Towards the Development of a Decision Support System for Emergency Vehicle Preemption and Transit Signal Priority Investment Planning

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(ABSTRACT)

Advances in microprocessor and communications technologies are making it possible to deploy advanced traffic signal controllers capable of integrating emergency vehicle preemption and transit priority operations. However, investment planning for such an integrated system is not a trivial task. Investment planning for such a system requires a holistic approach that considers institutional, technical and financial issues from a systems perspective. Two distinct service providers, fire and rescue providers and transit operators, with separate operational functions, objectives, resources and constituents are involved. Performance parameters for the integrated system are not well defined and performance data are often imprecise in nature.

Transportation planners and managers interested in deploying integrated emergency vehicle preemption and traffic priority systems do not have an evaluation approach or a common set of performance metrics to make an informed decision. There is a need for a simple structured analytical approach and tools to assess the impacts of an integrated emergency vehicle preemption and transit priority system as part of investment decision making processes. This need could be met with the assistance of a decision support system (DSS) developed to provide planners and managers a simple and intuitive analytical approach to assist in making investment decisions regarding emergency vehicle preemption and transit signal priority.

This dissertation has two research goals: (1) to develop a decision support system framework to assess the impacts of advanced traffic signal control systems capable of integrating emergency vehicle preemption and transit signal priority operations for investment planning purposes; and (2) to develop selected analytical tools for incorporation into the decision support system framework. These analytical tools will employ fuzzy sets theory concepts, as well as cost and accident reduction factors. As part of this research, analytical tools to assess impacts on operating cost for transit and fire and rescue providers have been developed. In addition, an analytical tool was developed and employs fuzzy multi-attribute decision making methods to rank alternative transit priority strategies. These analytical tools are proposed for incorporation into the design of a decision support system in the future.

Dedication

I would like to dedicate this work to my parents, Wah and Pui Lan Soo. They instilled in their children the desire to learn.

Acknowledgements

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Chapter 1:   Introduction

This chapter provides an introduction to integrated emergency vehicle preemption and transit signal priority systems, their potential impacts, and the need for a simple, structured analytical approach for planners and managers to use as part of their investment decision making processes. The need for a systematic approach to assess the impacts of advanced traffic signal control systems capable of integrating emergency vehicle preemption and transit signal priority operations is introduced and the research objectives are described. Also provided is a brief outline of the remaining chapters.

1.1 Background

Advances in modern information technology and communications are making possible the deployment of Intelligent Transportation System (ITS) applications to improve the transportation system and make it more effective, efficient and safer (Proper et al., 2001).   In some instances, technology applications may impact more than one domain. When that occurs, successful implementation requires decision makers and planners to consider institutional concerns as well as technical and financial issues in their planning process. Often, structured analytical approaches and precise performance data to assess the impacts of deploying integrated ITS applications may not always be available.

Advanced traffic control systems capable of integrating emergency vehicle preemption and transit priority operations is such an ITS application. Advances in microprocessor and communications technologies are making it possible to adapt current traffic signal controllers to provide preferential treatment for emergency vehicles and qualified transit vehicles in the form of emergency vehicle preemption and transit signal priority. Two distinctly separate service providers, fire and rescue providers and transit operators, that normally do not interact operationally may potentially share common system hardware as well as operational environments.

1.2 Problem Statement

Today, transportation planners and managers interested in assessing the deployment of integrated emergency vehicle preemption and traffic priority systems do not have an evaluation approach or a common set of performance metrics to make an informed decision. Decision making problems faced by planners and managers are complex in nature and include multiple and often conflicting criteria that contain uncertain, subjective, imprecise and ambiguous performance data.   There is a need for a simple structured analytical approach and tools for planners and managers to assess the impacts of an integrated emergency vehicle preemption and transit priority system as part of their investment decision making processes.

1.3 Research Goal

This dissertation has 2 research goals: (1) to develop a decision support system framework to assess the impacts of advanced traffic signal control systems capable of integrating emergency vehicle preemption and transit signal priority operations for investment planning purposes; and (2) to develop analytical tools for incorporation into the decision support system framework. These analytical tools employ fuzzy sets theory concepts, as well as cost and accident reduction factors. These tools will then be used in fuzzy multi-attribute decision making methods to rank alternatives. These analytical tools can be considered for incorporation in the design of a decision support system in the future.

1.4 Report Structure

Chapter 2 – Literature Review: This chapter reviews the pertinent research sources used to establish the background for this research to support this dissertation.

Chapter 3 – Decision Support System Framework: This chapter introduces a conceptual decision support system framework for use in investment planning of integrated emergency vehicle preemption and transit signal priority systems.

Chapter 4 – EVP and TSP Impacts on Operating Cost: This chapter presents two analytical tools developed to assess potential operation and maintenance (O&M) cost impacts to fire and rescue providers and transit providers due to integrated emergency vehicle preemption and transit signal priority operations.

Chapter 5 – Fuzzy Multi-attribute Decision Making Method: This chapter presents soft computing techniques to use uncertain, subjective, imprecise, and ambiguous transit signal priority strategy performance information in multi-attribute decision making methods.

Chapter 6 – Summary, Conclusions and Recommendations; This chapter will summarize the research products produced by this research; present conclusions pertaining to possible future applications of fuzzy MADM methods in transportation and traffic engineering; and offer recommendations for future research.

Appendix A – Application of Fuzzy Sets Theory Concepts to Multi-attribute Decision Making Methods: This appendix provides supplemental information on fuzzy sets theory applications to fuzzy multi-attribute decision making methods not covered in Chapter 4.

Appendix B – TRB Paper: This appendix contains a paper entitled "Evaluating the Impacts of Advanced Traffic Signal Control Systems: The Effect of Transit Signal Priority Strategies on Transit Operating Costs," that was presented in the 2004 TRB in Washington D.C. and published in the 2004 TRB CDROM

Appendix C – ITSA Paper: This appendix contains a paper entitled "An Analytical Framework for Evaluating the Impacts of Advanced Traffic Signal Control Systems for Emergency Vehicle Preemption and Transit Signal Priority," that was presented in the 2004 ITSA Annual Meeting in San Antonio, Texas and published in the 2004 ITSA Journal.

Chapter 2:   Literature Review

This chapter identifies the purpose and structure of the literature review that supports this research effort. The following elements are identified and outlined: key literature categories and the connection between research for this dissertation and key supporting works.

2.1.   Introduction

The purpose of the literature review is to identify and synthesize appropriate references to demonstrate and illustrate the presence of knowledge gaps to be addressed by this research. These references will include journal articles, conference papers, published reports, and other readily available sources of information, such as selected World Wide Webb pages from the Internet.

2.2.   Literature Categories

Literature used to support this research spans across several domains of transportation and traffic engineering. This reflects the cross cutting nature of the research. Research examined six distinct areas: transit signal priority, emergency vehicle preemption, economic analysis, fuzzy sets theory, multi-attribute decision making methods, and decision support systems.

- **Transit signal priority** was reviewed to determine the state-of-the-art in operational evaluation, planning considerations, impact analysis, and evaluation methods and measures from simulation and field studies.
- **Emergency vehicle preemption** was reviewed to determine the state-of-the-art in operational evaluation, planning considerations, impact analysis and evaluation methods and measures from simulation and field studies.
- **Economic analysis** was reviewed to determine the state-of-the-art in economic analysis approaches for Intelligent Transportation Systems, fire and rescue operational costs, and transit operating costs.

- **Fuzzy sets theory** was reviewed for applications to convert imprecise, uncertain and ambiguous performance measures for use in multiattribute decision making methods.

- **Multi-attribute decision making methods** were reviewed to determine the state-of-the-art in fuzzy multiattribute decision making methods for use in uncertain environments.

- **Decision Support Systems** were reviewed to determine the state-of-the-art in DSS developments and application of soft computing techniques for building intelligent decision support systems in the presence of uncertainty.

2.3. Transit Signal Priority

An Overview of Transit Signal Priority, (Advanced Traffic Management System and Advanced Public Transportation System Committees of the Intelligent Transportation Society of America, 2002)

This overview of transit signal priority was co-developed by the Advanced Traffic Management System (ATMS) and Advanced Public Transportation System (APTS) Committees of the Intelligent Transportation Society of America (ITS America). It is an introductory guide to implementing transit signal priority. Co-authored by both public transit operators and traffic engineers, it presents a balanced approach on the significance and consequences of transit signal priority.   This guide is intended as a reference aid to a broad spectrum of stakeholders involved in implementing transit signal priority strategies. Major topics addressed include: overview of transit signal priority fundamentals; transit signal priority benefits and costs; planning for deployment of transit signal priority; transit signal priority design and implementation issues; transit signal priority operations and maintenance issues; future directions and recommendations. The guide provides definitions of terminology, outlines benefit and cost measures, indicates deployment planning process elements, illustrates system architecture, and identifies some public policy issues related to deployment and implementation.

Evaluation of Service Reliability Impacts on Traffic Signal Priority Strategies for Bus Transit, (Chang, Collura, Dion, Rakha, 2002).

This report is based on Chang's dissertation research, which examined the evaluation of transit signal priority strategies on transit service reliability. This paper introduces an evaluation framework and plan that provides a systematic method to assess potential benefits and impacts of transit vehicle priority.

Results include specific performance measures corresponding to particular objectives of the project under evaluation. This framework was applied to a corridor along Columbia Pike in Arlington, Virginia. The INTEGRATION simulation tool was used to model the test corridor. Measures of Effectiveness included: bus schedule reliability, bus efficiency and other traffic related impacts. Both early green and green extension were employed. Results indicate that bus service reliability improved 3.2%, bus efficiency improved 0.9%, and non-transit delay in the overall corridor increased approximately 1.0% on a vehicle basis or 0.6% on a person basis.

Advanced Public Transpiration Systems: Evaluation Guidelines, (Casey and Collura, 1994).

This report presented guidelines for planning, implementing, and reporting the findings o federal Transit Administration (FTA) Advanced Public Transportation Systems (APTS) operational test evaluation. This guideline was developed to guide early ITS deployment in the public transportation area by fostering consistency of evaluation philosophy and techniques, compatibility and transferability of results to improve the quality and utility of information obtained from the APTS program. Suggestions presented that are applicable today include: (1) a common framework and methodology for developing and executing the evaluation of operational tests; (2) the type of measurements that may be important in establishing the benefits and impacts associated with ITS in public transportation systems; (3) the strategy for obtaining data is just as important as determining the measures themselves; (4) data collection and analysis should be structured around some form of comparison (e.g., before and after); (5) collected data by itself may not be as useful as data that is derived from collected data using empirical relationships statistical method, mathematical techniques and engineering principles borrowed from other fields.

Transit Preferential Streets Program Final Report, (City of Portland Office of Transportation, 1997)

This report summarizes the findings of a detailed operational analysis performed to improve transit travel times and service by implementing transit priority solutions to twelve intersections within five corridors in the City of Portland, Oregon.   The operational analysis showed that only 31% to 39% of the total bus travel time was for driving. The remaining 60% to 70% of the total travel time was distributed between time spent at traffic signals, bus stops, and in traffic. The report also discusses the results of an international inventory of previously applied treatment solutions. Among the solutions recommended for implementation were: signal priority for buses, signal timing changes, bus stop consolidation, bus stop relocation, queue bypass lanes for buses, fare collection changes, curb extension at bus stops, boarding island at bus stops, low-floor bus equipment technology, parking restrictions within bus corridors, exclusive bus

lanes, queue jump lanes for buses, and exempting busses from turn restrictions. The transit preferential street strategies were simulated using the microscopic simulation model VISSIM.

A Comprehensive Strategy for Transit Signal Priority, (Ngan, 2003)

This paper presents findings of simulation, using VISSIM, along the Granville Street corridor in Vancouver, Canada, to investigate the influence of five traffic parameters on the effectiveness and impact of a transit signal priority (TSP) application. These five parameters are: (1) bus approach volume, (2) cross-street volume-to-capacity ratio, (3) bus stop location, (4) bus check-in detector location and (5) signal coordination. Simulation results were summarized in three tables: (1) impact of TSP on cross-street performance at various volume-to-capacity ratios; (2) effectiveness of green extension for far side bus stops; and (3) impact of signal coordination on the effectiveness of TSP.   Based on these simulation results some generic guidelines and recommendations for TSP applications are proposed. These include: (1) TSP is most effective under moderate to heavy bus approach traffic conditions; (2) TSP may not be effective on cross-streets with high volume-to-capacity ratios; (3) active TSP is more effective with far-side bust stops; (4) TSP effectiveness is sensitive to far-side bus stop check-in detector locations; (5) for best corridor performance, signal coordination should be maintained.

Development and Evaluation of an Intelligent Bus Priority Concept, (Balke, Dudek, Urbanik, 2000)

This paper discusses the development and laboratory testing of an intelligent concept for providing priority to buses at signalized intersections. The concept uses bus positional information to predict when in the cycle a bus would arrive at a signalized intersection and whether priority is needed. The performance of the Intelligent Bus priority approach was examined at three volume-to-capacity (v/c) levels: 0.5, 0.8 and 0.95. Results indicated: (1) significant bus travel time reductions at all three v/c levels; (2) minor increases in main street non-transit travel time occurred at the 0.5 and 0.8 v/c levels; and (3) non-priority approaches were negatively impacted at v/c greater than 0.95.

Evaluation of Transit Signal Priority Strategies for Small-Medium Cities, (Ova and Smadi, 2001)

This study uses the VISSIM simulation tool to examine the impact of two TSP strategies: early green and extended green, on transit operations in conditions representing small-medium sized cities. The case study network is in the vicinity of the ground transfer center in the Fargo, North Dakota downtown area.   Key Measures of Effectiveness were side street person-delay, network person-delay, bus travel time, and bus delay. Four base cases were used to compare the TSP strategies: midday period with 15- and 30- minute headways, and an afternoon

period with 15- and 30-minute headways. Results suggest that early green performs better than extended green.

2.4.   Emergency Vehicle Preemption

<u>A Framework for Evaluation of Preferential Treatment of Emergency and Transit Vehicles at Signalized Intersections</u>, (Louisell and Collura, 2003)

This paper presents the notion of an evaluation framework to examine the impacts of emergency vehicle preemption and transit signal priority under the title of preferential treatments. The author focuses on the evaluation of emergency vehicle preemption. A method to evaluate the safety benefits of preemption based on conflict analysis is presented. The techniques of Conflict Point Analysis, an analytical approach used by the traffic engineering and safety community to examine the likelihood that accidents occur are used to investigate the potential for accidents between emergency vehicles and non-emergency vehicles at critical intersections. The potential for accidents can then be determined using a set of logic rules for the type of conflict, number of vehicles in each conflict stream, speed of the vehicles in the stream, and the degree of the situational understanding on the part of the drivers.

<u>A Simple Work Sheet Method to Evaluate Emergency Vehicle Preemption and the Impacts on Safety</u>, (Louisell, Collura, Teodorovic, Tignor, 2004)

This paper addresses the need for guidelines and methods to support jurisdictions seeking to make emergency vehicle preemption deployment decisions. A decision framework for the evaluation of specific intersections and corridors for emergency vehicle preemption deployment along with a worksheet is introduced. The decision framework has four decision elements: (1) safety, (2) delay, (3) proximity to an emergency vehicle origin or destination, and (4) location on planned emergency vehicle response route. The worksheet provides analysts with a simple 4-step tool to determine which intersections or corridors would benefit the most from emergency vehicle preemption.

<u>An Analysis of Emergency Vehicle Crash Characteristics</u>, (Vrachnou, 2003)

This thesis examines the distribution of emergency vehicle crashes in the Northern Virginia Area using data from the Fatal Accidents Reporting System (FARS) for the five-year period between 1997-2001. Results indicate that (1) approximately 31% of emergency vehicle crashes occurred at signalized intersections; and (2) crash damage at intersections are generally more severe at intersections than at non-intersections.

<u>Transition Strategies to Exit Preemption Control</u>, (Obenberger and Collura, 2001)

This paper presents a state-of-practice assessment of different transition strategies used to exit a preemption control plan and return to the coordinated operation of signal timing plan. The exit transition strategies available are typically restricted to the options supported by different types of traffic controllers or firmware products. Five commonly available exit transition strategies are reviewed and past experiences to determine the impacts of alternative transition strategies were examined. Each of these transition strategies have the potential to affect travel differently depending on: the frequency and direction of travel for the vehicle requesting priority; roadway capacity to accommodate turning movements; travel demand and roadway capacity; presence and frequency of pedestrian phases or actuated calls; green time available in cycle lengths to be reallocated to accommodate the desired exit strategy; cycle length, number of phases, and intervals to serve in the signal plan; and intersection spacing and quality of progression.

An Analysis of the Characteristics of Emergency Vehicle Operations in the Washington, D.C. Region, (Gkritza, Collura, Tignor, Teodorovic, 2004)

This paper presents analysis of emergency vehicle characteristics using data from Fairfax Country VA, and Montgomery County MD. Results indicate that emergency vehicle characteristics that merit attention include: temporal and spatial distribution of emergency vehicle travel, frequency and duration of preemption response requests, platoon responses, and crashes involving emergency vehicles. Analysis also indicated that: (1) the average cost of crash repair is about $5,700, with a range between $250 and $21,000, and (2) average duration of emergency vehicle preemption along the U.S. 1 corridor ranges from 16 seconds to 26 seconds with no significant viability by time of day.

