (0.498)**
Weight in Motion	**18 (0.464)**	**15 (0.498)**
Emergency Response	**19 (0.446)**	**20 (0.412)**
Emergency Routing	20 (0.446)	20 (0.412)

3.5 SUMMARY

In this chapter, a MAUT model was developed for ITS market plan development, which is a fundamental task in ITS planning. With the assessment of utility preferences and weights, the aggregated utilities of individual ITS market packages were computed. Based on the aggregated utilities, ITS market packages can be ranked so that decision makers can make rational choices accordingly. Sensitivity analyses were performed to examine the impact of sub-goal/performance measure weights on the ranking results. In a case study conducted in Austin, Texas, it was found that the MAUT approach is suitable for ITS market packages screening.

Compared to the conventional market package screening method, the MAUT approach provides decision makers more detailed information and data in order to better understand which ITS strategies may be more suitable to address local transportation problems and user needs. For example, in Austin, an ITS Master Plan was developed in 2001 through a Delphi decision-making process. The final ITS market package plan was the consensus of experts on each of the ITS market packages. Thirty-six ITS market packages were recommended, and no ranking information was provided. However, the ranking results from the MAUT approach provide decision makers not only a list of packages that can achieve local ITS goals, but also evidence to define the ITS implementation priority settings. Sensitivity analysis in the MAUT approach enables ITS planners and decision makers to examine the impact of goal/performance measure weights or weight assessment conflicts between various stakeholders on the final outcome.

Uncertainties that may influence final outcome are further examined using the MAUT model. A comparative study was performed on the original MAUT model and the MAUT model incorporating uncertainties. The results indicate that the assumed uncertainties in the benefits of ITS market packages will slightly affect the final rankings of the alternatives. With the consideration of uncertainties, decision makers can assess the risk of using a market package to achieve defined ITS goals.

Through this study, it is also found that there are some issues to be addressed. Since current technologies evolve rapidly, the ITS market package group is expanding rapidly as well. The benefits of newly-added ITS market packages should be evaluated periodically so that the MAUT approach can be applied. Additionally, performance measures used to evaluate market packages and their respective weights should be carefully defined according to local needs (FHWA has recommended six measures to define local needs). In practice, different ITS deploying agencies may have different concerns due to regional disparities in characteristics and constituent interests across the nation. For example, through interviews, it was found that TxDOT's district office in Austin is more concerned with safety, system efficiency, and environmental impact than economic productivity and ITS market environment. Additionally, it was found that cost, especially operating cost, is a big concern of TxDOT. The number of ITS market packages that can be implemented depends on funding availability. As the priority setting of ITS implementations depends on both initial and operating costs, an ITS plan should be developed based on available resources. The MAUT approach has shown its strength in addressing this issue. ITS planners can select market packages from the ranking list based on package cost and funding availability, which highlights the benefits of using the MAUT approach in ITS market package screening.

Chapter 4 An ELECTRE Method for ITS Deployment Comparison

4.1 INTRODUCTION

With an ITS master plan developed and a regional ITS architecture established, local ITS agencies know which ITS strategies can be implemented to address local transportation problems. Thereafter, various ITS deployments must be defined, evaluated, compared, and selected for implementation. To maximize the rewards of ITS investments, the most beneficial alternative that meets local objectives should be identified and deployed.

Previous studies have shown that the cost-benefit analysis (CBA) method is the prevailing way to address this issue. CBA fits well into the decision-making process when considering new initiatives, especially those requiring legislation. However, at the implementation level, decision makers may not be able to view an ITS deployment's operational performance from a cost-benefit perspective. In other words, cost-benefit analysis may not provide enough information to compare various ITS deployments. It is possible that the alternative with the highest cost-benefit ratio might not best fit local objectives and user needs. The ITS deployment comparison and selection problem emerges and should be addressed with a suitable method.

The ITS alternatives comparison and selection problem is a typical multiple-objective decision analysis problem. Given n ITS deployment alternatives, the decision analyst will evaluate them with respect to a set of objectives. Then n' (with $n' < n$) alternatives, which represent the best subset of the n feasible alternatives, are identified and chosen for implementation. Mathematically, it is represented as follows:

$$Maximize \quad Z = (Z_1, Z_2, \ldots, Z_m) \qquad (4.1.1)$$

$$\text{s.t.} \quad Z(a_i) \in M \qquad (4.1.2)$$

$$M = [Z(a_1), Z(a_2), \ldots, Z(a_n)] \qquad (4.1.3)$$

Where Z is the vector of ITS deployment objective functions Z_1, Z_2,…Z_m; a_1, a_2, …, a_n are feasible ITS alternatives; and M is a $m \times n$ matrix in which each column gives the outcomes for a given alternative on the set of objectives or corresponding performance measures. To solve this problem, there are several methods available. One such method is the ELECTRE method.

4.2 THE ELECTRE METHOD

4.2.1 An Introduction to the ELECTRE Method

The ELECTRE method is one of the most widely applied multicriteria decision analysis methods. It is a technique in which alternatives are evaluated using a series of pair-wise comparisons across the criteria set. The ELECTRE method has several unique features not found in other solution methods such as outranking, indifference, and preference thresholds. It leads itself well to decision analysis problems with a finite number of alternatives.

As shown in the literature review section, ELECTRE is a proven method that has been widely applied in engineering evaluation, including the applications in transportation for construction project ranking, policy evaluation, and new route comparison. However, no research has been found that applies this method to ITS deployments.

ELECTRE has evolved through a number of versions (I through IV); all are based on the same fundamental concepts but are somewhat operationally different. The basic model, the ELECTRE-I method, operates on an alternative impact matrix, which contains a vector of scores for each alternative on each of the chosen criteria. Two indices, the concord index and the discord index, are calculated in ELECTRE-I. The formulation of the ELECTRE-I method has been well documented by Goicoechea et al. (1982) as follows:

The concord index represents the degree to which one solution plan is preferred to another using a given weight scheme on the criteria. Let $I = \{1, 2, \ldots m\}$ represent the criteria set and let $\{w_k: k = 1, 2, \ldots m\}$ represent the weight set associated with the m criteria. Then divide the set I into three subsets:

$$I^+ = I^+ (i, j) = \{k \in I: i > j\} \tag{4.2.1}$$

$$I^= = I^= (i, j) = \{k \in I: i = j\} \tag{4.2.2}$$

$$I^- = I^- (i, j) = \{k \in I: i < j\} \tag{4.2.3}$$

Define

$$W^+ = \sum_{k \in I^+} w_k \tag{4.2.4}$$

$$W^= = \sum_{k \in I^=} w_k \tag{4.2.5}$$

$$W^- = \sum_{k \in I^-} w_k \tag{4.2.6}$$

The concord index is computed as

$$c(i, j) = (W^+ + \frac{1}{2} W^=) / (W^+ + W^= + W^-) \tag{4.2.7}$$

The discord index represents the degree to which one alternative is dominated by another. It is computed as

$$d(i,j) = \frac{Maximum \quad Interval \quad where \quad i < j}{Total \quad Range \quad of \quad Scale} \tag{4.2.8}$$

In the ELECTRE-I method, the outranking relation R is defined with concordance condition and discordance condition. The outranking relation R is then used to construct a composite graph, G_c. That is, alternative i is preferred to alternative j (i.e., an arc (i, j) will appear in the composite graph) if and only if

$$c(i,j) \geq p \, and \quad d(i,j) \leq q \tag{4.2.9}$$

where p and q are the thresholds for concordance condition and discordance condition, respectively. After the outranking relation is defined and the composite graph is constructed, the kernel of the graph, which contains the nodes representing those preferred solutions, can be determined. The remaining nodes that are not in the kernel will be eliminated from further consideration.