Improving the Emergency Vehicle Signal Priority Methodology in the ITS Deployment System (IDAS), (McHale and Collura, 2001)

This paper is based on MaHale's dissertation research to examine the ITSA Deployment Analysis Software (IDSA) estimates on emergency vehicle benefits (increase travel speed) and emergency vehicle impacts to cross street delay. The author suggests that current assessment techniques are designed for operational analyses and not for transportation planning analysis. The CORSIM microsimulation tool was used to model traffic signal preemption for emergency vehicles along a seven-signalized intersection arterial. Benefits were quantified in terms of reduced travel time and increase travel speed. Impact to cross-street traffic and time period to restore the network to equilibrium flows is also quantified. Results indicate that (1) travel time reductions of approximately 30% minor increases in delay to cross-street traffic were achieved; and (2) network response to preemption, in a high volume environment, would taper over time from around 12.3% over normal fifteen minutes after preemption to around 3% over normal sixty minutes after the preemption event.

Stakeholder Requirements for Traffic Signal Preemption and Priority in Washington, D.C. Region, (Gifford, Pelletiere, Collura, 2001)

This report summarizes a survey conducted to gather information on the needs, issues and concerns of local elected officials, transportation and emergency personnel from the greater Washington D.C. area concerning signal priority and preemption systems. The authors identify three major stakeholder communities: (1) fire and rescue, (2) transit operations, and (3) traffic operations. Stakeholder needs, issues and concerns collected by the survey were used to generate a set of system objectives and general requirements that state and local decision makers might use in evaluating these systems in the future. The authors found that the relationship between traffic operations and fire and rescue communities are more developed than the relationship between traffic operations and transit operating communities. More importantly, the authors found that the fire and rescue community were concerned that integrated emergency vehicle preemption and transit signal priority systems may reduce the effectiveness of preemption systems.

Impact of Signal Preemption on the Operation of the Virginia Route 7 Corridor, (Bullock, Morales, Sanderson, 1999)

This study analyzed the impact of emergency vehicle traffic signal preemption on the travel time and delay of traffic on a signalized corridor in Northern Virginia. The corridor was composed of three coordinated signalized intersections on Route 7 (Leesburg Pike near Landsdowne, VA). The study used the modified version of the CORSIM simulation tool with model Type 170 controllers to provide a hardware-in-the-loop environment. Results suggested travel time increased 1%-2%. This was a somewhat surprising result because preemption is typically considered to cause significant disruptions in traffic. Some possible explanations for this relatively modest impact might be: (1) relatively long spacing between intersection; (2) modest traffic demand that does not lead to terribly oversaturated conditions before and after preemption; (3) emergency vehicle detection that is close to the intersection; (4) The corridor had a very long cycle length which may mask the impact of preemption.

Impact Evaluation of Emergency Vehicle Preemption on Signalized Corridor Operation, (Nelson and Bullock, 2000)

This paper reports on a case study that used the CORSIM micro-simulation too to examine the impact of emergency vehicle preemption on closely spaced arterial traffic signals. The study was conducted on State Route 26 a principal arterial and main thoroughfare connecting Interstate 65 and US 52 on the East side of Lafayette, Indiana. This study examined four coordinated intersections along SR 26 using seven preemption paths and three transition algorithms (smooth, add, and dwell). The number of preempts varied from one to three for each simulation period. The findings show that a single preemption call had

minimal effect on the overall travel time and delay through the network and the smooth transitioning algorithm performed the best with most scenarios and paths. When multiple emergency vehicles preempt at closely spaced intervals, the impact of preemption was more severe. In the most severe case, delays in the order of 20-30 seconds per vehicle were computed.

Emergency Vehicle Accident Study (Year 1977), (Fire Chief, 1977)

This study is the only report about the benefits of emergency vehicle preemption contained in the ITS Benefits Database maintained by FHWA. This report was provided by the City of St, Paul Minnesota Fire Chief in response to a question from city officials. The report examined emergency accident data rates before and after the installation of an emergency vehicle traffic signal preemption system in St Paul Minnesota. In 1969, 28 Opticom systems were installed. Between 1969 and 1976, the accident rate for emergency vehicles decreased by 70.8%. During this same period, the number of signalized intersections increased from 274 to 308 and the number of intersections equipped with signal preemption grew from 28 to 285. The performance measure, emergency vehicle crash per alarm, was used to compare before and after results. Results indicate that the number of emergency vehicle crashes per alarm continued to improve despite increases in the number of alarms and volume of traffic.

Time Study of the Effectiveness of the Opticom Traffic Signal Control System (1978), (City of Denver Department of Safety, 1978)

This study reports on impacts to emergency vehicle response time due to signal preemption in the City of Denver, Colorado, between 1977 and 1978. The area of study included three fire stations and 75 signalized intersections. Results from before and after comparisons indicate that emergency vehicle response times decreased between 14%-23% saving approximately 70 seconds per response on a typical response that spanned three to six signalized intersections.

Montgomery Fire, Rescue Crashes Rise – Accidents Threaten County's Insurance, (Mosk, 2003)

This article reports on the impact of rising fire and rescue crashes on insurance coverage. Montgomery Country fire trucks and ambulances had over 1,100 accidents in the past five years (1997-2002) with losses totaling nearly $2 million. This amount exceeds trends from comparably sized fire services on both the East and West Coasts. As a result the Montgomery County fire and rescue service is at risk of losing its insurance coverage. The author reports that there is no national benchmark for emergency vehicle driving safety. In the three years ending December 31, 2002, Prince George's County logged 607 collisions, Fairfax Country has 414 crashes and Montgomery County has 704. Montgomery County's underwriter, Volunteer Firemen's Insurance Services Inc., charged the

county a 2002 premium of $1.2 million, which was 18% more than in the previous year.

2.5.   Economic Analysis

Advanced Vehicle Monitoring and Communication Systems for Bus Transit: Benefits and Economic Feasibility, (Morlok, Brunn, Blackman, 1991)

This report analyzes the economic feasibility of advanced vehicle monitoring and communication (AVM/C) systems for bus transit. The authors suggest the use of a financial impact analysis to determine the feasibility of a project from a purely financial perspective. This will provide a conservative evaluation. A favorable financial assessment would produce even more desirable results in a comprehensive evaluation that includes all user benefits and costs. A bus transit cost model is derived as a method for evaluating the feasibility of AVM/C systems. This model defines investment costs as a function of revenue-hours, revenue miles and fleet size.

Economic Evaluation of Signal Preemption Projects, (Khnasnabis, Rudraraju, Baig, 1999)

A procedure for economic evaluation of preemption (traffic signal priority) projects is presented. This procedure is a variation of benefit-cost analysis that provides an estimate of the maximum investment that can be justified by way of savings in delay, fuel consumption, and emissions. The authors argue that projects costing less than that maximum cost would be justified. The major component of the maximum investment was determined to be savings in delay. Fuel savings and emissions constitute a small fraction of the overall benefit. Conclusion is that the implementation of transit priority can, favor all practical purposes, be justified only by means of savings in delay.

Profitability Evaluation of Intelligent Transport System, (Leviakangas and Lahesmaa, 2002)

The objective of this study was to consider evaluation methods for Intelligent Transport System (ITS) investments, to point out some shortcomings of benefit-cost analysis, to develop alternative methods and to make recommendations for how the profitability of ITS investments should be evaluated. This work identifies the fundamental differences between ITS and road infrastructure investments and how they impact on profitability evaluations. The conclusion is that benefit cost analysis (BCA), which was developed for physical infrastructure investments, does not capture all the benefits or costs related to ITS. The paper also discusses and demonstrates the use of multi-criteria analysis in profitability analysis. The analytical hierarchy process (AHP) method was utilized to evaluate other risks that do not have specific monetary values and to compare the results of different profitability analysis.

<u>TCRP Report 78 Estimating the Benefits and Costs of Public Transit Projects: A Guidebook for Practitioners</u>, (ECONWest and Parsons Brinckerhoff Quade & Douglas, 2002)

This guidebook provides a practical framework for estimating the benefits and costs of public transportation projects. The guidebook was written for transit planners at all levels of government to evaluate transit investments. The analytical framework is consistent with economic theory and provides a solid basis for evaluating transportation options and some estimates of many of the benefits and costs of transit investments. It categorizes transit impacts into (1) travel impacts; (2) environmental impacts, (3) impacts on economic development, (4) land use and development impacts, (5) distribution of transit impacts.

<u>Benefit-Cost Evaluation of a Highway-Railroad Intermodal Control System</u>, (Lee and Carroll, 2001)

This paper presents an evaluation framework to assess the benefits of an ITS system that minimizes the conflicts between trains and vehicular traffic at at-grade crossings in an urban environment. A series of impact linkages are developed that takes into account all potential benefits. Algorithms and data is then developed that provide a range of magnitude of these impacts and their dollar valuation. Finally, these benefits are aggregated and associated to potential recipients.

<u>Evaluating the Impacts of Advanced Traffic Signal Control Systems: The Effect of Transit Signal Priority Strategies on Transit Operating Costs,</u> (Soo, Collura, Hobeika, Teodorovic, 2004b)

This paper presents an analytical approach to assess the impact of reduced transit travel time on transit operating and maintenance cost. The paper introduces an overarching evaluation framework to assess the efficiency and cost effectiveness of advanced traffic signal control systems capable of emergency vehicle preemption and transit priority.   Beneficiaries of the integrated emergency vehicle preemption and transit priority system include the general public, transit riders, non-transit users, fire and rescue service providers, and transit operators. Also presented is the notion of distributing investment costs and operating costs among three entities: the owner of the traffic signal system (the municipality), the fire and rescue service providers, and transit operators. Traditionally these three entities are separate functions with separate missions and make investment decisions independently. An integrated emergency vehicle preemption and transit priority system would require all three to coordinate on operational and financial issues. Treating integrated emergency vehicle preemption and transit priority as a system provides planners and managers a different perspective for investment planning.

An Analytical Framework for Evaluating the Impacts of Advanced Traffic Signal Control Systems for Emergency Vehicle Preemption and Transit Priority, (Soo, Collura, Hobeika, Teodorovic, 2004a)

This paper presents two analytical approaches to assess (1) the impact of reduced emergency vehicle crashes at signalized intersections on fire and rescue operation and maintenance costs and (2) the impact of reduced transit travel time on transit operating and maintenance cost. The paper presents an overarching evaluation framework to assess the efficiency and cost effectiveness of advanced traffic signal control systems capable of emergency vehicle preemption and transit priority. Economic analysis from a systems perspective suggests that investment and operating costs should be distributed among the owners of the traffic signal system, fire and rescue providers and transit operators.

2.6.   Fuzzy Sets Theory

Fuzzy sets theory applications in traffic and transportation, (Teodorovic, 1994)

This paper describes how fuzzy sets theory is a convenient mathematical device for treating the uncertainty, subjectivity, ambiguity, and imprecision found in complex traffic and transportation problems. The author reviews a number of fuzzy sets concepts applications in mathematical modeling of traffic and transportation processes. These include applications in traffic control, traffic assignment modeling, vehicle routing, scheduling and dispatching modeling, car parking, level of service calculations, origin-destination estimation, cost-benefit analysis, transportation investment planning, and air traffic flow management.

Application of fuzzy sets theory to the saving based vehicle routing algorithm, (Teodorovic and Kikuchi, 1991)

This paper applies fuzzy sets theory to transportation routing and scheduling problems. The use of triangular fuzzy numbers to represent travel time is introduced. An algorithm to solve a vehicle routing problem when the travel time is fuzzy is presented to illustrate how fuzzy sets theory can be applied to transportation problems.

Traffic Control and Transport Planning: A Fuzzy Sets and Neural Networks Approach, (Teodorovic and Vukadinovic, 1998)

This book presents a fuzzy and neural approach to modeling complex problems in traffic control and transport planning. The book provides a basic understanding of fuzzy sets theory, fuzzy logic, fuzzy logic systems, artificial neural networks, and neurofuzzy modeling, and presents many traffic and transportation engineering applications of fuzzy logic and neural networks.

2.7.   Multi-attribute Decision Making Methods

Fuzzy Multiple Attribute Decision Making: Methods and Applications, (Chen and Hwang, 1992)

This book is an introduction to the application of fuzzy set theory toward multiple attribute decision making (MADM). It gives a state-of-the art survey of methods to solve fuzzy MADM problems and demonstrate their applications. Fuzzy MADM methods consist of two phases: (1) the aggregation of the performance scores with respect to all the attributes for tech alternative, and (2) the rank ordering of the alternatives according to the aggregated scores.   The authors classify fuzzy MADM methods into two categories: (1) fuzzy ranking methods that focus on the second phase and are concerned with comparing fuzzy numbers and (2) fuzzy MADM methods that focuses on either the first phase of both the first and second phases together and are specifically designed to solve MADM problems which contain fuzzy data. Over two dozen fuzzy ranking methods are reviewed and the advantages and disadvantages of each method are discussed. The concepts, computational procedures, characteristics and an illustrative numerical example of over a dozen fuzzy MADM methods are also presented.

Multiple Attribute Decision Making: Methods and Applications, (Hwang and Yoon, 1981)

This monograph reviews and classifies methods and applications of multi-attribute decision making (MADM). Characteristics and applicability of existing models to analysis of multi attribute decision making problems are provided. Also reviewed are basic foundations of MADM models, fuzzy decision rules, and methods for assessing criteria weights. The basic concept, the computational procedure, and the characteristics of seventeen major MADM methods are presented. The computational procedure of each method is illustrated by a simple numerical example.

Development and Evaluation of Five Fuzzy Multiattibute Decision-Making Methods, (Triantaphyllou and Lin, 1996)

This article presents the development of five fuzzy multiattribute decision making (MADM) methods. These methods are based on the weighted sum method, the weighted product methods, the analytical hierarchy process (original and ideal mode) and the Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS) methods. The authors examine these methods in terms of two evaluation criteria. The first criteria deal with the consistency of the method in single-dimension as well as multi-dimension problems. The second criteria examine the stability of the results when a non-optimal alternative is replaced by a worse one. A method should not change its indication of the best alternative when a non-optimal solution is replaced by a worse one.

A Sensitivity Analysis Approach for Some Deterministic Multi-Criteria Decision-Making Methods, (Triantaphyllou and Sanchez, 1997)

This paper presents a methodology for performing sensitivity analysis on the weights of the decision criteria and the performance values of the alternatives expressed in the terms of the decision criteria. Two sensitivity analysis approaches are presented. One approach examines how critical each criterion is by determining how sensitive the actual ranking of the alternative is to changes on current weights of the decision criteria. The second approach determines how critical the various performance measures of the alternatives are in the ranking of the alternatives. The methodology is demonstrated on three widely used multi-criteria decision making methods. These methods are: the weighted sum method, the weighted product method, and the analytic hierarchy process.

Fuzzy multicriteria analysis for performance evaluation of bus companies, (Yeh, Deng, Chang, 2000)

This paper presents a fuzzy multicriteria analysis approach to performance evaluation of urban public transportation systems involving multiple criteria of multi level hierarchies and subjective assessments of decision alternatives. Linguistic terms are used to express the subjectiveness and imprecision of decision maker assessments. Triangular fuzzy numbers characterizes these linguistic terms. The concept of degree of optimality of each alternative with respect to each criterion is used to formulate a weighted fuzzy performance matrix into a fuzzy singleton matrix. Incorporated with the decision maker's attitude towards risk, a crisp overall performance matrix is obtained based on the concept of the ideal solution. A case study of 10 bus companies of an urban public transportation system in Taiwan is conducted to illustrate this approach.

A validation procedure for multicriteria analysis application to the selection of scholarship students, (Yeh and Willis, 2001)

This paper presents a means to validate the ranking outcomes of multicriteria analysis methods particularly where decision outcomes produced by different methods differ significantly. The authors present a procedure to examine the consistency between the relative sensitivity of individual criteria of a multicriteria analysis method and the relative degree of influence of criteria indicated by Shannon's entropy concept. The premise is that a decision outcome produced by the most appropriate multicriteria analysis method reflects the decision information embedded in the problem data set. Four methods were examined: the total sum method, the simple additive weighting method (weighted sum method), the weighted product method, and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method.

An algorithm for fuzzy multi-criteria decision making, (Yeh and Deng, 1997)

This paper presents an algorithm for solving general fuzzy multi-criteria decision making problems using fuzzy data expressed by means of linguistic terms. Triangular fuzzy numbers represents these linguistic terms. The α-cut concept is used to transform the fuzzy performance matrix into an interval performance matrix. The decision maker's attitude towards risk is incorporated by the use of an optimism index λ. The authors propose that a fuzzy multi-criteria decision support system framework can be designed based on the algorithm developed. By changing the α value and the λ value the DSS allows the decision maker to explore outcomes under various degrees of confidence in assessment under different attitudes towards risk.

Multiattribute Decision-Making: Use of three scoring methods to compare the performance of imaging techniques for breast cancer detection, (Azar, 2000)

This paper evaluates three multi-attribute scoring methods for assessing the performance of four imaging techniques used to detect cancers in female breasts. The three multi-attribute scoring methods are: the Simple Additive Weighting method (SAW), the Weighted Product Method (WPM), and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). The four imaging techniques that are compared are: Magnetic Resonance Imaging (MRI), Mammography, Ultrasonography, and Nuclear Medicine. Performance attributes was derived from experimental data, results from human studies and expert input from doctors and professors. Sensitivity analysis examined the effect of attribute weights. The author found that the most robust method to be the SAW method. TOPSIS yielded results similar to SAW however final ranking was strongly influence by the cost factor. WPM yielded results that were too extreme. Results indicated that MRI was best technology for classifying malignant cancer lesions in the breast and should be used if cost is not an issue. If cost is the leading factor, then mammography should be used.

2.8.   Decision Support Systems

Past, present, and future of decision support technology, (Shim, Warkentin, Courtney, Power, Sharda, Carlsson, 2002)

This paper presents the past, present, and future of decision support systems, including the latest advances in decision support tools. The paper discusses a number of important topics to include development of the DSS concept, data warehousing, on-line analytical processing, data mining, Web-based DSS, collaborative support system, virtual teams, knowledge management, optimization-based DSS, and active decision support for the next millennium.

Using soft computing to build real world intelligent decision support systems in uncertain domains, (Zeleznikow and Nolan, 2001)

This paper discusses the application of soft computing techniques for building intelligent decision support systems in the presence of uncertainty. The authors describe how soft computing techniques (such as fuzzy reasoning and neural networks) can be integrated with symbolic techniques to provide for efficient decision making in knowledge-based systems. They illustrate this concept using two decision support systems that have been constructed using soft computing techniques.

A decision support system for multiattribute utility evaluation based on imprecise assignments, (Jimenez, Rios-Insua, Mateos, 2003)

This paper describes a decision support system based on an additive or multiplicative multiattribute utility model for identifying the optimal strategy. This is intended to allay many of the operational difficulties involved in assessing and using multiattribute utility functions. The system admits imprecise assignment for weights and utilities and uncertainty in the multiattribute strategies, which can be defined in terms of ranges for each attribute instead of single values. Inputs can be subjected to different sensitivity analyses, permitting users to test the robustness of the ranking of the strategies and gain insight into and confidence about the final solution. An application of the system to the restoration of a contaminated lake is used to illustrate the technique.

Developing a Decision Support System for Evaluating Capital and Operating Costs of Alternative Fare Collection Systems in Public Transit, (Ghandforoush, Collura, Plotnikov, 2002)

This article presents the initial development of a decision support system (DSS) to assess cost impacts of upgrading or replacing a transit ticketing and fare collection (FTC) system. This DSS is intended to improve the decision-making process used by transit agency managers, transit industry researchers and policy makers. With the aid of this DSS, a transit manager or analyst is able to obtain estimates for capital costs, forecast operating costs, perform net present value and payback period analyses for alternative transit ticketing and fare collection systems. The DSS contains four modules: graphical user interface; database; model base; and knowledge base. The paper (1) provides a general description of the purpose, structure, and functions of a proposed DSS; and (2) provides a detailed description of the four DSS modules.

Chapter 3:   Decision Support System Framework

3.1   Introduction

Advances in microprocessor and communications technologies are
making it possible for current traffic signal controllers and vehicle detection
technology to accommodate both emergency vehicle preemption and transit
priority strategies as part of an integrated system. This in turn, has stimulated
many jurisdictions to consider investing in advanced traffic signal control systems
that can provide preferential treatment to both emergency vehicles and qualified
transit vehicles. However, investment planning for an integrated emergency
vehicle preemption and transit signal priority system is not a trivial task. Two
distinct service providers, fire and rescue providers and transit operators, with
separate operational functions, resources and constituents are involved.
Performance parameters for the integrated system are not well defined, and
performance data is often imprecise. More importantly, the objectives of the two
service providers may conflict. As a result, planners and managers will need to
address a variety of institutional and local concerns that range from the
identification of the important stakeholders, to the assessment of emergency
vehicle preemption and transit signal priority system impacts, to performing
economic analysis to determine efficiency and effectiveness of an investment
from a systems perspective.

Just as technology has made it possible to deploy advanced traffic signal
control system capable of integrating emergency vehicle preemption and transit
priority traffic signal operations, technology can also provide the means to gather
information from many sources, apply models and algorithms and even apply
expert knowledge to allow the user to make better informed decisions.   Decision
support systems are computer technology solutions that can be used to support
complex decision making and problem solving in semi-structured and
unstructured situations with unclear criteria for success (Shim et al., 2002).
Advances in personal computing have made decision support systems a
common tool for business decision making.

This chapter will present the initial development of a decision support system framework for assessing integrated emergency preemption and transit priority systems for the purpose of making investment decisions. Section 3.2 provides a statement of the problem. Section 3.3 describes an integrated emergency vehicle preemption and traffic signal priority system strategy from a systems perspective, reviews the current state-of-art in assessing potential impacts, and identifies system beneficiaries. Section 3.4 describes the desired functionalities and capabilities of the DSS designed to assist planners and managers assess integrated emergency vehicle preemption and transit signal priority systems in an uncertain environment.

3.2   Problem Statement

Research to date, has addressed the individual impacts of emergency vehicle preemption and transit priority systems from an operational perspective. Fire and rescue providers are interested in emergency vehicle preemption to reduce response time, increase safety and reduce emergency vehicle crashes at signalized intersections. Transit operators are interested in transit signal priority to reduce transit travel time, improve schedule reliability and reduce operating expenses. Evaluation frameworks, performance measures and guidelines have been developed that are specific to either emergency vehicle preemption or transit vehicle priority and oriented towards the assessment of their specific operational performance characteristics. As a result, planners and managers interested in assessing the deployment of integrated emergency vehicle preemption and traffic priority systems do not have a systematic evaluation approach or a common set of performance metrics to make informed planning decisions. In addition, results from field measurements and simulations for both emergency vehicle preemption and transit signal priority are often imprecise, uncertain and ambiguous in nature, thus making it difficult for planners and managers to accurately benchmark performance characteristics.

Planners and managers need a structured analytical approach to use as part of their investment planning decision making process. This need may be

met by a decision support system that: (1) is designed to assess simultaneously the impacts of integrated emergency vehicle preemption and transit signal priority systems for investment purposes; and (2) has the ability to process both quantitative and qualitative data at varying degrees of precision (Zeleznikow and Nolan, 2001).

3.3   A Systems Perspective

Emergency vehicle preemption and transit signal priority systems are similar from a systems perspective in that they both consist of a vehicle detection system, a communications system, and a traffic signal control system. This notion of treating emergency vehicle preemption and transit priority together as components of a system that provides preferential treatment to both emergency vehicles and qualified transit vehicles was recently presented by Louisell based on research at the Virginia Polytechnic Institute and State University which suggested that emergency and transit vehicles would benefit from preferential treatment strategies with minimal impact on other users (Collura et al., 2003; Louisell et al., 2004; Louisell et al., 2003).

This research will expand upon that concept and examine integrated emergency vehicle preemption and transit signal priority systems from a system perspective.   A system diagram of an integrated emergency vehicle preemption and transit priority traffic signal system is illustrated in Figure 3-1. Depicted on the left hand side are the three components of the system: the emergency vehicle preemption component, the transit signal priority component, and the system operational parameters component. System operational parameters include roadway characteristics, traffic characteristics, operational strategies and interdependent performance (Louisell and Collura, 2003).
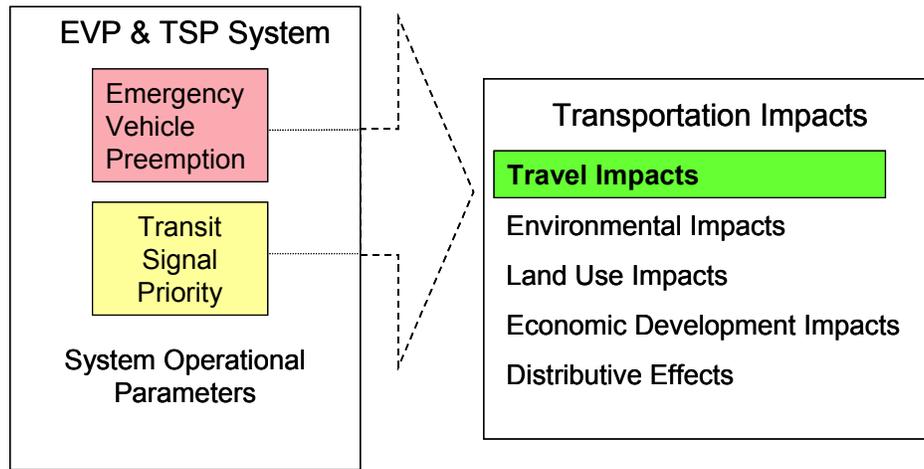
Adapted from
TCRP Report 78, *Estimating the Benefits and Costs of Public Transit Projects: A Guidebook for Practitioners*

**Figure 3-1 Systems Perspective of an Integrated Emergency Vehicle Preemption and
Transit Priority System**

Roadway characteristics include geometric properties, signal locations, distance between signals, signal controller systems, bus stop locations (near side, far side) and pedestrian facilities. Traffic characteristics include traffic volumes, approach and side street capacity, traffic signal timing parameters, and pedestrian activity. Operational strategies encompass the operational parameters of both preemption and transit signal priority. Preemption parameters include: duration of preemption, direction of preemption, and preemption recovery strategy. Transit signal priority parameters include the type of transit signal priority strategy alternative used (green extension, red truncation, queue jump or combinations), duration of priority (10 seconds, greater than 10 second, etc), conditional or non-conditional priority, route length, headway, current bus travel time, operational costs, schedule, and non-transit delay. Interdependent performance includes logic rules that prescribe system response to priority after a preemption event.   For example, a preemption recovery strategy that returns to normal operations in five cycles may preclude granting of transit priority until the sixth cycle (Obenberger and Collura, 2001).

Shown on the right hand side of Figure 3-1 are five potential impacts on the transportation system. Travel impacts are potential impacts on transportation system users.   Environmental impacts are concerned about potential air, water, and noise pollution impacts. Land use impacts are potential impacts due to changes in land development, property value, the cost of development and agglomerative economies based on improved accessibility. Economic development impacts include the impact of enhanced employment accessibility and property values. Finally, distributive impacts assess the equity or fairness of transportation project impacts.

Travel impacts are the primary impacts from emergency vehicle preemption and transit signal priority investments are the focus of this research. The remaining four are generally secondary impacts for transportation projects and are not impacted by the implementation of advanced traffic signal control systems (ECONWest and Parsons Brinckerhoff Quade & Douglas, 2002).
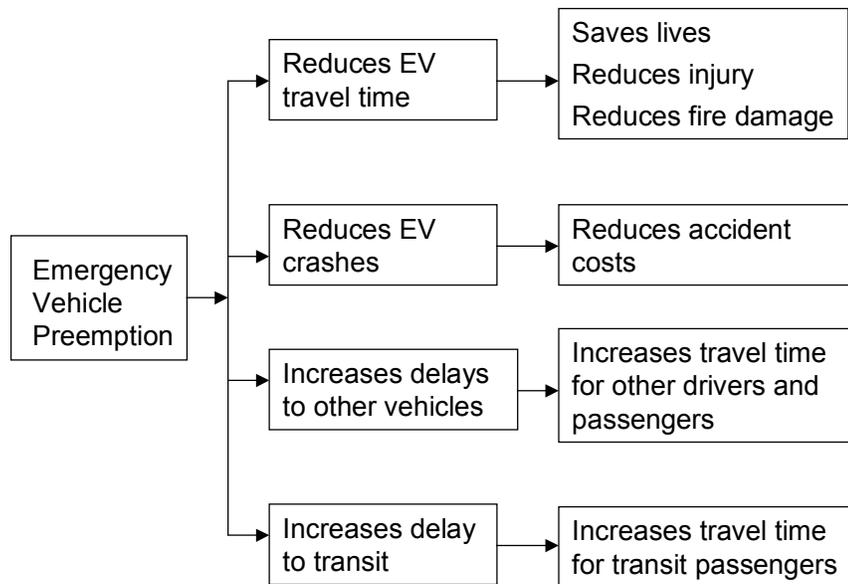
Adapted from
Lee, D. & Carroll, A., *Benefit-Cost Evaluation of a Highway-Railroad Intermodal Control System, January 2003*

Figure 3-2 Emergency Vehicle Preemption Travel Impacts

Emergency vehicle preemption travel impacts are shown in Figure 3-2. Research to date has predominantly focused on assessing the individual impacts for operational analyses (e.g., emergency vehicle travel time reduction, emergency vehicle crash characteristics).   There is no documented evidence of assessments that examine the impact of emergency vehicle preemption operations on transit signal priority. A short description of these impacts and an assessment of the state-of-the-practice methods to quantify those impacts follow.

Preemption may permit emergency vehicles to travel at a higher speed and thus reduce emergency vehicle travel time. The potential travel impacts of reduced emergency vehicle travel time include: saving lives, reducing injury, and minimizing fire damage. Experience from some agencies operating emergency vehicle preemption systems indicte that significant improvements (in the 14%-50% range) to emergency vehicle travel time may result (City of Denver Department of Safety, 1978; Collura et al., 2003). Factors that influence this impact include the degree of travel time reduction, types and frequency of responses by fire and rescue providers, and patient recovery statistics. Currently, standardized analytical tools to determine this impact are not available. Researchers have successfully used microsimulation tools to estimate emergency vehicle travel time reduction along corridors of interest (Bullock et al., 1999; Nelson and Bullock, 2000). Research is required to develop analytical tools to quantify the impact of savings lives, reducing injury or reducing property damage. This may require access to data from fire and rescue provider logbooks and hospital admission records of fire and rescue patients to determine statistical trends for use in defining the contribution of reduced emergency vehicle travel time.

Changing signals to favor emergency vehicles provides drivers on cross streets with a red signal. This can potentially reduce the number of crashes involving emergency vehicles at signalized intersection, and as a result may reduce operating costs for fire and rescue service providers. Factors influencing this impact include local roadway characteristics, traffic characteristics and driver response to external stimulation. Evidence from past deployments in St Paul,

Minnesota has indicated crash reductions of 70% have been achieved (Fire Chief, 1977). Determining the value of this impact requires information on emergency vehicle crashes at the local level and expected emergency vehicle crash reduction. As part of this research an analytical tool was developed to obtain order of magnitude estimates for this impact using Fatal Accident Reporting System (FARS) emergency vehicle crash data, local emergency vehicle crash data and average cost of vehicle repair(Gkritza et al., 2004; Soo et al., 2004a; Vrachnou, 2003). The development and application of this analytical tool to estimate the impact of reduced emergency vehicle crashes at signalized intersections on fire and rescue provider operating cost is provided in Appendix C (Soo et al., 2004a).

A preemption event can potentially negatively impact overall traffic flow and increase delays to other vehicles (mainly auto) and transit. Researchers using simulation have found that preemption impact is a function of intersection spacing, transition algorithm, saturation level of the intersections, frequency and duration of the preemption and the amount of slack time available in each intersection (Collura et al., 2003). Recovery from preemption could potentially disrupt the normal traffic flow in all directions with potential travel impacts being increased travel times for other vehicles and buses (Obenberger and Collura, 2001). Recovery from preemption events depends on the duration of the preemption, recovery strategy and traffic conditions. Currently, an analytical tool to determine this has not been developed. Determining the degree of impact of emergency vehicle preemption on transit and non-transit users may require the use of simulation analyses using microsimulation tools such as CORSIM and VISSIM to model the location, roadside characteristics and traffic characteristics (McHale and Collura, 2001). Travel time impacts could then be determined by aggregating the results of on a per person basis based on person travel time and non-travel time costs factors.

Transit signal priority travel impacts are shown in Figure 3-3. Research on transit travel time impacts has also been predominantly focused on the assessment of operational performance characteristics (e.g., transit travel time

reduction, side street impacts).   There is no evidence of assessments that examined the impact of transit signal priority on emergency vehicle preemption operations. A short description of these impacts and a review of current methods to determine those impacts follow.
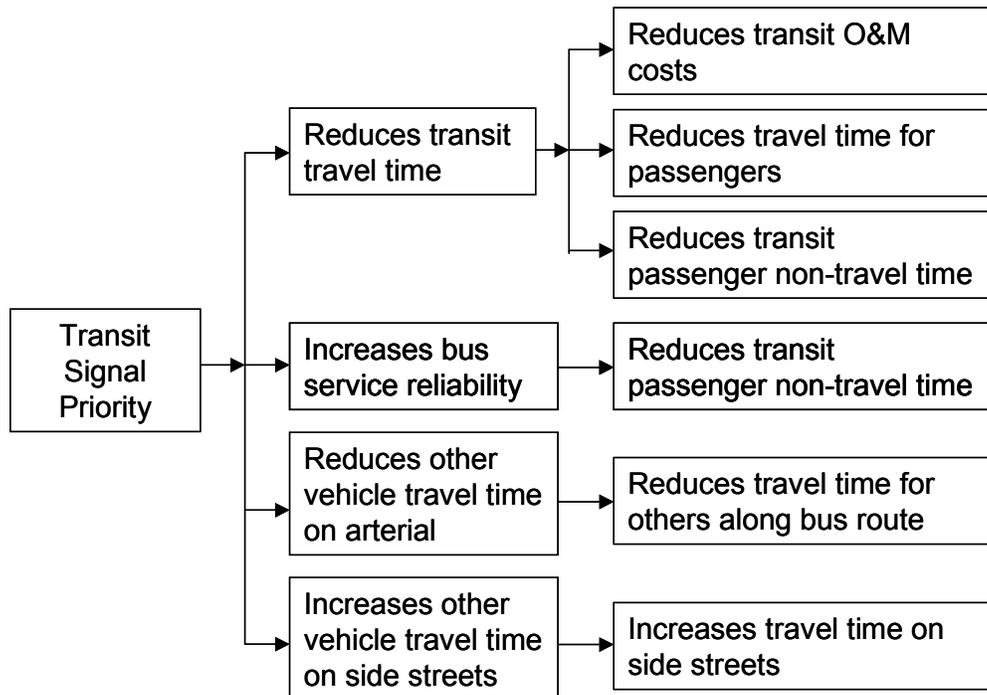
Adapted from
Lee, D. & Carroll, A., *Benefit-Cost Evaluation of a Highway-Railroad Intermodal Control System, January 2003*

Figure 3-3 Transit Signal Priority Travel Impacts

Transit signal priority is expected to reduce bus delays at signalized intersections. This in turn, could potentially reduce transit travel time. Potential impacts of reduced transit travel time include: reduced transit operating and maintenance costs for transit service operators, reduced travel time for transit passengers, and reduced non-travel time for transit passengers. There is extensive research of transit travel time reduction from an operational perspective. Results indicate that the degree of impact depends on the transit priority strategy employed and the specific conditions that influence the corridor of interest. These conditions include: frequency and direction of travel for vehicles requesting priority, roadway characteristics, travel demand, presence and frequency of pedestrians phases, transition strategy, cycle characteristics,

and intersection spacing and progression strategy (Obenberger and Collura, 2001). As part of this research, an analytical tool to determine transit operating cost savings due to transit travel time reduction was developed. This analytical tool incorporates the bus transit cost model, results from simulation modeling and National transit operating data (Morlok et al., 1991; Soo et al., 2004b). The development and application of this analytical tool in estimating the impact of transit travel time reduction on transit operating cost is provided in Appendix B. Additional research is required to fully define the impact of reduced transit travel time on transit passenger. The SAIC SCRITS spreadsheet model (SAIC, 1999) could be used as a start point to quantify the impact of reduced transit travel time for transit passengers.