4.2.2 The Graph and Its Kernel

A graph, G, consists of two types of elements: vertices and edges that connect pairs of vertices. Edges may be endowed with direction, making the graph G a directed graph or a digraph. In an ELECTRE graph, the vertices represent alternatives and edges represent the outranking relationships. A vertex, v, dominates another vertex, u, if there is an arc, i.e. a directed edge, from v to u. When the outranking relation is defined and the composite graph is constructed using the

ELECTRE method, finding the kernel of the graph results in the identification of the nondominated alternatives. A kernel in a directed graph G is a set S of vertices of G such that

1) No two vertices in S are adjacent and
2) For every vertex u in G-S, there is a vertex v in S such that $u \rightarrow v$ is an arc of G.

An example used by Goicoechea et al. (1982) is used to illustrate how the ELECTRE-I method identifies the nondominated subset in an ELECTRE graph. As shown in Figure 4.2-1, each node represents an alternative. The arrows emanating from the nodes represent the outranking relationship. That is, it can be said that Alternative 2 is preferred to Alternative 1, Alternative 1 is preferred to Alternative 5, Alternative 5 is preferred to Alternative 3, Alternative 4 is preferred to Alternative 6, and so on. Based on the definition of "kernel", it can be seen that the kernel of this ELECTRE graph consists of Nodes 2, 5 and 4. These three nodes represent the subset of nondominated alternatives in a decision problem.

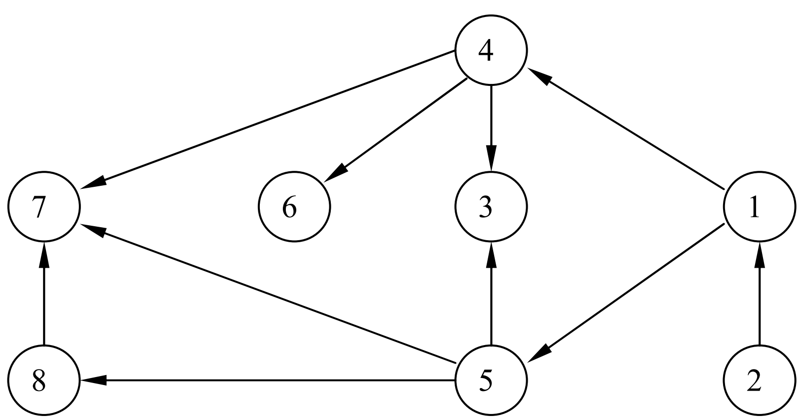

Figure 4.2-1: An ELECTRE Graph

4.2.3 A Modified ELECTRE Method

Assigning weights to criteria is a critical part of a multicriteria evaluation problem. A weight is assigned to each criterion to represent that criterion's relative importance. When there are multiple objectives, decision makers need a balanced alternative that yields good performance in achieving multiple objectives. Additionally, when there are multiple decision makers or stakeholders involved in the decision-making process, they may emphasize different objectives/criteria. It is possible that they may express conflicting preferences.

Given this situation, one set of weights may not be enough to identify the most balanced alternative or represent decision makers' various viewpoints. A set of representative weight schemes are more useful if each weight scheme represents a different point of view or emphasis. In this study, a modified ELECTRE-I method is proposed to accommodate this need, in which the ELECTRE-I procedure is used in an iterative way to identify the best compromise solution.

In the modified ELECTRE-I method, the subset of the nondominated alternatives is identified by systematically altering the objective weights. The alternative(s) remaining in the nondominated set when the weights are varied will be defined as the best compromise solution(s) (Giuliano 1985). However, that alternative does not guarantee the best solution under every weight scheme, which means that it may not be the top-ranked alternative under some weight schemes although it fulfills the threshold requirements of the iterative ELECTRE-I procedure. Figure 4.2-2 illustrates this idea with a graph.

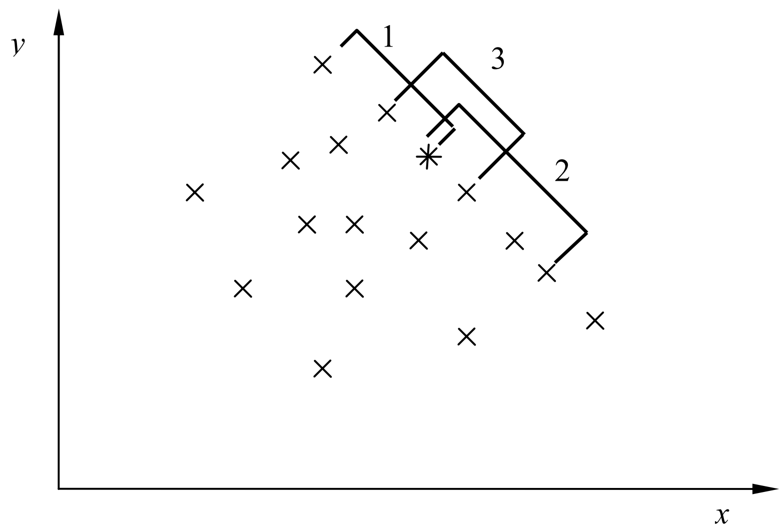

Figure 4.2-2: Best Compromise Alternative under Multiple Weighting Schemes

As shown in Figure 4.2-2, if a number of alternatives are evaluated with respect to multiple weighting schemes (three weighting schemes in Figure 4.2-2), the alternative ✳ that always stays in the nondominated set under each weighting scheme will be identified as the best compromise alternative.

The benefit of this approach is that it is flexible in evaluating multiple objective problems or dealing with multiple decision makers. If a decision maker has a substantial interest in one objective, his or her preference can be reflected by emphasizing its weight. By doing that in an iterative manner, various interests in multiple objectives can be handled in the decision-making process with the ELECTRE method.

4.3 VALIDATION OF THE ELECTRE METHOD

To validate the ELECTRE method, a case study was conducted in Austin, Texas. Figure 4.3-1 presents an overview of the Austin transportation network. The Austin area has grown from a population of 465,000 in 1990 to more than 650,000 people in 2000 (US Census, 2000). Hays, Travis, and Williamson Counties' combined 2000 population of 1.16 million is projected to increase to more than 1.4 million by 2010 (CAMPO prediction). The rapid growth in population results in a rapid increase of travel demand.