Traffic, in the direction of priority, may benefit from the additional green time. The potential impact from this is reduced travel time for other (non-transit) vehicles along the bus route. Recent research results suggest that non-transit vehicles along the direction of priority benefit from the additional green time afforded to transit (Chada, 2004). The degree of impact is a function of the density of vehicles in the vicinity of the transit vehicle receiving priority. Currently there is not a standardized analytical tool to quantify this impact. Determining the impact may require the use of microsimulation tools such as VISSIM to collect data specific to the transit corridor being studied.

Traffic on cross streets may be impacted by transit priority along the bus route. Results from deployments and simulation indicate that while non-transit vehicles on cross streets experience some increased delay, the magnitude of cross street delay, while statistically significant, is not critical since most drivers could not detect such small increases in delay (Chada and Newlan, 2002). More importantly, researchers have found that the degree of non-transit delay is more a function of the v/c ratios of both the approach and cross streets (Balke et al., 2000; Ngan, 2003). A standard analytical tool to determine the impact of cross street delay has not yet been developed.

Lastly, transit priority may improve bus service reliability. A potential impact of improved schedule reliability is reduced waiting time (non-travel time)

for transit passengers. Researchers, using simulation, have determined that transit signal priority can potentially impact service reliability. Several different measures of effectiveness are used to assess service reliability. These include: on-time performance; time reliability; perceived on-time performance; spacing ; and arrival reliability. Improvements in the range of 2.8% to 3.2% have been reported (Chang et al., 2002; Deshpande et al., 2004). Currently there is not a standardized analytical tool and a standard performance measure to quantify this impact.

The distribution of system impacts is shown in Table 3-1. The stakeholders are the recipients of these impacts, which include both positive and negative impacts. Stakeholders include the general public, transit passengers, non-transit users, emergency service providers and transit operators. Interestingly, the benefit from reduced operating costs for the two service providers (transit and fire and rescue) may be eclipsed by the impact to the general public, transit riders, and motorist. As a result planners and managers must also consider input from elected officials and other affected groups in their investment decisions forums.

	Impact	Stakeholder
Emergency Vehicle Preemption	Saves lives, Reduces injury, Reduces fire damage	General public (Elected officials)
	Reduces accident costs	Fire and rescue provider
	Increases travel time for other drivers and passengers	Motorist
	Increases travel time for transit passengers	Transit passengers
Transit Signal Priority	Reduces transit O&M costs	Transit service provider
	Reduces travel time for passengers	Transit passengers
	Reduces passenger non-travel time	Transit passengers
	Reduces travel time for others on bus route	Motorist
	Increases travel time on side streets	Motorist
	Reduces transit passenger non-travel time	Transit passengers

Table 3-1 Advanced Traffic Signal Control System Impact Distribution

The ten travel impacts delineated in Figures 3-2 and 3-3 and the distribution of recipients shown in Table 3-1 illustrates the complex and interdependent nature of integrated emergency vehicle preemption and transit priority systems. Research to date has developed algorithms that can quantify the individual impacts. These ten impacts have been the subject of research efforts designed to assess operational performance characteristics of the specific system. Two analytical tools have been developed to estimate the impact of service providers operating cost. There is still a need to develop analytical tools to assess the remaining eight impacts. More importantly, there is a need to develop analytical tools and techniques to assess impacts fro a system perspective.

Planners and managers need an analytical approach that examines integrated emergency vehicle preemption and transit signal priority systems from a systems perspective. This will require coordination among the major stakeholders to address institutional, technical and financial issues. One obvious example is in the area of investment planning. Traditionally, each service provider has separately planned and cost their version of the system. With a system perspective, that investment may be better received when it can be demonstrated to benefit more than one recipient: the general public; transit riders; non-transit riders; the fire and rescue providers; and the transit service providers.

3.4   Decision Support System Framework

Decision support systems (DSS) are computer technology solutions that can be used to support complex decision making and problem solving. A generic DSS consists of three components: a database management module, a model management module, and a user interface module. An intelligent DSS would also include a knowledge management module (Alter, 1999; Zeleznikow and Nolan, 2001).

The structure of a conceptual DSS framework designed to assess the impacts of integrated emergency vehicle preemption and transit signal priority systems is shown in Figure 3-4.

Decision-makers
- Transportation planners and engineers
- Transportation researchers
- Policy makers

Input
- System operational parameters (e.g., roadway characteristics, traffic characteristics, operating strategies, route length, headway, current bus travel time, operational costs, schedule, non-transit delay)
- Transit priority strategy alternatives
- Stakeholder concerns and preferences

Output
- Estimated reduction in transit O&M costs
- Estimated reduction in EV accident costs
- Estimated payback period
- Estimated Net Present Value
- Estimated transit travel time reduction impacts
- Estimated non-transit delay impacts
- Estimated schedule reliability impacts
- Others…

Decision Support System Components

Graphic User Interface (GUI)
- Facilitates data input
- Access to model base, knowledge base, and data base
- Assessment criterion

Model Base
- Transit cost model
- Economic analysis models
- EVP crash cost reduction model
- Fuzzy multi-attribute decision making methods

Knowledge Base
- Facts (e.g.,cost data)
- Rules (e.g., Preemption recovery strategy, allocation of capital costs)
- Fuzzy sets theory

Data base
- FTA National Transit Database
- FARS crash data
- System operational data
- Standard interest tables

Figure 3-4 Decision Support System Framework Structure

This DSS is intended for transportation planners and engineers, transportation researchers and policy makers. It consists of four modules: a database management module, a model management module, a knowledge base module, and a user interface module. User input would include system operational parameters (roadway characteristics, traffic characteristics, system operational strategies), transit signal priority alternatives, and stakeholder

concerns and preferences. Desired DSS output include graphic and numeric results relating to economic analysis (pay back period, capital recovery period, NPV, etc.), operational performance (transit run time reduction, schedule reliability impacts), operating cost savings, and transit signal priority strategy alternatives.

A short description of the desired functionality and capability for each of the four DSS modules follow.

The database management module would contain information concerning operational and financial data for transit operations, fire and rescue operations, accident and safety statistics, as well as system operational data. At a minimum, the database management module would contain data tables stored at various National, State and local sources. Transit data may include information extracted from the National Transit Database and the National Transit Summaries and Trend Report (Federal Transit Administration, 2001a; Federal Transit Administration, 2001b), performance parameters from local transit operators, and transit travel time reduction data (Soo et al., 2004b). Fire and rescue data may include information extracted from national accident databanks such as: the National Highway Traffic Safety Administration's (NHTSA) Fatal Accident Reporting System (FARS), which is complied by the National Center for Statistics and Analysis; National Injury Surveillance System (NISS), which complies accident data collected at emergency rooms at hospitals; local police accident report data; and fire and rescue log books and response statistics. (Garber and Hoel, 1999; Gkritza et al., 2004; Louisell and Collura, 2003; Vrachnou, 2003). Local operational databases may include Opticom system data files which record the frequency, time, and duration of preemption and priority requests. At the highest level of functionality, the database management system may include Web access to Web-data warehouses and the capability to use on-line analytical processing (OLADS) and data mining techniques (Desrochers et al., 1999).

The model management module provides the environment for storing, retrieving, and manipulating models. It links the user to the appropriate models. The model management module would include mathematical models and

optimization methods, analytical tools and procedures to perform various types of analyses. At a minimum, the model management module should include: the bus transit cost model for evaluating the impacts of transportation improvements on bus operating costs (Morlok et al., 1991), economic analysis procedures for determining payback analysis and net value analysis (Ghandforoush et al., 2002; SAIC, 1999), analytical tools for computing the impact of emergency vehicle crash reduction on fire and rescue operating costs (Soo et al., 2004a), and mathematical methods such as fuzzy multi-attribute decision making methods (Chen and Hwang, 1992). As the DSS architecture evolves and matures, other models may be included.

The knowledge base module would contain problem specific rules and facts relating to transit operations, fire and rescue operations, advanced traffic signal control systems costs, as well as the ability to use soft computing techniques. This module makes available expert knowledge to substitute human expertise for missing efficient algorithms. The incorporation of intelligent decision support systems functionalities in the form of soft computing adds the ability to process both quantitative and qualitative data (at varying levels of precision) (Zeleznikow and Nolan, 2001).

The user interface module provides the means for the user to interface with the DSS. The cost of user interface can cost up to 70% of the total cost of building a DSS. Until recently, the development of user interfaces received relatively little attention. DSS designers were more concerned with the programming of internal architecture. System designers developed user interfaces without the benefit of a formal framework for design. As a result, many user interfaces were rigid and difficult to learn and use (Sankar et al., 1995). Design of the user interface module would, at a minimum, include a user controllable graphical user interface (GUI), typically a workstation screen, that would allow the user to: (1) access the database, the model base, and expert knowledge base; (2) input information such as performance characteristics; (3) display and analyze data, formulate and evaluating alternative decisions; and (4) view output displays.

The conceptual DSS framework outlined above describes the desired functionalities and capabilities of a decision aid for transit planners and managers to use for assessing the impacts of integrated emergency vehicle preemption and transit priority systems as part of their investment planning process. Research to date in the development of this conceptual DSS framework has developed three analytical tools that could be incorporated in future DSS design. Chapter 4 will describe two analytical tools. The first addresses the potential impact of transit travel time reduction due to transit signal priority on transit operating costs. The second addresses the potential impact of reduced emergency vehicle accidents on signalized intersection due to emergency vehicle preemption. Chapter 5 will describe the development of the third analytical tool. This analytical tool will utilize soft computing techniques in the form of fuzzy sets theory concepts to deal with the uncertainty, ambiguity and subjectivity normally associated with transit signal priority strategy alternative performance characteristics.

Chapter 4: EVP and TSP Impacts on Operating Cost

4.1 Introduction

Integrated emergency vehicle preemption (EVP) and transit signal priority (TSP) systems have the potential to: (1) reduce emergency vehicle crashes at signalized intersections which may reduce fire and rescue provider operating and maintenance costs; and (2) reduce transit travel time which may reduce transit operator operation and maintenance costs. This chapter will present two analytical tools to assess potential emergency vehicle preemption and transit signal priority impacts at the corridor level. Section 4.2 will present the first analytical tool - a spreadsheet model that examines the potential impacts of transit travel time reduction on transit operation and maintenance (O&M) costs. Section 4.3 will present the second analytical tool – an algorithm to assess the potential impact of reduced emergency vehicle crashes at signalized intersections on fire and rescue provider O&M costs.

The transit O&M cost impact tool is contained within a paper accepted for presentation at the 2004 Transportation Research Board (TRB) Annual Meeting and published in the 2004 TRB Annual Meeting CD-ROM. A copy of the paper is provided Appendix B. The emergency vehicle crash reduction cost impact tool is contained within a paper accepted for presentation at the 2004 Intelligent Transportation System of America (ITSA) Annual Meeting and published in the meeting proceedings. A copy of that paper is provided as Appendix C.

4.2 Transit O&M Cost Impact

A potential impact of transit signal priority is reduced transit travel time. Reduced transit travel time is of interest to transit service providers because of the potential to save operating costs; and to transit passengers because of the potential to reduce both travel time and non-travel time.   Initial results from deployments and simulations of transit signal priority system indicate that the values for both efficiency and cost effectiveness of the adopted transit priority strategies and preferential treatment solutions are a function of many variables, such as: the magnitude of transit travel time delay; the transit fleet size; the labor

rules; the apportionment of preemption and priority system costs among transit operators, emergency service providers and the municipality; and the cost of money.

The Portland Department of Transportation conducted a detailed operational analysis to determine the most effective transit signal priority to twelve intersections within five corridors in the City of Portland, Oregon.   The operational analysis showed that only 31% to 39% of the total bus travel time was for driving. The remaining 60% to 70% of the total travel time was distributed between time spent at traffic signals, bus stops, and in traffic. The distribution of transit travel time among actual travel time, bus stop delay, congestion delay, and traffic signal delay is illustrated in Figure 4-1.
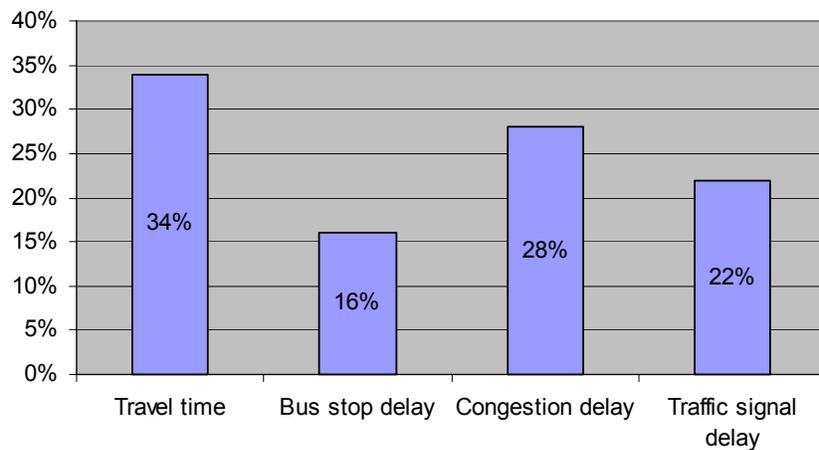
Source: City of Portland Transit Preferential Street Program Final Report, June 1997

Figure 4-1 Distribution of Transit Travel Time

Among the solutions recommended for implementation were: implement signal priority for buses, signal timing changes, and queue jump lanes to reduce traffic signal delay; implement bus stop consolidation, bus stop relocation, fare collection changes, curb extension at bus stops, boarding island at bus stops, and low-floor bus equipment technology to reduce bus stop delay; and implement parking restrictions within bus corridors, exclusive bus lanes, queue jump lanes

for buses, and exempting busses from turn restrictions to reduce congestion delay (City of Portland Office of Transportation, 1997).

The Portland transit travel time data is consistent with experience from a number of transit priority projects in the U.S. and aboard suggests that transit signal priority may, depending on the transit signal priority strategy employed and other factors, reduce transit travel times between 0 to 28% with little or no negative impacts on non-transit travel time, if properly deployed (Advanced Traffic Management System and Advanced Public Transportation System Committees of the Intelligent Transportation Society of America, 2002; Soo et al., 2004b).

Economic analysis of ITS projects such as integrated emergency vehicle preemption and transit signal priority systems are hard to quantify. Morlok, Brunn and Blackman introduced how a transit agency might evaluate the feasibility or the desirability of an ITS project as a subset of a comprehensive benefit-cost evaluation approach (Morlok et al., 1991). They posited that if an evaluation demonstrated that the ITS project was desirable from a purely financial perspective; it would be even more desirable from a more comprehensive perspective. The bus transit cost model, a widely used and accepted model for the total cost of operating a bus fleet, was adapted to relate the investment cost to a change in transit operating cost. That model is presented in equation 4-1:

Investment Cost = A(Revenue-hr) + B(Revenue-mi) + C(Fleet size) (4 -1)

where:

A = Unit cost associated with revenue-hours
  = (Vehicle operations expense %) x (Total expense)/ (Total Revenue-hours);
B = Unit cost associated with revenue-miles
   = (Material & utilities per vehicle-mile) + (Vehicle maintenance per vehicle-mile);
C = Unit cost associated with fleet size
   = [(Non-vehicle maintenance %) + (General admin %)] x (Total expense/fleet size) + (bus cost) x (CRF)
CRF = Capital recovery factor

Khasnabis, Rudraraju and Baig suggested using the magnitude of passenger delay savings to set the maximum possible investment from a transit signal priority project. They determined, through simulation, that passenger delay savings was significantly large enough and the benefits from fuel and emissions savings modest enough, that passenger delay savings can be used as the maximum investment threshold (Khnasnabis et al., 1999).

Leviakangas and Lahesmaa later suggested that tradition benefit-cost analysis might not be suited for ITS projects because of their shorter life span and different investment profiles in comparison to traditional transportation projects (Leviakangas and Lahesmaa, 2002).

In the austere public fiscal environment both efficiency (will society benefit from this investment?) and cost effectiveness (can we afford to do this?) are important factors to be considered in the decision-making process. Efficiency measures the economic feasibility of an investment from a societal perspective and is an outcome of a benefit-cost analysis. It answers the question "are the total net benefits received by society as a whole increased by the project?" (ECONWest and Parsons Brinckerhoff Quade & Douglas, 2002; Lee and Carroll, 2001). Cost effectiveness addresses the question "will this improvement generate enough money to pay for its development and operation?" and measures the financial feasibly of a project (ECONWest and Parsons Brinckerhoff Quade & Douglas, 2002; Morlok et al., 1991). Ideally, society should benefit from the deployment of an integrated emergency vehicle preemption and transit priority system and the cost of deployment should be recouped directly from operating and capital cost savings.

An assessment of financial feasibility examines the impact of reduced transit O&M costs and whether that reduction is sufficient to warrant the investment costs. It answers the question "can we afford to do this investment". Ideally, operating cost and capital cost savings should cover the cost for the improvement. A simple three-step spreadsheet model to determine financial feasibility is presented in Table 4-1.

	2001National Average	
	Input	Output
Step 1		
Operating cost parameters		
Operating expense per vehicle revenue-hr	$82.79	
vehicle revenue-hrs (millions)	2452.4	
vehicle revenue-miles (millions)	1821.2	
material and utilities ($millions)	$128.5	
vehicle maintenance ($millions)	$238.1	
vehicle operations %	0.60	
Y = (revenue-hrs)/(revenue-miles)		1.35
A = (vehicle operations %)*(operating expense/veh-hr)		$50.07
B = (mat & Util + veh maint)/(vehicle revenue-miles)		0.20
BY		0.27
(A+BY)		$50.34
Revenue hour savings		
Miles on which priority treatment is implemented	10	
Number of buses per weekday during peak period	60	
bus travel time (minutes)	35	
Annual revenue hrs		8750.00
Estimated bus travel time savings	0.09	
Δ Revenue hours		787.50
Operating cost savings		
operating cost savings = (A+BY)*(Δ revenue-hrs)		$39,644.68
Step 2		
Determine investment cost		
Roadside equipment		
Cost per intersection	$6,000	
Number of intersections	10	
Roadside equipment cost		$60,000
Onboard equipment cost		
Cost per emitter	$750	
number of buses	35	
Onboard equipment cost		$26,250
Determine annual system costs		
Annual O&M costs	$3,000	
Other	$500	
Annual system cost		$3,500
Step 3		
Financial Feasibility Assessment		
Payback Period (yrs)		
(Total investment cost)/Annualized savings		2.26
Capital Recovery Period (yrs) (7%)		
Capital Recovery Factor =		
(operating cost)(Δ Revenue hours) - System O&M		0.4491
Total Investment cost		
number of years @ 7% interest		2.8 yrs
Net Present Value		
NPV (i =7%, n=5) (P/A,7%,5) =	4.1002	$76,301.13
NPV (i=7%, n=10) (P/A, 7%, 10) =	7.0236	$216,780.99

Step 1 computes the operating cost savings based on the total transit travel time reduction using the simple relationship

National Transit Database

Bus Corridor Characteristics

Modeling and Simulation

Step 2 computes the investment costs and annual operating costs.

Intersection characteristics

3M OPTICOM emitter cost

O&M cost estimates

Step 3 computes: payback period, capital recovery period; and NPV.

Payback Period

Capital Recovery Period

NPV

Table 4-1 Transit O&M Cost Impact Model

Step 1 computes the operating cost savings based on the total transit travel time reduction using the following relationship derived from equation 4-1:

$$\Delta \text{Operating Cost} = (A+BY)(\Delta \text{Revenue-hr}) \qquad (4\text{-}2)$$

where:
A = Unit cost associated with revenue-hours
  = (Vehicle operations expense %) x (Total expense)/ (Total Revenue-hours);
B = Unit cost associated with revenue-miles
  = (Material & utilities per vehicle-mile) + (Vehicle maintenance per vehicle-mile);
Y = Revenue hr/Revenue-mi

A, B and Y can be determined using data from the transit agency's operational database or estimated using data from the National Transit Database

and the National Transit Summaries and Trends Report.   Average operating cost per vehicle revenue-hour, and vehicle revenue-miles can be found in the National Transit Profile. Annual vehicle revenue miles and vehicle revenue hours, and total operating expenses for a select number of transit agencies can be found in Table 28 and Table 31 of the National Transit Database. The average values of expense functions (vehicle operations, vehicle maintenance, non-vehicle maintenance, and general administration), and object class (salaries, fringe benefits, services, materials and supplies, utilities, and other) can be found in Tables 11 and 12 of the National Transit Database (Federal Transit Administration, 2001a; Federal Transit Administration, 2001b).

Revenue-hr savings for a particular bus corridor can be determined by using:

$$\Delta \text{ revenue-hrs} = \sum_{i=1}^{n} (N_i)(TTT_{ib} - TTT_{ia}) \qquad (4\text{-}3)$$

where:
N_i = number of trips on route n.
TTT_{ib} = transit travel time on route n before priority.
TTT_{ia} = transit travel time on route n after priority.

Step 2 computes the investment costs and annual costs associated with this deployment. The capital costs can be subdivided into two categories: roadside equipment such as detectors, controllers, and onboard equipment such as emitters. A capital cost model that can be used for both categories is (Ghandforoush et al., 2002):

$$TCC = [(\sum_{i=1}^{n} (UC_i)(q_i))(1 + x_{PS} + x_{IC} + x_{ESPM})](1 + y_C) \qquad (4\text{-}4)$$

where:
TCC = Total capital costs;
UC_i = unit cost of nth equipment ;
q_i = quantity of nth equipment;
x_{PS} = non-recurring parts and services expressed as percent of the equipment costs;
x_{IC} = non-recurring installation and construction costs expressed as percentage of the equipment costs;

x_{ESPM} = non-recurring engineering, software and project management costs
expressed as percentage of the equipment costs;
y_C = contingency costs

Determining cost estimates for advanced traffic signal control systems is complicated for a number of reasons. First, the technology is relatively immature so there is a lack of a universal standard, and competing manufacturers have different cost structures. Second, desired system functionalities will impact cost; thus, a complex system will cost more. Third, the existing traffic signal control system may be inadequate to execute preferential treatment. Replacement will increase implementation cost. And, fourth there is a paucity of published information on the costs of operational deployments. Data from deployments indicate per-intersection costs range from $5,000 to $11, 000 (Collura et al., 2003).

Step 3 provides the result of several assessments: payback period analysis, capital recovery period analysis and net present value analysis.

The payback period represents the amount of time that it takes for a project to recover its initial cost ignoring the time value of money. It answers the question "how quickly can the investment be recovered based on savings in operating costs associated with the transit priority system." The formula for payback period analysis is (Ghandforoush et al., 2002):

$$\text{The payback period } x = \text{Investment cost/Annual savings} \qquad (4\text{-}5)$$

$$x = TCC/(TP\ OC_E - TP\ OC_N) \qquad (4\text{-}6)$$

where:
TCC = Total capital cost
TP OC_E = Existing system operating costs
TP OC_N= New system operating costs

Capital recovery period represents the amount of time that it takes for a project to recover its initial cost taking into account the time value of money. Table 4-1 uses an interest rate of 7% based on prevailing Federal requirements (ECONWest and Parsons Brinckerhoff Quade & Douglas, 2002). This interest rate is determined by the Federal government to standardize analysis based on the economic environment. The number of years required to recover the

investment can be found by first determining the capital recovery factor (CRF) and then look up the number of periods (years) using the CRF in the 7% interest tables (Ghandforoush et al., 2002):

$$CRF = [(\text{Operating cost})(\Delta\text{Revenue-hrs}) - (\text{O\&M costs})]/(\text{TCC}) \qquad (4\text{-}7)$$

Where:

$$CRF = (A/P, i\%, N) = [i(1+i)^N]/[(1+i)^n - 1]$$

Net present value (NPV) analysis projects the present value of future savings expected from an investment. The formula for NPV is:

$$NPV = [(\text{Annual savings}) (P/A, i\%, n)] - \text{Investment Cost} \qquad (4\text{-}8)$$

Where $(P/A, i\%, n)$ = uniformed series present worth factor

$$= [(1+i)^n - 1]/[i(1+i)^N]$$

For illustrative purposes, Table 4-1 computes NPV @ 5 years, and NPV @ 10 years.

4.3   Emergency Vehicle Crash Reduction Operating Cost Impact

A potential impact of reduced emergency vehicle crashes on signalized intersections is reduced fire and rescue provider operating costs. In the 5-year period from 1997 to 2001, more than 554 emergency vehicle crashes involving one or more fatalities were recorded in the 2003 Fatality Analysis Reporting System (FARS) (U.S. Department of Transportation, 2003). Operational experience suggests that the deployment of emergency vehicle preemption may decrease the number and severity of accidents involving emergency vehicles and other vehicles at signalized intersections. The ITS Benefits Database contains a 1977 report from the Fire Chief from the City of St. Paul, Minnesota that describes the impact of emergency vehicle preemption deployment on emergency vehicle crash reduction. This report spanned a 9-year period of time from 1968 to 1976 in which the City of St. Paul incrementally deployed 285 3M Opticom systems on 308 intersections. The report indicated a decrease in emergency vehicle crashes in spite of an overall increase in the total number of emergency alarms and in the volume of traffic on St. Paul roadways. In 1968, prior to the deployment of emergency vehicle preemption, there were 7

emergency vehicle crashes among the 7,594 total emergency alarms. After the initial deployment of 28 3M Opticom systems, there were 6 emergency vehicle crashes among 8,300 total emergency alarms. This suggests that the initial introduction of preemption reduced emergency vehicle crashes by approximately 22% (Fire Chief, 1977).

Research on emergency vehicle crashes in Northern Virginia indicates that: approximately 31% of emergency vehicle crashes occurred at signalized intersections; crash damage at intersections are more severe at intersections than at non-intersections; and crash damage cost ranged between $500 and $10,000 with the average around $6,330 (Vrachnou, 2003). Reduced emergency vehicle crashes at signalized intersections will reduce the cost to fire and rescue providers to repair emergency vehicle damaged in crashes, reduce cost of vehicle insurance, and reduce non-availability time awaiting repairs. The number of emergency vehicle crashes and their distribution on signalized and non-signalized intersections and non-intersections can be determined from fire and rescue operational data or from regional accident report databases. A simple spreadsheet model that can be used to assess average savings is presented in Table 4-2. The illustrative example shown in Table 4-2 examines the impact of a 22% crash reduction to a fire and rescue provider that has 10 signalized intersection crashes per year and an average repair cost of $6,330. A potential annual savings of $12,660 could be realized.

FARS and local crash data   Local cost data

	Average	
	Input	**Output**
Number of crashes per year at signalized intersections	10.00	
Average cost to repair	$6,330.00	
Crash Prevention Estimate	22%	
Number of potentially avoidable crashes		2.2
Potential accident savings		$12,660.00

Extracted from St Paul data

Table 4-2 Emergency Vehicle Crash Reduction Impacts on O&M costs

4.4   Case Study: U.S. Route 1 Northern Virginia

Virginia Tech in collaboration with George Mason University and supported by the Washington Regional Council of Governments and the Virginia and Maryland Departments of Transportation has been conducting an operational field test to assess the impact of deploying an advanced traffic signal control system capable of emergency vehicle preemption and transit priority along U.S. 1 from the Prince William Country Line to I-495 in Northern Virginia. U.S. 1 is a major arterial that carries over 2700 vehicles per hour as it winds along one of the most densely populated areas in Northern Virginia. Two transit agencies operate four bus routes and three fire and rescue facilities provide emergency service along the corridor.

The operational test site is an 1.3-mile long segment of U.S. 1 that includes seven signalized intersections. It is located within close proximity to a Washington Metropolitan Area Transit Agency (WMATA) terminal subway station, a natural trans-loading point, and is along the travel route of one the fire companies that provide emergency services to the community. As part of the study, 3M Opticom systems were installed at the seven signalized intersections within the test site and pole-mounted video cameras were positioned to record traffic conditions.

Regional FARS data reported 11 emergency vehicle crashes on signalized intersections on U.S. 1 in Northern Virginia over the 5-year period from 1997 to 2001. Analysis of that data indicated that approximately 31% of emergency vehicle crashes on U.S. 1 in Northern Virginia occurred at signalized intersections (Vrachnou, 2003). Based on the above, Table 4- uses 2.2 crashes per year along with the default inputs of 22% for anticipated crash reduction and an average accident cost of $6,330. Results indicate a potential of avoiding 0.484 emergency vehicle crashes per year as a result of initial emergency vehicle preemption deployment. So, in a two-year period there is the potential to avoid one crash. This translates into a potential annual operating cost savings of $3,165 to fire and rescue providers.

	Input	Output
Number of crashes per year at signalized intersections	2.20	
Average cost to repair	$6,330.00	
Crash Prevention Estimate	22%	
Number of potentially avoidable crashes		0.484
Potential accident savings		$3,165.00

Table 4-3 U.S. 1 Emergency Vehicle Accident Cost Reduction

To determine the impact of transit priority on transit operating costs, results from a VISSIM simulation was used. VISSIM is a microscopic, time-based, and behavior based simulation tool. VISSIM was used to model the impacts of a 10 second green extension and unconditional priority. This followed VDOT guidance to minimize potential disruption to vehicular traffic flow. The model was calibrated using 2002 weekday peak hour traffic data from SYNCHRO data supplied by VDOT, and operational site characteristics (such as traffic speed, control delay, and number of stops) obtained using the "floating car" technique. Results from 30 pairs of "before" and "after" simulations provided data on bus service reliability, bus service efficiency and queue lengths on side streets were obtained. Bus service reliability was measured as the standard deviation of elapsed time between the end points of the corridor. Bus service efficiency was measured as the average run time between the end points of the corridor. And queue lengths on side streets were measured. Simulation results indicated bus service reliability increased by 3.6%, bus travel time reduced by 2.64% and side street queue length increased by less than one queue length.

These results were extrapolated to assess the financial feasibility of deploying an advanced traffic signal control system along a 13-mile long 22-intersection corridor under three investment cost allocation scenarios.

The distribution of benefits suggests that apportioning the investment costs of an integrated emergency vehicle preemption and transit priority system among the municipality, emergency service providers, and transit providers is appropriate. Three funding allocation cases were considered:

Case 1: The transit agency pays 100% of the roadside equipment cost. This represents a method of analysis in which the transit provider assumes the cost of the system.

Case 2: The transit agency shares the cost of the roadside equipment with the emergency service providers. The total investment cost is divided between the two major users.

Case 3: Fairfax County pays the cost of the roadside equipment. In this scenario, the County or VDOT installs the advanced traffic signal controller system to up grade the traffic signal system with general funds. The emergency service provider and the transit provider would pay with funds from their respective budgets to connect to the system and their share of the O&M costs.

Inputs:
Operating Costs parameter (A+BY) = $35.20
Annual Revenue-hrs = 4375 hrs
Roadside Investment Costs = $5,000/Intersection x 22 Intersections = $110,000
Onboard equipment costs (transit) = $750/vehicle x 32 transit vehicles = $24,000
Annual O&M costs = $3,500

Figure 4-2 Impacts of Transit Travel Time Reductions on Payback Period

Operational experience and simulations suggests that the choice and combinations of transit priority strategies will impact transit travel time reductions. Results indicate that strategies that employ combinations of green extension, red truncation and queue jump provide progressively better transit travel time reductions. This in turn would impact the payback period. Figure 4-2 shows the impact on payback period as a result of increased transit travel time reductions. Figure 4-2 suggests there are threshold levels from a payback period perspective where the incremental improvement may not be worth the incremental cost. For example: for case 1 a payback period of 11 years can be realized with a transit travel time reduction of 10%. That same payback period can be realized with a transit travel time reduction of 7% for case 2. In case 3 a payback period of less than 3 years can be realized with a transit travel time reduction of 8%. This suggests that modest transit travel time reductions may be sufficient to justify the investment depending on the strategy (e.g., green extension only versus a combination of green extension and/or red truncation) and the financial apportionment scheme chosen.

4.5   Summary

The two analytical tools presented in this chapter can be used to asses the impact of emergency vehicle preemption and transit signal priority systems on service provider operation and maintenance costs at the corridor level. The transit O&M cost impact model assesses the impact of reduced transit travel time on transit O&M costs. The emergency vehicle crash reduction O&M impact model assesses the impact of reduced emergency vehicle crashes on signalized intersections may have on fire and rescue O&M costs.

A case study, using data collected at the Virginia Tech/George Mason University/Virginia Department of Transportation (VT/GMU/VDOT) integrated emergency vehicle preemption and transit signal priority operational field test on U.S. 1 in Northern Virginia, assessed the impact of apportioning investment costs among fire and rescue service providers, transit service providers and the municipality (who owns the traffic signals). This study provided insights on the

changing nature of investment decisions when integrated emergency vehicle preemption and transit signal priority systems are considered from a systems perspective. Prior to this, fire and rescue service providers and transit service providers each estimated deployment costs from a myopic perspective. The notion of cost sharing among the two service providers and the municipality recognizes the interactive role of these agencies in providing quality service to the public. Results from this system level analysis suggests that planners and managers may need to consider apportioning the investment costs of integrated emergency vehicle preemption and transit signal priority systems.

Chapter 5:   Fuzzy Multi-attribute Decision Making Method

5.1   Introduction

Transportation planners and managers responsible for implementing transit signal priority systems must prioritize and determine the most preferred type of transit signal priority strategy to use along a transit corridor. In addition to design factors such as roadway geometry, traffic volume, travel demand, presence and frequency of pedestrian phases, transition strategy, cycle characteristics, intersection spacing and progression strategy (Obenberger and Collura, 2001), they must also consider the performance parameters for the various transit signal priority strategy alternatives under consideration, and input from the various stakeholders (Gifford et al., 2001; Levine et al., 1999; Noyce, 1996).