Austin is a pilot area in ITS implementation. The Texas Department of Transportation (TxDOT) District Office in Austin shows great interest in looking for beneficial ITS deployments to solve transportation problems caused by increasing demand. A statewide sketch ITS deployment plan has been developed to guide TxDOT districts in statewide planning of ITS. The Austin office has also developed a regional early deployment plan and has shown strong interest in ITS deployments, such as freeway corridor management and traveler information system. However, the unclear impact and potential benefits of ITS deployments have posed substantial difficulties to TxDOT when developing more ITS projects. Thus, the timing of the proposed method and the case study is very appropriate.

The purpose of this case study is to compare a number of deployment alternatives using the proposed ELECTRE method and identify the best one so that deployment recommendations can be made accordingly.

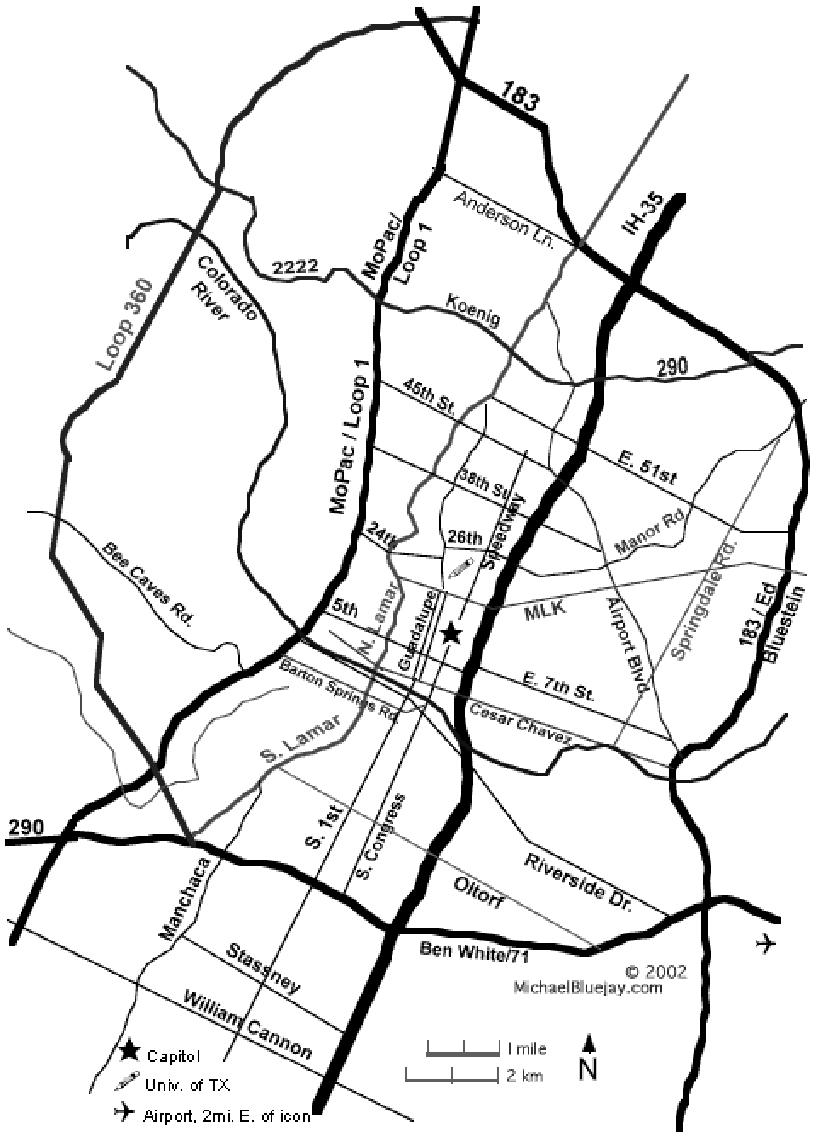

Figure 4.3-1: An Overview of Austin Transportation Network

4.3.1 Goals and Evaluation Criteria

The mission of TxDOT is to "provide the safe, effective, and efficient movement of people and goods". In order to fulfill its mission, TxDOT focuses on a number of objectives, some of which include: reliable mobility, improve safety, economic vitality, system preservation, and accelerated project delivery. ITS deployment plays an important role in satisfying TxDOT's mission and objectives.

Before an ITS deployment is developed, goals must be established. Goals enable decision makers to define concerns that are important for ITS deployments. As mentioned in Chapter 3, typical ITS deployment goals include:

1) Increase operational efficiency and capacity of the transportation system;
2) Enhance personal mobility, convenience, and comfort of the transportation system;
3) Improve the safety of the nation's transportation system;
4) Reduce energy consumption and environmental costs;
5) Enhance the present and future economic productivity of individuals, organizations, and the economy as a whole;
6) Create an environment in which the development of ITS can flourish.

These goals are suggested by FHWA for ITS deployments and reflect the interests and concerns of a broad range of ITS practitioners and stakeholders. Based on the goals of ITS deployment, evaluation criteria can be developed accordingly. As suggested by the ITS Joint Program Office in FHWA, there are six measures important for ITS evaluation: mobility, safety, efficiency, productivity, energy and environment, and consumer satisfaction. With the consideration of typical ITS evaluation measures (Brand 1998), TxDOT perspective, and the functional capabilities of the ITS deployment evaluation tools, a list of goals and corresponding criteria are presented in Table 4.3-1.

Table 4.3-1: Goals and Measures for ITS Deployment Evaluation

Goals	Criterion
Improve System Efficiency	Travel delay
Improve Mobility	Speed
Improve Safety	Accident rate reduction
Reduce Environmental and Energy Cost	Emissions reduction
Minimize Cost	Initial cost and operating cost

4.3.2 ITS Deployment Alternatives

An important step in ITS project development is to define a number of alternatives to be compared and ranked. In this study, the modified ELECTRE-I procedure is applied to the evaluation of six ITS alternatives described in Table 4.3.2. These alternatives consist of various improvements designed to provide a balanced transportation system for the Austin area. They are defined based on the goals of ITS implementation in the Austin area, the TxDOT Austin office's ITS deployment plan, and the functions of the ITS market packages defined in the National ITS Architecture. Loop 1 (Mopac), which is a main corridor for north- and southbound traffic, was selected as the corridor that can be improved with ITS deployments.

Table 4.3.2: ITS Deployment Alternatives in Loop 1 (Mopac) Study

ITS Deployment	Description
1. FC[1] /NS[2]	An integrated deployment of Freeway Control and Network Surveillance systems
2. IMS[3]/NS	An integrated deployment of Incident Management and Network Surveillance systems
3. ATIS[4]/NS	An integrated deployment of Advanced Traveler Information and Network Surveillance Systems
4.FC/ATIS	An integrated deployment of Freeway Control and Advanced Traveler Information systems
5. FC/IMS	An integrated deployment of Freeway Control and Incident Management systems
6. ATIS/IMS	An integrated deployment of Advanced Traveler Information and Incident Management systems

[1]: The Freeway Control System refers to ramp metering deployments on all entrance ramps to Loop 1.