Traditional multi-attribute decision making (MADM) methods require the use of precise input data to determine the preferred alternative based on the performance characteristics of each alternative. Unfortunately, only a limited amount of before and after operational data exists for deployed transit signal priority systems. Moreover, the limited available data is not standardized, is dependent on the geometric and operational conditions, and is characterized by uncertainty, subjectivity, imprecision and ambiguity. In addition, stakeholders representing multiple constituencies such as elected officials, traffic representatives, transit representatives, emergency service providers, transit riders, non-transit operators, community organizations and pedestrians often have conflicting interests that must be incorporated in the decision process.

Fuzzy sets theory provides a mathematical means to treat that uncertainty, subjectivity, imprecision and ambiguity (Teodorovic, 1994). The combination of fuzzy sets concepts and multi-attribute decision making methods provide a means to preference order alternatives using imprecise, subjective, and uncertain performance characteristics and subjective and ambiguous stakeholder opinions and preferences (Chen and Hwang, 1992).

The goal of this research is two fold: (1) to present analytical techniques to convert uncertain, subjective, imprecise and ambiguous data on transit travel

reduction, schedule reliability, non-transit delay and stakeholder preferences to measures that can be used in fuzzy multi-attribute decision making methods; and (2) to demonstrate the practical application of these methods to rank order transit signal priority strategy alternatives for planning and investment decision making purposes.

Section 5.2 provides a statement of the problem. Section 5.3 provides: (1) a brief description of the two multi-attribute decision making methods to be used in this analysis; and (2) a review of some fuzzy sets theory fundamentals. Section 5.4 describes the concepts used to: (1) transform the performance of transit signal priority strategy alternatives and the three criteria into triangular fuzzy numbers; and (2) determine stakeholder preference-based weights for each criterion. In section 5.5, an illustrative example will be presented to demonstrate the application of the fuzzy sets theory concepts using both the fuzzy WSM and fuzzy TOPSIS MADM methods. Finally in section 5.6, two techniques for sensitivity analysis will be used to examine the sensitivity of the two MADM methods. Shannon's entropy method will be used to evaluate the significance of the criterion used in the illustrative example and results from computational experiments will be used to determine the sensitivity of the two fuzzy MADM methods to stakeholder preferences.

5.2   Problem Statement

Most decision making problems faced by transportation planners and managers are complex in nature and include multiple and often conflicting criteria that contain uncertain, subjective, imprecise and ambiguous performance data and subjective and ambiguous stakeholder concerns. Previous research has produced useful information on transit travel time reductions (Chang, 2002; Soo et al., 2004b), schedule reliability (Chang et al., 2002; Deshpande and Collura, 2004), non-transit delay (Balke et al., 2000; Garrow and Machemehi, 1998; Ngan, 2003), and stakeholder concerns (Gifford et al., 2001; Levine et al., 1999; Noyce, 1996). Their information reinforces the uncertainty and imprecision of the available data. While these results are dependent on the method of collection

as well as geometric and operational conditions, they are useful in providing "order of magnitude" estimates to improve our understanding of the impacts of transit signal priority, but they do not have the precision desired for use in more systematic mathematical modeling.

To this end, this chapter develops systematic evaluation tools using multi-attribute decision making (MADM) methods and fuzzy sets concepts. Such tools attempt to quantify the expected impacts of transit travel time reductions, non-transit delays, and service reliability as they relate to alternative transit signal priority strategies with varying stakeholder preferences.

5.3   Technical Approach

The technical approach is to solve a multi-attribute problem that involves a set of m alternatives A_i (i = 1,2,…,m). These alternatives are to be evaluated with respect to n criteria (or attributes) C_j (j = 1,2,…,n). The weighting vector, W will represent the relative importance of the criteria to the stakeholders. The decision objective is to rank order all the alternatives in terms of their overall preference value.

The four alternatives to be considered are: (1) signal optimization; (2) green extension; (3) green extension and red truncation; and (4) green extension, red truncation and queue jump. The three attributes to which these four alternatives will be measured are: (1) transit travel time reduction; (2) non-transit delay; and (3) schedule reliability.

In addition, attribute (criteria) weighting will be stakeholder preference-based. Stakeholders to be considered include elected officials, traffic representatives, transit representatives, fire and rescue service providers, and transit riders.

Fuzzy sets theory will be used to treat imprecise data, uncertainty, and ambiguity in defining the performance attributes of the alternatives and to treat ambiguity and subjectivity in stakeholder preferences.

The analytical procedure will follow the following steps:

1. Determine the relevant criteria and alternatives to be evaluated

2. Identify relevant participants in the decision process

3. Convert alternative performance measures to fuzzy numbers

4. Generate stakeholder preference-based criteria weights

5. Rank the alternatives using multi-attribute decision making methods

6. Perform a post-evaluation, sensitivity analysis

Two fuzzy multi-attribute decision making methods will be used. One is the weighted sum method (WSM) and the other is the Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS). The fuzzy WSM will use Kaufmann and Gupta's method for comparing fuzzy numbers to rank order the alternatives based on their calculated preferences (Teodorovic, 1992). The fuzzy TOPSIS method will rank order the alternatives based on their closeness to ideal solutions (Triantaphyllou and Lin, 1996; (Chen and Hwang, 1992).

Shannon's entropy method will be used to investigate the significance of each criterion based on the amount of uncertainty represented by the distribution of information within that criterion (Hwang and Yoon, 1981); in addition, results from computational experiments will be used to assess sensitivity to stakeholder preference.

5.3.1 Multi-attribute Decision Making Methods (MADM)

The WSM and the TOPSIS methods were selected for use in evaluating the impact of transit signal priority strategy alternatives based on their wide spread usage, computational efficiency and ability to obtain a utility index (ranking preference) from multidimensional and fuzzy data.

The WSM is probably the best known and the most commonly used MADM approach. Introduced in 1957 to select a business investment policy (Hwang and Yoon, 1981), it continues to be used in MADM applications. Its computational efficiency and ease of usage has universal appeal. The best alternative is the one that satisfies the following expression:

$$\mathbf{A}^* = \{\mathbf{A}_i \mid \max_i \sum_{i=1}^{n} a_{ij} W_j \} \tag{5-1}$$

where **A*** is the most preferred alternative, a_{ij} is the outcome of the ith alternative about the jth attribute and W_j is the weight of importance of the jth attribute (Hwang and Yoon, 1981).

Hwang and Yoon developed the TOPSIS technique in 1981 based on the concept that the preferred alternative should have the shortest distance from the ideal solution and the farthest distance from the negative-ideal solution in a geometric (Euclidean) sense. TOPSIS assumes that each attribute in the decision matrix takes either monotonically increasing or monotonically decreasing utility. (The larger the attribute outcomes, the greater the preference for benefit criteria and the less the preference for the cost criteria) (Hwang and Yoon, 1981).   Several steps are needed in order to implement this technique:

Step 1 Construct the normalized decision matrix

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^{2}}} \qquad i = 1,2,\dots m, \; j = 1,2,\dots n \qquad (5\text{-}2)$$

where:

x_{ij} is the performance measure of the ith alternative in terms of the jth attribute

r_{ij} is an element of the normalized decision matrix

Step 2 Construct the weighted normalized decision matrix

$$v_{ij} = w_j \, x_{ij} \qquad (5\text{-}3)$$

where:

v_{ij} is an element of the weighted normalized decision matrix

w_j represents the significance of a criterion.

Step 3 Identify the positive-ideal and negative-ideal solutions

The positive-ideal solution **A*** is the composite of all the best attribute ratings attainable, and is denoted:

$$\mathbf{A^*} = \{(\max_i \ v_{ij} \mid j \in J), \ (\min_i v_{ij} \mid j \in J') \mid i = 1,2,\ldots,m)\}$$

$$\mathbf{A^*} = \{v_1^*, v_2^*,\ldots,v_j^*,\ldots,v_n^*\} \tag{5-4}$$

Where v_i^* is the best value for the ith attribute among all alternatives and

$$J = \{j = 1,2,\ldots,n \mid j \text{ belongs to the benefit criteria}\} \tag{5-5}$$

The negative-ideal solution **A⁻** is the composite of all worst attribute ratings attainable, and is denoted:

$$\mathbf{A^-} = \{(\min_i \ v_{ij} \mid j \in J), \ (\max_i v_{ij} \mid j \in J') \mid i = 1,2,\ldots,m)\}$$

$$\mathbf{A^-} = \{v_1^-, v_2^-,\ldots,v_j^-,\ldots,v_n^-\} \tag{5-6}$$

Where v_i^- is the worst value for the ith attribute among all alternatives and

$$J' = \{j = 1,2,\ldots,n \mid j \text{ belongs to the cost criteria}\} \tag{5-7}$$

Step 4 Calculate the separation measures

The separation or distance of each alternative from the positive-ideal solution **S$_i$***, is given by:

$$\mathbf{S_i^*} = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_j^*)^2} \tag{5-8}$$

Where i is the index related to the alternatives (i=1,2,…,m) and j to the attributes (j=1,2,…,n).

The separation from the negative-ideal solution **S$_i$⁻**, is given by:

$$\mathbf{S_i^-} = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_j^-)^2} \tag{5-9}$$

Step 5 Calculate the relative closeness to the ideal solution

The closeness C_i^* to positive-ideal solution, for alternative A_i, is

$$C_i^* = \frac{S_i^-}{S_i^* + S_i^-} \qquad 0 \le C_i^* \le 1 \qquad\qquad (5\text{-}10)$$

Step 6 Rank the alternatives

The alternatives are ranked according to the descending order of C_i^*. The best alternative is A_i with the largest value of C_i^*.

5.3.2 Fuzzy Sets Concepts

The merit of using a fuzzy approach to multi-attribute decision making is to assign the relative importance of attributes using fuzzy numbers instead of crisp numbers. The specific fuzzy sets concepts to be applied include triangular fuzzy numbers, basic operations on triangular fuzzy numbers, the intersection of fuzzy sets, and ranking of fuzzy sets. A brief review of these concepts is provided in this section. A more detailed review is provided in Appendix A.

Triangular fuzzy numbers represent a special set of fuzzy numbers. Their name is derived from the shape of their membership function. Figure 5-1 shows a typical triangular number $A = (a_1, a_2, a_3)$. Where a_1 is the lower (left) boundary of the triangular fuzzy number, a_2 is the number corresponding to the highest level of presumption, and a_3 is the upper (right) boundary of the fuzzy number.
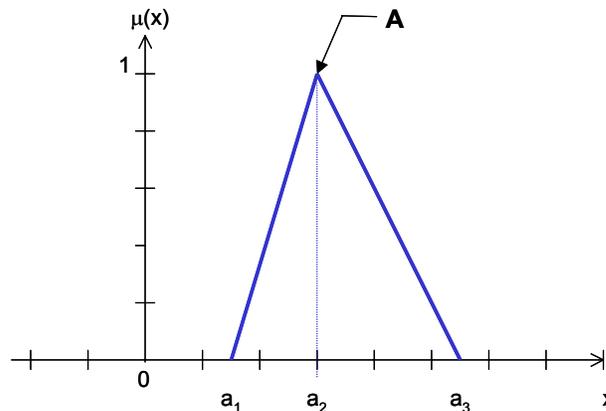
Figure 5-1 Membership Function of Triangular Fuzzy Number A

The membership function of **A** is:

$$\mu_A(x) = \begin{cases} 0, & x < a_1 \\ \dfrac{x - a_1}{a_2 - a_1}, & a_1 \le x \le a_2 \\ \dfrac{a_3 - x}{a_3 - a_2}, & a_2 \le x \le a_3 \\ 0, & x > a_3 \end{cases}$$

(5-11)

Triangular fuzzy numbers are added, subtracted, multiplied and divided using the following basic operations:

Addition: **A** (+) **B** = (a_1, a_2, a_3) + (b_1, b_2, b_3) = $(a_1 + b_1, a_2 + b_2, a_3 + b_3)$

Subtraction: **A** (-) **B** = (a_1, a_2, a_3) - (b_1, b_2, b_3) = $(a_1 - b1_3, a_2 - b_2, a_3 - b_3)$

Division: **A** (÷) **B** $\cong (a_1, a_2, a_3)$ ÷ (b_1, b_2, b_3) = $(a_1/b_3, a_2/b_2, a_3/b_1)$

Natural logarithm: ln (**A**) $\cong$ (ln (a_1), ln (a_2), ln (a_3))

(5-12 – 5-15)

The intersection of fuzzy sets **A** and **B** is denoted by **A**∩**B** and is defined as the largest fuzzy set contained in both fuzzy sets **A** and **B** and corresponds to the "and" operation. Its membership function $\mu_{A \cap B}$ is defined as:

$\mu_{A \cap B}$ (x) = min { $\mu_A(x)$, $\mu_B(x)$ }   (5-16)

The membership function of fuzzy sets **A**, **B** and **A**∩**B** are shown in Figure 5-2.

There are several different approaches to ranking fuzzy numbers. Some important factors in deciding which ranking method is most appropriate include the complexity of the algorithm, its flexibility, accuracy, ease of interpretation, and the shape of the fuzzy numbers used (Chen and Hwang, 1992; Triantaphyllou and Lin, 1996). Kaufmann and Gupta's method is chosen for its simplicity, particularly in comparing triangular fuzzy numbers (Teodorovic and Kikuchi, 1991; Teodorovic and Vukadinovic, 1998).
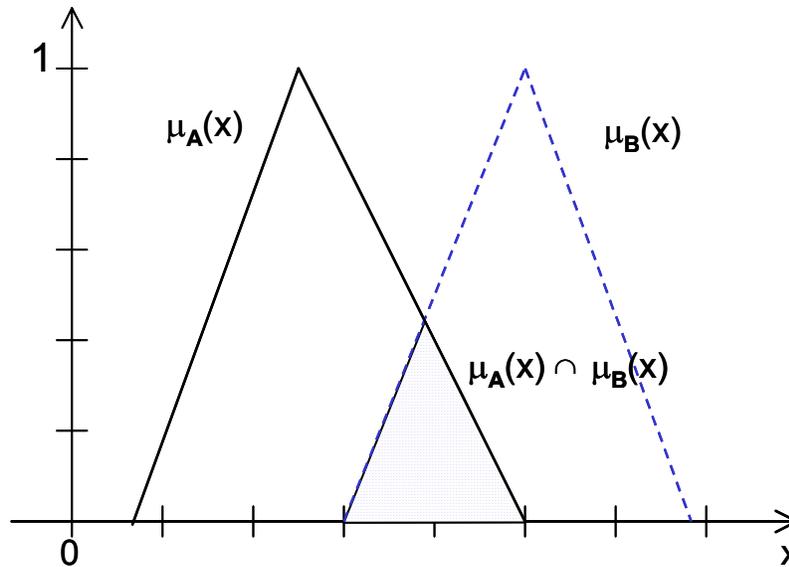
Figure 5-2 Membership Function of A, B and A ∩ B

Kaufmann and Gupta's method to compare the ranking of two triangular fuzzy numbers **A** = (a$_1$, a$_2$, a$_3$) and **B** = (b$_1$, b$_2$, b$_3$) consists of three progressive steps: (1) compare removals; (2) compare modes and (3) comparing divergences.

Step 1: Compare the "removal "of the numbers

The removal of fuzzy number **A** with respect to an ordinary number k if the membership function of **A** is a triangular form and $k=0$ is:

$$\mathbf{R}(\mathbf{A},k) = \frac{(a_1 + 2a_2 + a_3)}{2} \tag{5-17}$$

The fuzzy number **A** is smaller than fuzzy number **B** if

$$\mathbf{R}(\mathbf{A},k) < \mathbf{R}(\mathbf{B},k) \tag{5-18}$$

If a conclusion can be made based on this comparison, the algorithm is ended. If not go to Step 2.

Step 2: Compare the values that correspond to the highest grade of membership.

If a number order can be determined after this comparison, the algorithm is ended. Let x_A^* and x_B^* denote the highest grade of membership of fuzzy sets **A** and **B**. The fuzzy number **A** is smaller than fuzzy number **B** if

$$x_A^* < x_B^*$$

If a conclusion cannot be made based on this comparison, then go to step 3.

Step 3: Compare the length of the fuzzy numbers' bases.

5.4   Converting to Fuzzy Measures

This section describes the concepts used to obtain fuzzy measures for the four transit priority alternatives and the three criteria discussed above, and to convert ambiguity and subjectivity in stakeholder concerns to stakeholder preference-based weights for each criterion.

Three fuzzy set concepts will be used to derive triangular fuzzy numbers for use in fuzzy MADM methods. The concept of triangular fuzzy numbers will be used to describe the impact of transit signal priority strategy alternatives on transit travel time reduction; linguistic variables will be used to describe their impact on non-transit delay; and the intersection of fuzzy sets will be use to uniquely measure the impact of the four alternatives on schedule reliability. Linguistic variables will also be used to determine stakeholder preference-based weighting for the three criteria.

5.4.1   Fuzzifying Transit Travel Time Reduction Performance Data

The impact of various transit signal priority strategy alternatives on transit travel time reduction is a key criterion. Transit travel time reduction is an important consideration for transit operators interested in operating efficiency and schedule adherence. In addition, travel time reduction is important to transit riders because it can decrease in-vehicle and out-of-vehicle traveler travel time. Results from deployments and simulation analyses indicate that the degree of transit travel time reduction is a function of the type and combination of transit signal priority strategy used and is influenced by local traffic conditions. Due to

uncertainties in data collection and other factors most measures of transit travel time reduction are expressed in terms of an interval range, i.e., 2% - 4%. Transit travel time reduction results of various transit signal priority strategies are summarized in Table 5-1 (Soo, Collura, Hobeika, and Teodorovic, 2004).