[2]: The Network Surveillance System refers to CCTV and loop detections along Loop1.

[3]: The Incident Management System refers to a combination of incident detection and incident response.

[4]: The Advanced Traveler Information System refers to dynamic message signs (DMSs) along Loop 1, a total of 18 DMSs are planned.

4.3.3 Impact Matrix

Once ITS deployment alternatives and evaluation criteria are defined, the impact matrix of ITS deployments can be constructed. In this study, the impact matrix was established based on ITS evaluation results from the National ITS Architecture documentation and IDAS program. As mentioned in Chapter 2, IDAS is a sketch planning analysis tool for predicting the impacts of ITS improvements. It is designed to "assist public agencies and consultants in integrating ITS in the transportation planning process" by estimating potential impacts, benefits, and costs of different ITS improvements. IDAS is capable of evaluating ITS deployments' impact on user mobility, travel time/speed, travel time reliability, fuel costs, accident costs, emissions, and noise.

The data required by IDAS are obtained from the Capital Area Metropolitan Planning Agency (CAMPO) in Austin, Texas. Node coordinates, network links, and origin-destination matrices were exported from CAMPO data. Once all data files were imported into IDAS, it created different ITS alternatives for analysis. The impact matrix is then constructed by getting scores for each criterion for each of the six alternatives. The evaluations of these ITS alternatives in achieving the objectives were categorized into five levels: excellent, very good, good, fair, and poor. The alternatives' impact matrix is presented in Table 4.3.3.

Table 4.3.3: Impact Matrix of ITS Alternatives in Loop 1 (Mopac) Study*

Objective	FC/NS	IMS/NS	ATIS/NS	FC/ATIS	FC/IMS	ATIS/IMS
Improve System Efficiency	Very Good	Good	Fair	Very Good	Excellent	Good
Improve Mobility	Good	Good	Good	Very Good	Very Good	Very Good
Improve Safety	Poor	Fair	Poor	Poor	Good	Fair
Reduce Environmental and Energy Cost	Good	Very Good	Fair	Good	Excellent	Very Good
Minimize Cost	Fair	Poor	Fair	Very Good	Good	Good

*: The ratings in this impacts matrix are generated based on the evaluation results of IDAS and the benefit estimations in the National ITS Architecture. The baseline alternative is a do-nothing scenario, which means no ITS deployments. The baseline data are shown as follows:

Total Annual VMT in Austin area: 2,618.2 million miles; total annual travel delay: 10.71 million hrs;

Accident Data in Austin Area: 149.8 accidents/10^8VMT, 1.7 deaths/10^8VMT, and 157.5 injuries/10^8VMT;

Automobile Emissions: 58 tons of NOx/day, 48 tons of HC/day, and 336.2 tons of CO/day.

4.3.4 The Iterative ELECTRE-I Procedure

The modified ELECTRE method, which applies the ELECTRE-I procedure iteratively to identify the best ITS alternatives, can be conducted using the following four steps:

1) *Define weighting schemes*. In this step, various weighting schemes are defined to reflect decision makers' strong interests in the goals/criteria. Each scheme reflects an emphasis on one of the goals/criteria.
2) *Calculate the concord index and the discord index for each alternative.* In this step, concord and discord indices are computed to construct the outranking relationship.
3) *Identify the nondominated subset and best compromise alternative.* A graph will be established based on the outranking relationship developed in Step 2. Then the kernel of the graph, which represents the nondominated alternative(s), will be identified.
4) *Sensitivity analysis*. Sensitivity analysis is used to examine the impact of the concordance and discordance conditions on the final solutions. The size of nondominated set could be further reduced with sensitivity analysis.

4.3.4.1. Weight Schemes

Six different weighting schemes were developed for the modified ELECTRE-I analysis in this study. The first weighting scheme distributes weights equally over the five criteria. Each of the remaining five weighting schemes represents an emphasis on one criterion. For example, Weighting Scheme II has an emphasis on the ITS deployment's impact of increasing transportation system efficiency. Weighting Scheme III has an emphasis on the ITS alternative's effectiveness of improving travelers' mobility. With multiple weighting schemes on the criteria set, and by avoiding the extreme weights, the best solution identified by the modified ELECTRE procedure is more likely to be close to the theoretical optimal solution. Detailed settings of these weighting schemes are shown in Table 4.3.4.

Table 4.3.4: Weighting Schemes for ELECTRE Analysis

	Efficiency	**Mobility**	**Safety**	**Emission**	**Cost**
Scheme I (Equal Weights)	0.2	0.2	0.2	0.2	0.2
Scheme II (Emphasis on Efficiency)	0.3	0.175	0.175	0.175	0.175
Scheme III (Emphasis on mobility)	0.175	0.3	0.175	0.175	0.175
Scheme IV (Emphasis on Safety)	0.175	0.175	0.3	0.175	0.175
Scheme V (Emphasis on Environment)	0.175	0.175	0.175	0.3	0.175
Scheme VI (Emphasis on Cost)	0.175	0.175	0.175	0.175	0.3

4.3.4.2. Concord Index and Discord Index

The concord and discord indices are two important concepts when using the ELECTRE method for decision analysis. The concord index represents the degree to which one alternative is preferred to another when a given weighting scheme is assessed to the criteria. The discord index represents the degree to which one alternative is dominated by another.

According to Equation 4.2.7, the concord indices are calculated for each of the six weighting schemes. The results are shown below:

Weighting Scheme I:

$$C_I = \begin{vmatrix} & 0.5 & 0.8 & 0.3 & 0 & 0.2 \\ 0.5 & & 0.7 & 0.4 & 0 & 0.3 \\ 0.2 & 0.3 & & 0 & 0 & 0 \\ 0.7 & 0.6 & 1 & & 0.3 & 0.5 \\ 1 & 1 & 1 & 0.7 & & 0.8 \\ 0.8 & 0.7 & 1 & 0.5 & 0.2 & \end{vmatrix}$$

Weighting Scheme II:

$$C_{II} = \begin{vmatrix} & 0.5625 & 0.825 & 0.325 & 0 & 0.3 \\ 0.4375 & & 0.7375 & 0.35 & 0 & 0.325 \\ 0.175 & 0.2625 & & 0 & 0 & 0 \\ 0.675 & 0.65 & 1 & & 0.2625 & 0.5625 \\ 1 & 1 & 1 & 0.7375 & & 0.825 \\ 0.7 & 0.675 & 1 & 0.4375 & 0.175 & \end{vmatrix}$$

Weight Scheme III:

$$C_{III} = \begin{vmatrix} & 0.5 & 0.7625 & 0.2625 & 0 & 0.175 \\ 0.5 & & 0.675 & 0.35 & 0 & 0.2625 \\ 0.2375 & 0.325 & & 0 & 0 & 0 \\ 0.7375 & 0.65 & 1 & & 0.325 & 0.5 \\ 1 & 1 & 1 & 0.675 & & 0.7625 \\ 0.825 & 0.7375 & 1 & 0.5 & 0.2375 & \end{vmatrix}$$

Weight Scheme IV:

$$C_{IV} = \begin{vmatrix} & 0.4375 & 0.825 & 0.325 & 0 & 0.175 \\ 0.5625 & & 0.7375 & 0.475 & 0 & 0.325 \\ 0.175 & 0.2625 & & 0 & 0 & 0 \\ 0.675 & 0.525 & 1 & & 0.2625 & 0.4375 \\ 1 & 1 & 1 & 0.7375 & & 0.825 \\ 0.825 & 0.675 & 1 & 0.5625 & 0.175 & \end{vmatrix}$$

Weight Scheme V:

$$C_{V} = \begin{vmatrix} & 0.4375 & 0.825 & 0.325 & 0 & 0.175 \\ 0.5625 & & 0.7375 & 0.475 & 0 & 0.325 \\ 0.175 & 0.2625 & & 0 & 0 & 0 \\ 0.675 & 0.525 & 1 & & 0.2625 & 0.4375 \\ 1 & 1 & 1 & 0.7375 & & 0.825 \\ 0.825 & 0.675 & 1 & 0.5625 & 0.175 & \end{vmatrix}$$

Weight Scheme VI:

$$C_{VI} = \begin{vmatrix} & 0.5625 & 0.7625 & 0.2625 & 0 & 0.175 \\ 0.4375 & & 0.6125 & 0.35 & 0 & 0.2625 \\ 0.2375 & 0.3875 & & 0 & 0 & 0 \\ 0.7375 & 0.65 & 1 & & 0.3875 & 0.5625 \\ 1 & 1 & 1 & 0.6125 & & 0.7625 \\ 0.825 & 0.7375 & 1 & 0.4375 & 0.2375 & \end{vmatrix}$$

According to Equation 4.2.8, discord indices are also calculated. The criteria have been assigned the following maximum scales:

Efficiency:	45
Mobility:	50
Safety:	50
Environmental and Energy Cost:	45
Cost:	50

The results are shown below:

$$D = \begin{vmatrix} & 0.2 & 0 & 0.4 & 0.4 & 0.2 \\ 0.2 & & 0.2 & 0.6 & 0.4 & 0.4 \\ 0.36 & 0.4 & & 0.4 & 0.6 & 0.4 \\ 0 & 0.2 & 0 & & 0.4 & 0.2 \\ 0 & 0 & 0 & 0.2 & & 0 \\ 0.18 & 0 & 0 & 0.2 & 0.36 & \end{vmatrix}$$

4.3.4.3. The Nondominated Alternatives

Define a minimum concordance condition of p = 0.80 and a maximum discordance condition of $q = 0.20$; that is, $c(i, j) \geq 0.80$ and $d(i, j) \leq 0.20$. Using this specification, the graph G_c can be constructed. The directed paths that appear in the graph are determined by the set of indices that simultaneously satisfy the requirement that $c(i, j) \geq 0.80$ and $d(i, j) \leq 0.20$.

Under weighting scheme I, the indices show the following outranking relationships: (1, 3), (4, 3), (5, 1), (5, 2), (5, 3), (5, 6), (6, 1), and (6, 3). Similar results are obtained under weighting scheme II, IV and V. The resulting graph is illustrated below in Figure 4.3-2. The kernel of this graph can be easily determined to be {4, 5}.

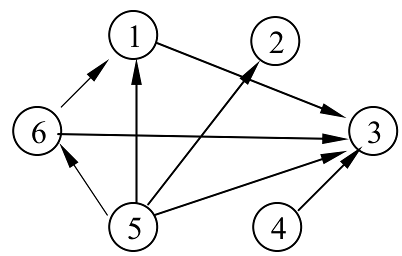

Figure 4.3-2: ELECTRE Graph for Loop1 Study under Weighting Scheme I, II, IV and V, p = 0.8, q = 0.2, Kernel = {4, 5}

The results under weighting schemes III and VI indicate some differences. Under weighting scheme III and weighting scheme VI, the indices that satisfy the requirements are (4, 3), (5, 1), (5, 2), (5, 3), (6, 1), and (6, 3). The resulting graph is shown below in Figure 4.3-3. The kernel of this graph is {4, 5, 6}

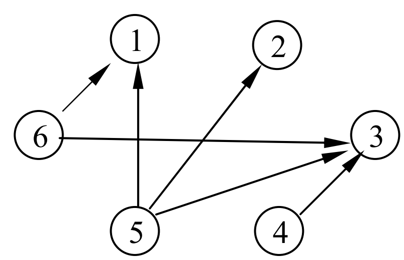

Figure 4.3-3: ELECTRE Graph for Loop1 Study under Weighting Scheme III and VI, p = 0.8, q = 0.2, Kernel = {4, 5, 6}

Therefore, when p = 0.8 and q = 0.2, the nondominated subsets under weighting schemes I, II, IV and V contain nodes {4, 5} and the nondominated subsets under weighting schemes I, II, IV and V contain nodes {4, 5, 6}. Nodes 4 and 5 remain in the nondominated subsets under all weighting schemes. At this point, it can be said that Alternative 4 and Alternative 5 dominate Alternative 1, Alternative 2, Alternative 3, and Alternative 6.

4.3.4.4. Sensitivity Analysis

To determine how sensitive the above solution is to the values of p and q, a sensitivity analysis is performed. Keeping discordance conditions unchanged (holding q constant), the relaxation of concordance condition changes the solution when $p = 0.7375$. When $p = 0.7375$, an outranking relationship develops between Nodes 5 and 4. As seen in the graph in Figure 4.3-4, Nodes 1, 2, 3, 4, and 6 will be eliminated from the graph. The choice set now consists of only one node: Node 5. So Alternative 5 is identified as the best compromise solution to this problem.

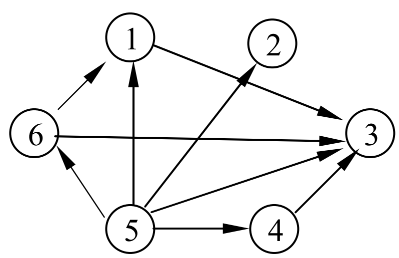

Figure 4.3-4: ELECTRE Graph for Loop1 Study in Sensitivity Analysis, $p = 0.7375$, $q = 0.2$, Kernel = {5}

Other changes in concordance and discordance conditions do not yield significant difference in results. From the above sensitivity analysis, it can be seen that under each weighting scheme Alternative 5 is always in the nondominated set. Based on the sensitivity analysis result, it can be concluded that Alternative 5 is the best compromise. It is the solution that is closest to the "ideal point" in the nondominated subset.