Strategy	Deployment	Simulation
Signal Optimization	2% - 5%	None
Green Extension Only	0% - 9.7%	0% - 6%
Red Truncation Only	None	1% - 10.6%
GE + RT	1.4% - 20%	1.6% - 14.2%
GE + RT + Queue Jump	0% - 18%	none
Combinations	1.8% - 28%	2.7% - 17.6%

Source: Soo, Collura, Hobeika, Teodorovic, "Evaluating the Impacts of Advanced Traffic Signal Control Systems: The Effect of Transit Signal Priority Strategies on Transit Operating Costs," Transportation Research Board 2004 Annual Meeting Compendium of Papers CD-ROM

Table 5-1 Summary of Transit Travel Time Reductions Impacts on Transit

Teodorovic and Kikuchi introduced the use of a triangular shaped membership function to represent an approximate travel time in order to simplify arithmetic operations (Teodorovic and Kikuchi, 1991). The concept of a fuzzy number as the generalization of a confidence interval is perfectly suited to convert the estimated range of transit travel time reduction into a triangular fuzzy number. The membership function of fuzzy set **A** is shown in Figure 5-3. The base of the triangle (a_1 and a_3) represents the confidence interval range of the transit travel time reduction, and the estimation of the approximate mean is denoted as a_2.
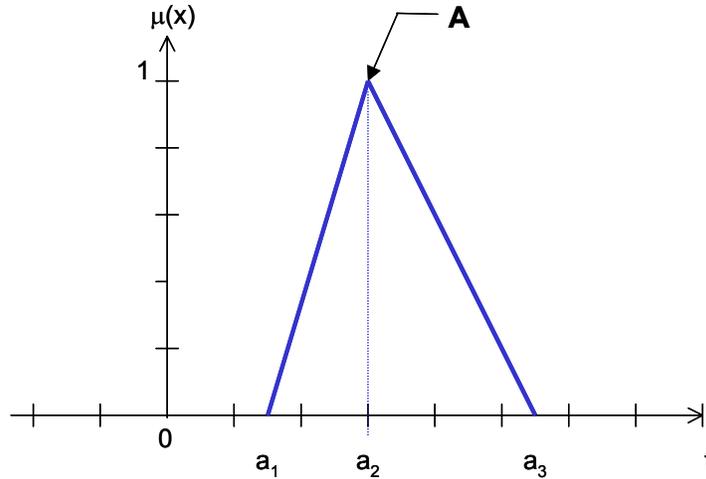
Figure 5-3 Membership Function of Triangular Fuzzy Number A

The membership of **A** would be given by:

$$\mu_A(x) = \begin{cases} 0, & x < a_1 \\ \dfrac{x - a_1}{a_2 - a_1}, & a_1 \le x \le a_2 \\ \dfrac{a_3 - x}{a_3 - a_2}, & a_2 \le x \le a_3 \\ 0, & x > a_3 \end{cases}$$

(5-19)

The triangular fuzzy number representing a transit travel time reduction of 2% - 4% is shown in Figure 5-4.   Using this concept, the impact of each transit signal priority strategy alternative on transit travel time may be uniquely represented.

Table 5-2 illustrates how this technique can be applied using the transit travel time reduction data from Table 5-1.
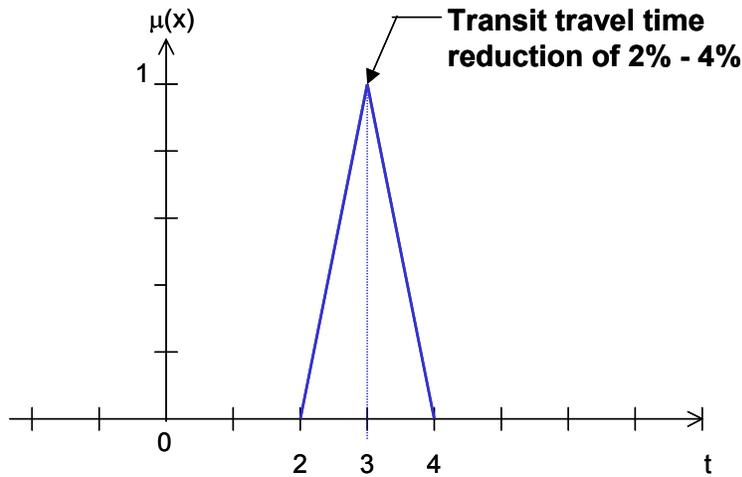
Figure 5-4 Membership Function of Transit Travel Time Reduction of 2%-4%

Strategy	Deployment	Simulation	Fuzzy Membership
Signal optimization	2%-5%	None	(2, 3.5, 5)
Green extension	0%-9.7%	0%-6%	(0.4, 8, 9.7)
Green extension & red truncation	1.4%-20%	1.6%-14.2%	(1.4, 9.3, 20)
Green extension & red truncation & queue jump	0%-18%	None	(0, 9, 18)

Table 5-2 Transit Travel Time Reduction Fuzzy Membership

5.4.2　Fuzzifying Non-transit Delay Performance Data

The potential impact of transit signal priority on non-transit delay is of considerable concern among all the stakeholders (Gifford et al., 2001). Key traffic parameters associated with transit signal priority impacts on non-transit delay include transit approach volume and capacity (v/c) ratio, cross street v/c ratio, signal coordination and bus stop location (Ngan, 2003). Results from deployments and simulations indicate that non-transit vehicles along the priority route generally benefit from transit signal priority while non-transit vehicles on cross streets experience some increased delay. Based on analysis of results from deployments and simulation some researchers consider the magnitude of cross street delay, while statistically significant, is not critical since most drivers

60

could not detect such small increases in delay (Chada and Newlan, 2002). Moreever, researchers have found that the degree of non-transit delay is strongly related to the v/c ratios of both the approach and cross streets (Balke et al., 2000; Ngan, 2003).

Simulation results reported by Balke, Dudel and Urbanik (2000) and Ngan (2003) suggest that transit approach v/c ratios between approximately 0.20 and 0.9 are best suited for transit signal priority applications. (Balke et al., 2000; Ngan, 2003). Ngan also introduced the notion of using the linguistic variables "minimal," "moderate," and "significant" to describe the impact of transit signal priority on cross street performance across the entire range of v/c ratios. This is presented in Table 5-3. The membership function that represents Table 5-3 is shown in Figure 5-5. The cross street v/c ratio is used to determine the corresponding linguistic variable and the linguistic variables can be easily converted into fuzzy numbers by means of a conversion scale (Teodorovic and Vukadinovic, 1998). A conversion scale is presented in Figure 5-6, which shows the membership functions of fuzzy sets "negative impact," "moderate impact," and "minimal impact." Since non-transit delay is a cost attribute, there is a higher value assigned to the linguistic variable "minimal impact." Table 5-4 shows how the non-transit delay linguistic variables are converted to triangular fuzzy numbers. To illustrate how to apply this methodology, consider the cross street v/c ratios of 0.2 and 0.6. The 0.2 v/c ratio corresponds to the linguistic variable "minimal impact" which can be translated to the triangular fuzzy number (5,10,10). Similarly, the 0.6 v/c ratio corresponds to the linguistic variable "moderate impact" and is converted to the triangular fuzzy number (0,5,10).

Cross street v/c	$0.25 < v/c \leq 0.5$	$0.50 < v/c \leq 0.9$	v/c>0.90
Impact of transit signal priority on cross street	Minimal	Moderate	Significant

Adapted from Ngan, V., "A Comprehensive Strategy for Transit Signal Priority" ITE Journal, November 2003, Pg. 28-32

Table 5-3 Impact of Transit Signal Priority on Cross Street Performance at Various v/c Ratios

μ(x)
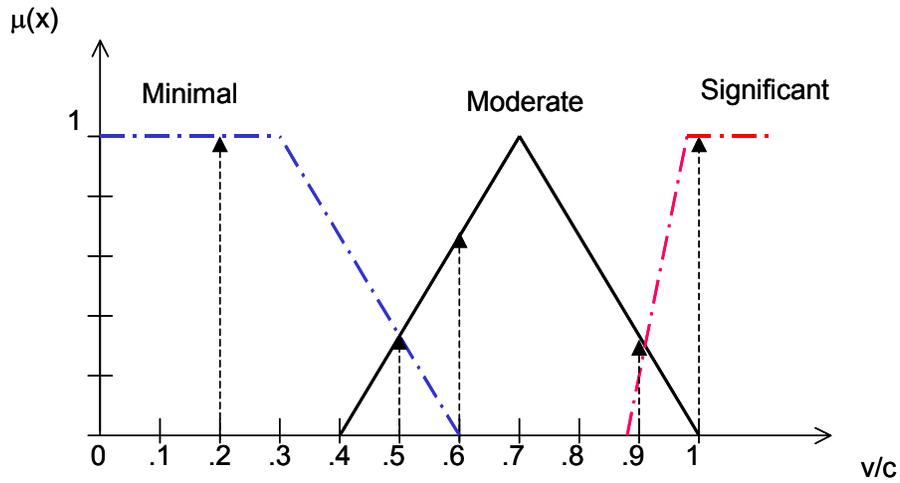
Figure 5-5 Membership Function for Cross Street Non-Transit Delay

μ(x)
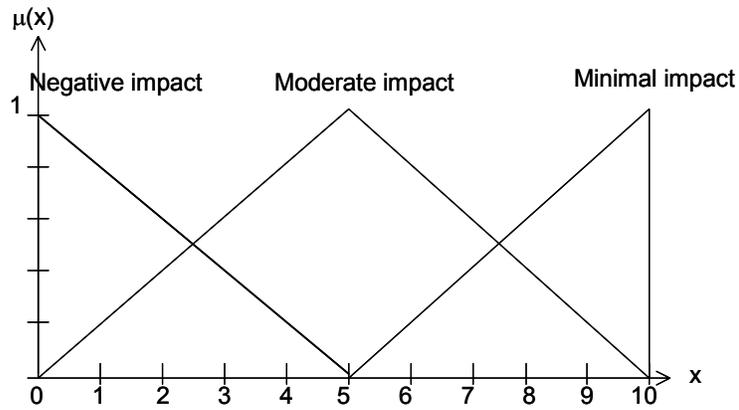
Figure 5-6 Membership Functions of "Negative Impact," "Moderate Impact," and "Minimal Impact"

Impact	Minimal Impact	Moderate Impact	Significant Impact
Linguistic	Minimal Impact	Moderate Impact	Negative Impact
Fuzzy Membership	(5,10,10)	(0,5,10)	(0,0,5)

Table 5-4 Non-Transit Delay Conversion to Triangular Fuzzy Number

5.4.3 Fuzzifying Schedule Reliability

Transit signal priority has the potential to improve bus schedule reliability. The notion of schedule reliability, also referred to as schedule adherence, is simply to get buses to arrive at bus stops on schedule, i.e., within a certain threshold range.   Researchers have used several different measures of effectiveness to measure service reliability. Some of these performance measures include: on time performance, time reliability, perceived on time performance, spacing, and arrival reliability (Chang, 2002).   A useful performance measure to the transit passenger is arrival time reliability, which measures the deviation of actual arrival times versus scheduled arrival times; this is in part due to the fact that the majority of transit passengers use the bus to go to work usually at the same time each day and rely on consistent arrival schedule windows to arrive at work on time.

Each of the transit signal priority strategy alternatives should have some impact on schedule reliability. A technique to assess these impacts is to use the concept of triangular fuzzy numbers and the intersection of fuzzy sets to assess the value of each alternative's arrival time in relation to the acceptable threshold. Two membership functions will be used to define the fuzzy sets **A** and **B**. Fuzzy set **A** is defined as "acceptable deviation from the arrival schedule" and represents the acceptable threshold range. This range is generally determined by the transit agency.   Fuzzy set B_i is defined as "arrival time is approximately t_2 minutes" and represents the range of arrival times for each alternative (i = 1 to n). Arrival times can be measured from simulations or on-site data collection.

The membership function of fuzzy set **A** is shown in Figure 5-7 with a_2 representing the most desired time and a_1 and a_3 representing the beginning and ending of the desired time range. Figure 5-8 shows the membership function of the fuzzy set B_i ("approximately t_2 minutes late") with the values of t_1 and t_3 corresponding to the beginning and the ending of the alternative's arrival times.
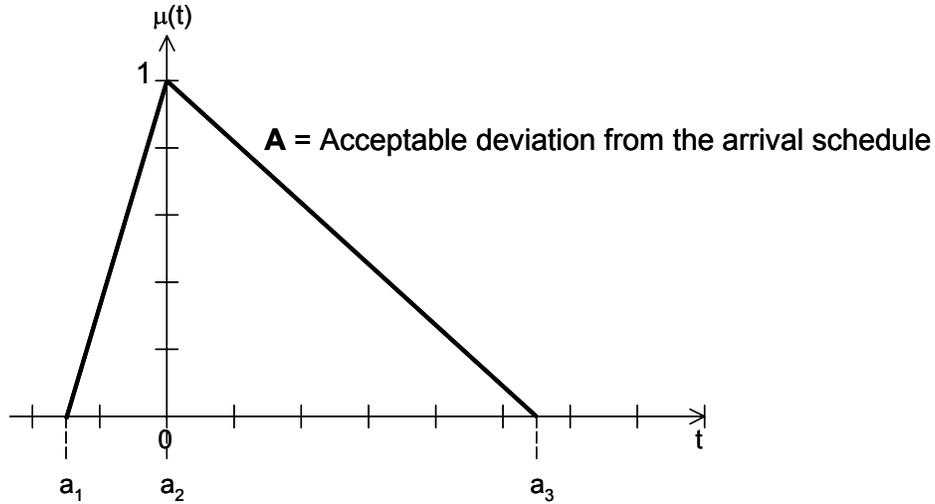
Figure 5-7 Membership Function of "Acceptable Deviation from Arrival Schedule"
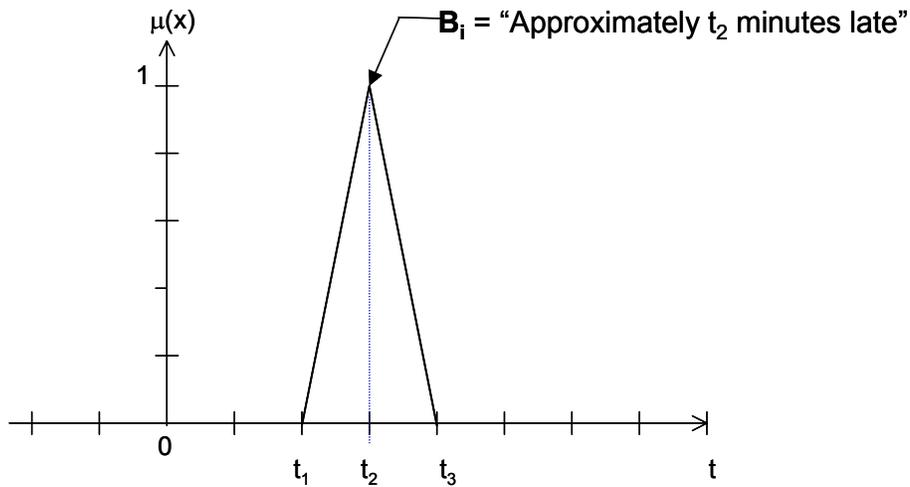
Figure 5-8 Membership Function of "Approximately t_2 Minutes Late"

The impact of the any alternative can be uniquely described by the highest membership value of the intersection of the two fuzzy sets **A** and **B$_i$**. This is the shaded area graphically illustrated in Figure 5-9, which defines **T$_i$**, the intersection of the fuzzy sets **A** and **B$_i$.** **T$_i$** is defined as "approximately t_2 is acceptable deviation."

Truth value of "Approximately t_2
minute late is acceptable deviation"

A = "Acceptable deviation from the arrival schedule"

B_i = "Approximately t_2 minutes late"

T_i = "Approximately t_2 minutes late is
acceptable deviation"
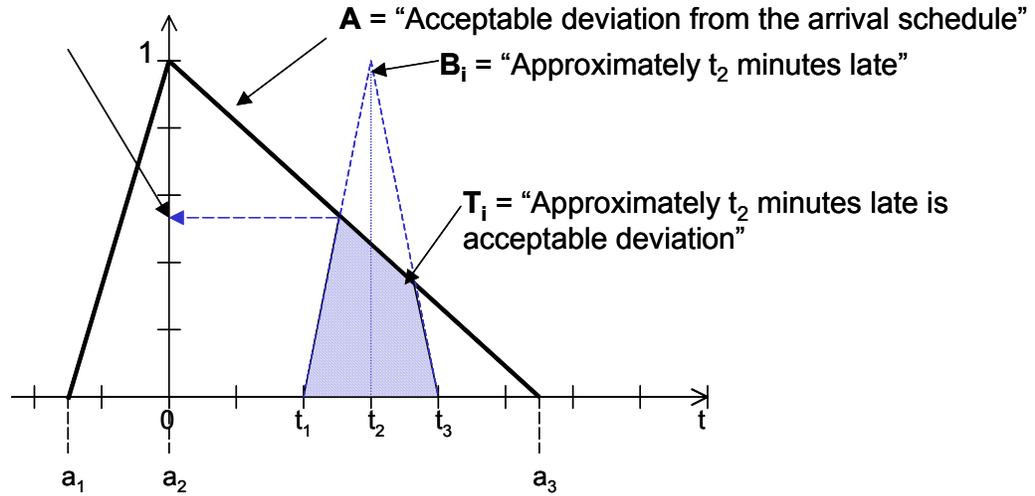
**Figure 5-9 Membership Function of "Approximately t_2 Minutes Late is Acceptable
Deviation"**

Figure 5-10 illustrates how this can be applied in determining the
performance attributes of alternatives. The acceptable threshold **A** is between
1.5 minutes early and 4 minutes late. The fuzzy sets **B₁**, **B₂**, **B₃**, B₄, represent four
different arrival times (approximately 1 minute early, approximately 1 minute late,
approximately 2 minutes late, approximately 3 minutes late and approximately 5
minutes late). The shaded areas represent the intersection of these alternatives
to the acceptable deviation from arrival time. The truth values (0, 0.38, 0.64, and
0.8) corresponds to the intersection of **B₄**, **B₃**, **B₁**, **B₂**, to **A** and uniquely defines
the performance of those alternatives with respect to the threshold range. For
instance, the arrival time of "approximately 5 minutes late" (**B₄**) is outside the
threshold interval and therefore not within the acceptable deviation from arrival
time, and is scored 0. Whereas the arrival time of "approximately 3 minutes late"
(**B₃**) is within the threshold and the value of the highest membership of the
intersection of **B₃** and **A** (approximately 3 minutes late is acceptable deviation) is
0.38.