4.4 A Comparative Study of ELECTRE and MAUT

The ELECTRE and MAUT methods both belong to the category of multicriteria decision analysis approaches. Both have been applied to multi-objective decision making problems with a finite number of alternatives. However, there are a few differences between these two methods. First, the MAUT method requires a decision maker to specify the best and worst case for each criterion in order to generate the utility function. Secondly, the MAUT method uses an aggregated utility to rank alternatives, and the ELECTRE method uses pairwise comparisons to determine outranking relationships between alternatives. Finally, the MAUT approach uses an interval scale to measure utility, and the ELECTRE method uses a ratio scale of measurement.

In order to better understand these methods, a comparative study was conducted on the ITS deployment comparison. ITS deployment alternatives are ranked implementing the MAUT method and ELECTRE-II method using the same settings in the decision maker's preferences. The results are reported in Table 4.4-1.

Table 4.4-1: A Comparative Study of MAUT and ELECTRE in Ranking ITS Deployments

		Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5	Alternative 6
Weighting Scheme 1 (even)	**MAUT Ranking**	3	3	4	2	1	2
	ELECTRE Ranking	3	3	4	2	1	2’
Weighting Scheme 2 (efficiency)	**MAUT Ranking**	4	5	6	2	1	3
	ELECTRE Ranking	3	3’	4	2	1	2’
Weighting Scheme 3 (mobility)	**MAUT Ranking**	4	4	6	2	1	2
	ELECTRE Ranking	3	3	4	2	1	2’
Weighting Scheme 4 (safety)	**MAUT Ranking**	5	4	6	3	1	2
	ELECTRE Ranking	3’	3	4	2	1	2’
Weighting Scheme 5 (environment)	**MAUT Ranking**	5	4	6	3	1	2
	ELECTRE Ranking	3’	3	4	2	1	2’
Weighting Scheme 6 (cost)	**MAUT Ranking**	4	5	6	2	1	3
	ELECTRE Ranking	3	3’	4	2	1	2’

As shown in Table 4.4-1, the ranking results of the MAUT approach and the ELECTRE method show similarities as well as differences.

Under Weighting Scheme 1 and Weighting Scheme 3, both models rank the alternatives in the same order. The only difference is that the ELECTRE method reveals that Alternative 4 is slightly more beneficial than Alternative 6 if the concordance and discordance conditions are further relaxed (in Table 4.4-1, ranking 2 is slightly better than ranking 2', and ranking 3 is slightly better than ranking 3'). Under Weighting Scheme 2 and Weighting Scheme 6, the MAUT approach explicitly ranks Alternative 1 higher than Alternative 2; and Alternative 4 is ranked higher than Alternative 6. However, the ELECTRE method yields many tied rankings. The ties between Alternatives 1 and 2, and Alternatives 4 and 6 cannot be altered without further changing the concordance and discordance conditions. Once the concordance and discordance conditions are further relaxed, the ELECTRE method ranks Alternative 1 higher than Alternative 2; and Alternative 4 is ranked higher than Alternative 6, which is consistent with the results from the MAUT approach.

Under Weighting Scheme 4 and Weighting Scheme 5, the MAUT approach and the ELECTRE method tend to rank alternatives differently. Conflicts occur between Alternatives 1 and 2, and Alternatives 4 and 6. In the MAUT approach, Alternative 2 is ranked higher than Alternative 1 and Alternative 6 is ranked higher than Alternative 4. However, using the ELECTRE method, further examination indicates that Alternative 1 is slightly better than Alternative 2 and Alternative 4 is slightly better than Alternative 6.

The differences in ranking results are essentially caused by the different methods by which MAUT and ELECTRE calculate the outranking relationships.

The MAUT approach uses an overall utility function to assess outranking relationships among a set of alternatives. The utility functions are defined based on decision makers' preferences. Although various methods and questionnaires have been developed to assist decision makers' preference assessment, results are still inevitably affected by decision makers' subjectivity, knowledge level, and insight to the problem. The ELECTRE method, on other hand, uses pairwise comparison to develop the outranking relationships. The degree of dominance is usually assumed to be a linear function of the alternative's performance in achieving the objectives. However, such linearity is not assumed in the MAUT model. The MAUT model can better handle decision makers' preferences using nonlinear utility functions.

Although there are specific advantages to using each of these methods, it is still difficult to determine which one is better. Both methods are proven. However, based on the applications of these two methods in ITS deployment analysis, the author makes following recommendations:

1) If multiple decision makers or stakeholders are involved in the decision-making process and they have conflicting interests, the modified ELECTRE method is suitable. A "best compromise" alternative can be identified to balance the interests of these decision makers or stakeholders. If the MAUT method is used to solve this type of problem, decision analysts must work on decision makers' or stakeholders' preference settings and generate a single group preference. The process to generate the group preference has already been discussed by Levine and Underwood (1996).

2) In a situation in which there is a single decision-maker, the MAUT approach and the ELECTRE method are both applicable. As indicated in this study, these methods can successfully identify a best alternative, although the rankings of the alternatives show some conflicts. The MAUT approach is more powerful in handling decision makers' preferences. The ELECTRE method, on the other hand, aids decision makers in solving the problems with less involvement of preferences.
3) If some ITS deployments show equally balanced performances in achieving objectives, the ELECTRE method may yield many tie rankings without proper concordance and discordance condition settings. Given this situation, sensitivity analysis can be performed to break the ties. However, ties may only be broken based on weak outranking relationships. The MAUT approach, on the other hand, ranks the alternatives at different positions even if there is only a minor difference in their utilities. Decision makers should not only check alternative rankings, but also examine alternative utilities, because the minor difference in utilities could be significantly affected by subjectivities.
4) As the number of alternatives increases, the computational complexity of concord and discord indices in the ELECTRE method will also increase. Identifying the kernel of an ELECTRE graph also becomes more difficult. The computational complexity of the ELECTRE method is $O(mn^2)$, assuming m is the number of criteria and n is the number of alternatives. The computational complexity of the MAUT approach is $O(mn)$. Therefore, if there are a large number of alternatives, the MAUT

approach handles the problem more efficiently than the ELECTRE method.

4.5 SUMMARY

The National ITS Architecture provides good guidance for ITS system deployment. However, due to limited funding availability, it is not feasible to deploy a complete ITS framework immediately. Deployments that better solve local transportation problems should receive higher priority for implementation. Therefore, identifying the best deployments among several candidates becomes an issue in practice. This chapter presented a modified ELECTRE method to address this issue.

The ELECTRE method is a proven method for multicriteria decision analysis. Given a number of alternatives, a set of criteria, and a weighting scheme, the nondominated subset can be identified based on the alternatives' values on the criteria set. If a number of ITS deployments are evaluated with respect to multiple weighting schemes, in which each scheme favors an objective, the deployment that always remains in the nondominated subset will be identified as the best compromise solution to achieve all objectives. If a decision maker wants to compare a number of ITS deployments' performance in achieving multiple objectives, developing multiple weighting schemes and using the ELECTRE method in an iterative manner is a good option. The modified ELECTRE method proposed in this study illustrates the benefits.

The modified ELECTRE method was validated through a case study in Austin, Texas. By varying the weighting schemes to favor different criteria and then performing a sensitivity analysis, a nondominated alternative is obtained, which is the alternative of *Freeway Control/Incident Management System* integration. In practice, this ELECTRE helps ITS planners and decision makers identify the best ITS deployments to fit their objectives.

A comparative study was conducted on the MAUT and ELECTRE methods. Both were used to rank a number of ITS deployments. The ranking results indicate that both the MAUT and ELECTRE methods can be applied. They successfully identified the best alternative in this study, although the rankings of some alternatives indicate conflicts. In most cases, a multicriteria decision problem can be solved using both methods. However, MAUT and ELECTTRE differ in several aspects. For example, the MAUT approach uses an aggregated utility to rank alternatives, while the ELECTRE method uses pair-wise comparisons to determine the outranking relationships between alternatives. The two methods also differ with respect to how they accommodate decision makers' preferences. Differences in preferences may make one method more suitable than the other in determining the most beneficial alternative. Recommendations were made in Section 4.4 on applications of the MAUT approach and the ELECTRE method following a comparative study.

Chapter 5 Conclusions

5.1 SUMMARY AND CONCLUSIONS

ITS planning is characterized by deciding which ITS strategy produces the most beneficial results. Because this type of decision making has historically lacked the inclusion of a systematic process and only a limited number of studies have been undertaken to address this problem, this dissertation focuses on decision analysis approaches in ITS planning. The primary objective of this research is to understand, formulate, and solve two major problems that have been identified by the author in ITS planning: 1) At the strategic level, develop an ITS market package plan that fits local transportation problems and needs; 2) At the executive level, identify ITS deployments that are most beneficial to the planning area. To accomplish this objective, two studies are proposed, each addressing one of the identified problems. In this section, the studies will be reviewed and the findings discussed.

The first study constructed a multi-attribute utility theory (MAUT) model for ITS market package screening, a central element in ITS strategic planning. A multi-attribute utility function (MUF), which was evaluated with respect to a number of goals recommended by the Federal Highway Administration (FHWA), was established to assess each ITS market package that was defined in the National ITS Architecture. Based on the aggregated MUF values, ITS market packages were ranked so that ITS planners could make choices accordingly. The MAUT approach was applied to a case study in Austin, Texas to identify the most beneficial ITS market packages for the planning area. Sensitivity analyses were performed to examine the impact of sub-goal/performance measure weights on ranking results.

Based on the original MAUT model, uncertainties that may influence final outcomes were further investigated. Instead of using deterministic assessments, the benefit levels of the package were evaluated using probabilistic assessments. The resultant rankings of the ITS alternatives were then assessed using the expected utility values. A comparative study was performed on the original MAUT model and the MAUT model that integrated uncertainties. The results indicated that the uncertainties in the benefits of ITS market packages slightly affected the final rankings of the alternatives.

Compared to the conventional ITS market package screening method, the MAUT approach provides decision makers more detailed information and data in order to better understand which ITS market package may be most suitable to address local transportation problems. Ranking results from the MAUT approach not only provide decision makers a list of packages that can better achieve local ITS goals, but evidence to define ITS deployment priority settings. Sensitivity analyses, on the other hand, allow ITS planners to examine the impact of goal/performance measure weights on final outcomes and the impact of potential weight assessment conflicts between various stakeholders. Additionally, incorporating uncertainties into the MAUT model, which is a feature of this study, allows decision makers to evaluate ITS market packages more realistically. The risk of choosing one market package over another can be further investigated with the consideration of uncertainties.

The second study developed an ELECTRE method to address problems that arise when comparing ITS deployments. A modified ELECTRE method was developed to compare a number of ITS deployment alternatives with respect to multiple objectives. By varying the weighting schemes to favor different criteria and performing a sensitivity analysis, the nondominated alternative can be obtained using the modified ELECTRE method. This method was applied in a case study in Austin, Texas and the best ITS deployment identified, which was an integrated freeway control and incident management system.

Compared to conventional ITS deployment analysis methods, the ELECTRE method provides decision makers with insight into the potential impact of ITS deployments on traffic operations. It allows decision makers to analyze ITS alternatives using flexible weighting schemes to represent their concerns or preferences on the ITS deployment objectives. Therefore, the proposed ELECTRE method is especially useful in handling the decision-making problems with multiple objectives or multiple decision makers in ITS planning.

In order to examine each method's strengths and weaknesses, a comparative study was conducted on the MAUT and ELECTRE methods. It was found that although both methods can be applied to ITS deployment analysis, the MAUT method and ELECTTRE method differ in several ways that makes one method more suitable than the other in some cases. For example, the MAUT method uses an aggregated utility to rank alternatives, and ELECTRE uses pairwise comparisons to determine outranking relationships between alternatives. Recommendations for the applications of the two methods are made in Section 4.4 based on the comparative study.

All in all, this research proposed two types of multicriteria decision analysis approaches to address the decision-making issues that emerged in ITS planning. The MAUT and ELECTRE models were established and validated with case studies. The alternatives, goals and objectives, performance measures, decision makers' preferences, and uncertainties were discussed in detail. The most significant research effort in this study involved integrating uncertainties into the MAUT model for ITS market package screening, a flexible ELECTRE model to compare ITS deployments, and the analysis on the strengths and weaknesses of the MAUT and ELECTRE models. Consequently, the proposed methods have an advantage over conventional methods by providing decision makers with more data and information to compare ITS alternatives, enabling decision makers to prioritize the alternatives, allowing decision makers to evaluate the ITS alternatives more realistically by considering uncertainties, and enabling decision makers to rank the alternatives with a higher level of confidence. Under the new transportation law, the Safe, Accountable, Flexible, Efficient Transportation Efficiency Act: A Legacy for Users (SAFETEA-LU), ITS projects must compete with other proposed transportation improvement projects for funding opportunities. This research makes an important contribution in improving ITS planning and ITS investments analysis by providing a rational framework for assessment and better use of limited resources.

5.2 RECOMMENDATIONS AND FUTURE RESEARCH

The approaches developed and validated in this research can be immediately applied to ITS planning process at both strategic and executive levels. In effect, this is the purpose of this research. The MAUT approach—with and without uncertainties incorporated—can be applied to develop a regional ITS master plan and to define implementation priority settings. The ELECTRE method can be applied to compare and prioritize various ITS projects. However, like many research efforts, this study also has limitations and several issues should be addressed in future studies.

First, since technologies evolve rapidly, ITS market package group is expanding rapidly as well. The benefits of the newly-added ITS market packages should be evaluated periodically so that the MAUT approach can be applied to analyze them. However, the ITS benefit evaluation is difficult. The options are limited to field tests, post-project evaluation, and simulations, all which require much effort and resources. However, the planning and implementation of ITS rely on these evaluation results. Developing methods to predict ITS impacts more accurately is a challenge.

Second, since the MAUT approach and ELECTRE method are preference-based, it is advantageous to examine the preference characteristics of various stakeholders in ITS planning. The purpose of doing so is to better develop the system and better serve the community. In this study, the interests of a single stakeholder, TxDOT, were considered to illustrate the concept. In actual use one would wish to examine the preferences of other stakeholders such as various citizen groups, transit agency, metropolitan planning organization, transportation industry, and private companies in ITS business. In addition, stakeholders' preferences may vary in different areas. For example, stakeholders preferences will vary whether in a large metropolitan area, a medium-sized area, and a rural area. Examining stakeholders' preferences of different groups will sharpen the insight of applying the multicriteria decision analysis approaches such as MAUT and ELECTRE. There remains considerable research to be performed and expanded case studies to be undertaken. However, as mentioned before (Levine and Underwood,1996), stakeholders' level of knowledge and experience with respect to ITS implementation will vary presenting challenges. These techniques offer a process for addressing these challenges and more examination and case studies are recommended.

Finally, there are several multicriteria decision analysis approaches available with inherent advantages and disadvantages. MAUT, ELECTRE, and analytical hierarchy process (AHP) are all proven methods. They not only share some common features, but also differ in several ways. The comparative study reported in this dissertation shows that, in some cases, one method maybe more suitable than another. Without question, it would be beneficial to perform more comparative studies so that the strengths and weakness of these methods can be further explored in the context of ITS planning.

Appendix

A.1 A Questionnaire for ITS Planning and Deployment Project Participants

This questionnaire was developed for an interview with ITS planners and engineers in TxDOT's District Office in Austin. The purpose of the interview was to examine TxDOT's perspective with respect to ITS planning and implementation.

(Please see next page for the questionnaire)

1. Did you use any version of the Federal Highway Administration's *ITS Planning Process* in your early ITS deployment project?

   ___ Yes. Please specify the version: ____________________

   ___ No.

2. If you did not use the FHWA Planning Process, please briefly outline the process you did use. Please check the process you used from the following options:

Steps/Features	Included?
(1) Define Problems	
(2) Establish Institutional Framework & Stakeholder Coalition	
(3) Establish User Service Objectives	
(4) Short, Medium, Long User Service Plan	
(5) Establish Performance Measures	
(6) Identify Needed Functional Areas	
(7) Define System Architecture. *(Define Functional Requirements to Support User Services)*	
(8) Identify System Component Options *(Identify and Screen Market Packages, Alternative Technologies, and Related Issues)*	
(9) Pre-evaluate and Compare Different ITS Alternatives	
(10) Define Implementation and Operational Strategies (Phasing, Partnerships, etc.)	
(11) Strategic Deployment Plan (Set of Projects)	
(12) Project Monitoring and Evaluation	
Others. Please specify:	
(13)	
(14)	
(15)	
(16)	

3. a) What was the time frame for carrying out the ITS planning process (start and completion dates)?

   Start Date: _________ Completion Date:_________

   b) What parts would you have spent more (or less) time on?
   Please specify: __________________

____
____

4. What is the time frame for implementation, or "planning horizon," for your early ITS deployment project?
   (short medium long) term ___________ years

5. Do you think a planning guidance is helpful for ITS system development?
   ___ Yes ___ No

6. Please indicate the agencies represented on the "steering" committee which guided the ITS deployment project in your region and the number of committee members:
   a) Agencies: ___________________________________
   ____
   ____
   ____

   b) Number of committee members: ______

7. Please indicate the transportation stakeholders for ITS implementations in your region. What were the views, opinions, needs, etc. gathered from the transportation stakeholders in your region? Are they met in the ITS implementations?

Stakeholders	**Views/Opinions/Needs**	**Are they met?**

8. Implementation Goals. What are your implementation goals of ITS projects? Please specify from the following goals recommended by ITS JPO of USDOT. You can use a number (0~10) to represent the relative importance of that goal in your region (10 represents extremely important, 0 represents no importance):

Goals	**Included?**	**Importance**
ITS JPO Goals:	–	–
1) Increase operational efficiency and capacity of transportation system		
2) Enhance personal mobility, convenience, and comfort of the transportation system		
3) Improve the safety of the transportation system		
4) Reduce energy consumption and environmental costs		
5) Enhance the present and future economic productivity of individuals, organizations and the economy as a whole		
6) Create an environment in which the development of ITS can flourish		
Others. Please specify:	–	–
7)		
8)		
9)		
10)		

9. ITS Deployments Comparison:
   a) For those ITS projects deployed in your region, were they evaluated before and after deployment?
      ___ Yes ___ No

   b) Are there multiple alternatives developed or involved?
      ___ Yes ___ No

   c) If evaluated, what evaluation method is used?
      ____

d) Please specify the measures that were used or can be used for ITS deployment evaluation in your region and their importance. You can use a number (0~10) to represent the relative importance of that goal in your region (10 represents extremely important, 0 represents no importance):

Measures	Included?	Importance
ITS JPO Measures:	–	–
1) Mobility		
2) Safety		
3) Efficiency		
4) Economic Productivity		
5) Energy Consumption and Environment		
6) User Satisfaction		
Cost Measures:	–	–
7) Initial Cost		
8) Operational Cost		
Others. Please specify:	–	–
9)		
10)		
11)		
12)		

10. ITS Technologies Selection:

a) For those ITS hardware and software components deployed in your region, Were they evaluated before and after deployment?

(1) Yes (2) No

b) Are there multiple options identified or involved?

(1) Yes (2) No

c) If evaluated, what evaluation method is used?

____

d) Please specify the measures that were used or can be used for ITS technological products (Traffic Detection System) evaluation in your region and their importance. You can use a number (0~10) to represent the relative importance of that goal in your region (10 represents extremely important, 0 represents no importance):

Measures	Included?	Importance
General Measures:	–	–
1) Maintainability		
2) Reliability		
3) Accuracy		
4) Ease of Integration		
5) Feasibility		
Cost Measures:	–	–
6) Installation Cost		
7) Operational Cost		
Others. Please specify:	–	–
8)		
9)		
10)		

e) Please specify the measures that were used or can be used for ITS technological products (***Surveillance Camera System***) evaluation in your region and their relative importance. You can use a number (0~10) to represent the relative importance of that goal in your region (10 represents extremely important, 0 represents no importance):

Measures	Included?	Importance
General Measures:	–	–
1) Color		
2) Daylight Resolution		
3) Night Resolution		
4) Bright Light Effect		
5) Ease of Control (zoom in/out, rotate, etc.)		
Cost Measures:	–	–
6) Installation Cost		
7) Operational Cost		
Others. Please specify:	–	–
8)		
9)		
10)		

f) Please specify the measures that were used or can be used for ITS technological products (***Communication System***) evaluation in your region and their relative importance. You can use a number (0~10) to represent the relative importance of that goal in your region (10 represents extremely important, 0 represents no importance):

Measures	**Included?**	**Importance**
General Measures:	–	–
1) Maintainability		
2) Reliability		
3) Bandwidth		
4) Video Clarity		
5) Ease of Integration		
Cost Measures:	–	–
6) Installation Cost		
7) Operational Cost		
Others. Please specify:	–	–
8)		
9)		
10)		

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