Arrivial time	Truth Value
B1	0.64
B2	0.80
B3	0.38
B4	0.00
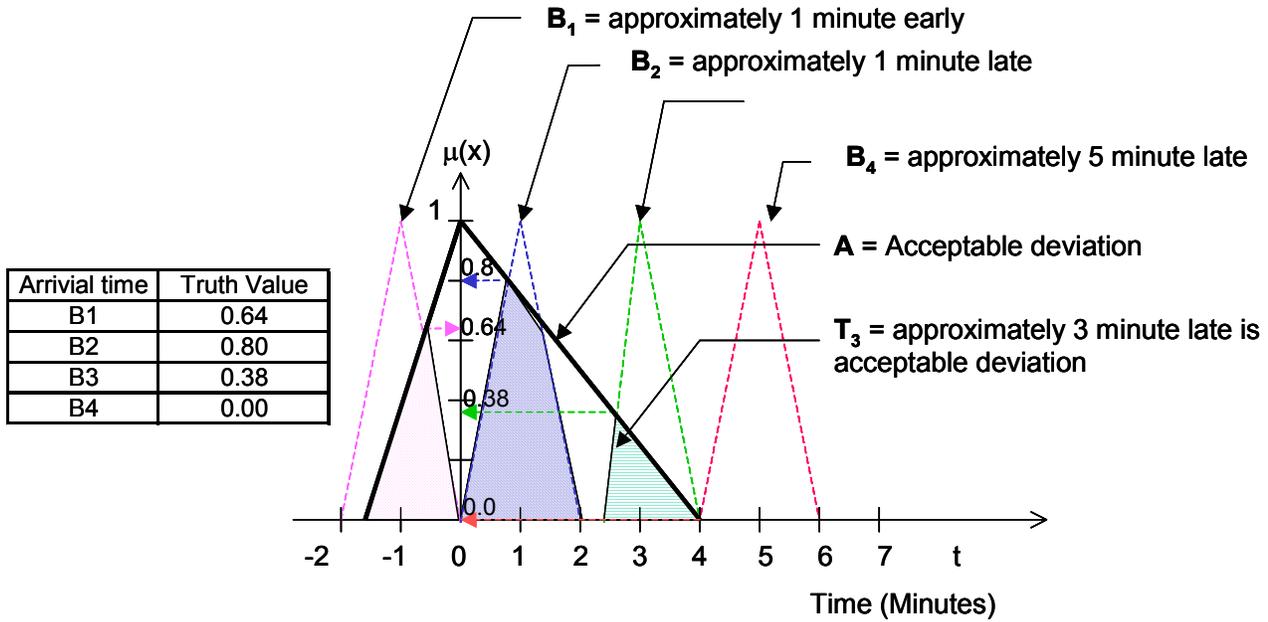
Figure 5-10 Truth Values of Alternative Arrival Times to Acceptable Deviation

5.5 Fuzzifying Stakeholder Concerns

Stakeholder objectives, needs and preferences are an important consideration in planning of integrated traffic signal control systems capable of both emergency vehicle preemption and transit signal priority. Potential stakeholders include elected officials, traffic representatives, transit representatives, fire and rescue providers, and transit riders.

Researchers have found that there is a general lack of knowledge and understanding of priority systems on the part of the traffic and transit officials and the public (Noyce, 1996). Some transit planners believe that priority reduces delay to buses and do not think transit signal priority creates any significant delays to non-transit vehicles (Chada, 2004). Results from interviews with stakeholders indicate that while there is significant interest on signal priority and preemption, it is not top priority among elected officials, traffic or transit agencies. As indicated in Table 5-5 stakeholder concerns to the implementation of transit signal priority are centered about system costs and traffic disruptions, schedule adherence, impact on ridership, and interoperability (Gifford, Pelletiere, Collura, 2003).

	Elected Officials	Traffic Agency Representatives	Transit Officials	Fire and Rescue Providers
Disrupt traffic, worsen congestion and delay	X	X		X
Improve schedule adherence	X		X	
Increased transit ridership	X		X	
Cost	X	X		
Interoperability		X	X	X

Source:
Gifford, Pelletiere, Collura, "Stakeholder Requirements for Traffic Signal Preemption and Priority in the Washington D.C. Region", Transportation Research Record 1748

Table 5-5 Stakeholder Concerns

Linguistic variables can be used in cases where performance criteria are not described quantitatively but with appropriate linguistic expressions. The linguistic variables of "not important," "important," and "very important," will be used to represent stakeholder preferences to the three criteria of transit travel time reduction, non-transit delay, and schedule reliability. These linguistic variables, in turn, can be represented as triangular fuzzy numbers. The fuzzy membership function to describe the linguistic variables of "not important," "important," and "very important," is shown in Figure 5-11. Table 5-7 demonstrates how to apply this methodology. The linguistic variables for an illustrative set of stakeholder preferences for transit travel time reduction, non-transit delay and schedule reliability are shown along with their corresponding triangular fuzzy numbers.
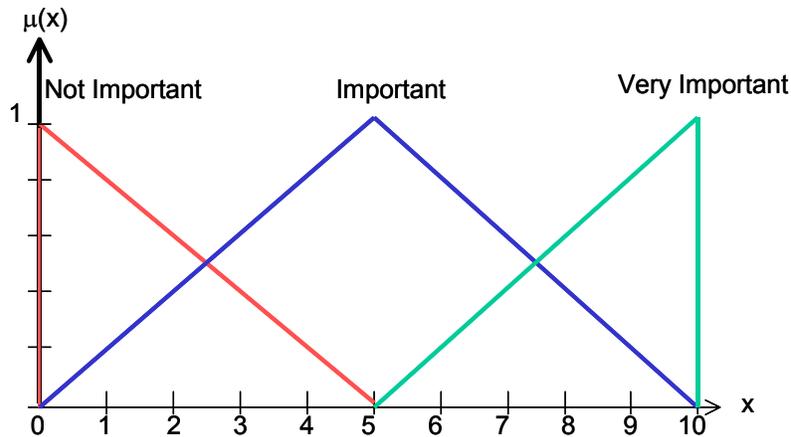
Figure 5-11 Membership Function of Fuzzy Sets "Not Important," "Important," and "Very Important"

	Transit Travel Time Reduction	Non-Transit Delay	Service Reliability
Elected Officials	Important (0,5,10)	Very Important (5,10,10)	Very Important (5,10,10)
Traffic Representatives	Not Important (0,0,5)	Very Important (5,10,10)	Not Important (0,0,5)
Transit Representatives	Very Important (5,10,10)	Not Important (0,0,5)	Very Important (5,10,10)
Emergency Service Providers	Not Important (0,0,5)	Not Important (0,0,5)	Not Important (0,0,5)
Transit Riders	Very Important (5,10,10)	Not Important (0,0,5)	Very Important (5,10,10)

Table 5-6 Converting Stakeholder Linguistic Variables and Fuzzy Triangular Numbers

5.6   Illustrative Example

The following illustrative example demonstrates the application of the fuzzy set concepts previously presented. Four transit signal priority strategy alternatives will be evaluated using three criteria. Stakeholder preferences will also be considered. The objective is to rank order transit signal priority strategy alternatives.

The analytical procedure will follow the following six steps:

1. Determine the alternatives and relevant criteria to be evaluated

2. Identify relevant participants in the decision process

3. Convert alternative performance measures to fuzzy numbers

4. Generate stakeholder preference-based criteria weights

5. Rank the alternatives using multi-attribute decision making methods

7. Perform a post-evaluation, sensitivity analysis

1. <u>Determine the alternatives and relevant criteria to be evaluated</u>

The four transit signal priority strategy alternatives for consideration on a signalized intersection are: (A_1) signal optimization; (A_2) green extension, (A_3) green extension and red truncation; and (A_4) green extension, red truncation, and queue jump.   The three evaluation criteria are: (C_1) transit travel time reduction; (C_2) non-transit delay; (C_3) schedule reliability. Data available for transit travel time reduction, non-transit delay, and schedule reliability are as follows:

The transit travel time reduction performance measures for each alternative is as shown in Table 5-7

	Transit travel time reduction
Signal optimization	2%-5%
Green extension only	0%-9.7%
Green extension and red truncation	1.4%-20%
Green extension, red truncation and queue jump	0%-18%

Table 5-7 Alternative Transit Travel Time Reduction

The approach volume capacity ratio is between 0.5 and 0.8, and the cross street volume capacity ratio is 0.6.

The acceptable arrival threshold is one minute early and five minutes late. The approximate arrival times for the four alternatives are:

Alternative	Approximate arrival time
Signal optimization	approximately 2 minutes late
Green extension only	approximately 1.5 minutes late
Green extension and red truncation	approximately 1 minutes late
Green extension, red truncation and queue jump	approximately 0.5 minutes late

Table 5-8 Alternative Approximate Arrival Times

2. <u>Identify relevant participants in the decision process</u>

The relevant stakeholders include elected officials, traffic representatives, transit representatives, fire and rescue service providers, and transit riders. Results complied from a survey of their concerns and preferences with regard to the three criteria are provided in Table 5-9.

	Transit Travel Time Reduction	Non-Transit Delay	Service Reliability
Elected Officials	Interested in operational efficiency	Concerned TSP would disrupt traffic and worsen congestion	Primary objective should be schedule adherence Concerned TSP would not provide any significant improvement for bus on-time performance
Traffic Representatives		Concerned about traffic being disrupted	Concerned TSP would not improve schedule adherence
Transit Representatives	Interested in reduced operating costs	No noticeable delay to side traffic	Objective of TSP would be to Improve on-time performance
Fire and Rescue Providers		Concerned TSP will disrupt EVP	
Transit Riders	Reduce transit travel time		Improve schedule reliability

Table 5-9 Stakeholder Concerns for Transit Travel Time, Non-Transit Delay, Service Reliability

3. <u>Convert alternative performance measures to fuzzy numbers</u>

Transit travel time reduction is converted to triangular fuzzy numbers using the concept of a fuzzy number as a generalization of confidence intervals. This conversion is shown in Table 5-10.

Strategy	Fuzzy Membership
Signal Optimization	(2,3,5)
Green Extension Only	(0,4.8,9.7)
GE + RT	(1.4, 9.3, 20)
GE + RT + Queue Jump	(0,9,18)

Table 5-10 Transit Travel Time Fuzzy Number

The approach volume capacity ratio between 0.5 and 0.8 indicates that priority can be used.   The cross street volume capacity ratio of 0.6 can be converted to the linguistic variable "moderate impact" using Figure 5-12. From Figure 5-13, the triangular fuzzy number associated with the linguistic variable "moderate impact" is (0,5,10).
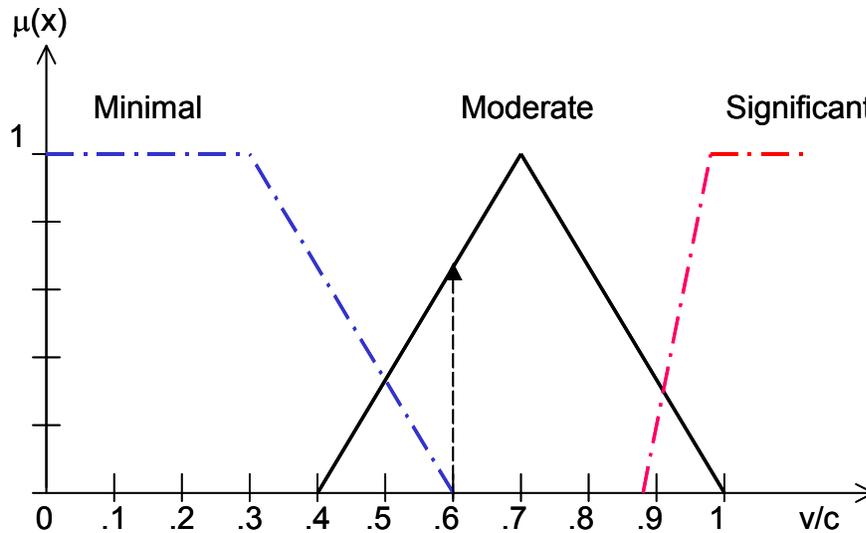
Figure 5-12 Determining Non-Transit Delay Linguistic Variable
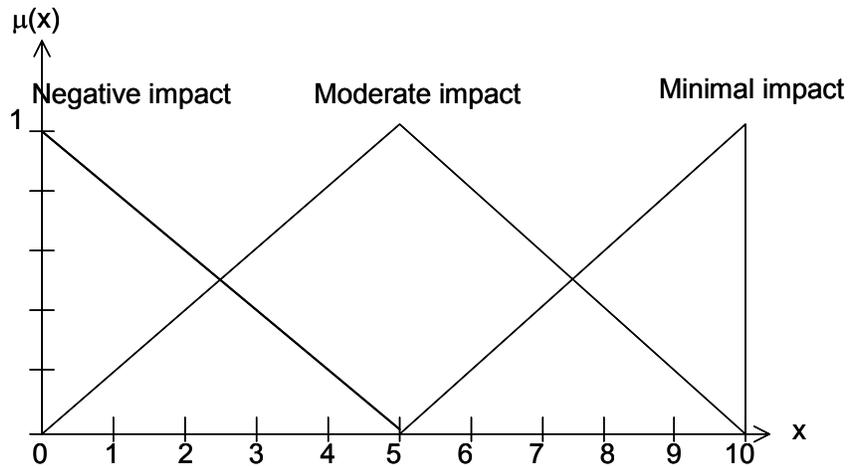
Figure 5-13 Fuzzy Membership Function for "Negative Impact," "Moderate Impact," "Minimal Impact"

Schedule reliability can be converted to fuzzy numbers using the technique of intersection of fuzzy sets.   The arrival times of the four alternatives are overlaid on to the acceptable arrival threshold as illustrated in Figure 5-14.
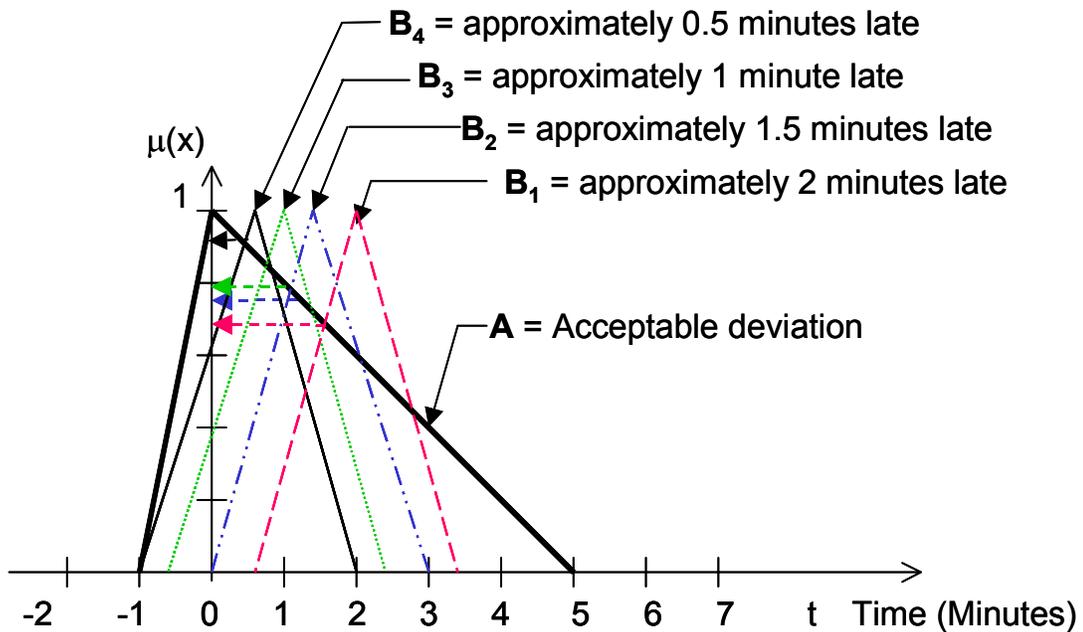
Figure 5-14 Membership Functions for Acceptable Threshold and Four Arrival Times

The truth values of the intersection of each alternative to the acceptable threshold are presented in Table 5-11.

Alternative	Arrival time	Linguistic Description	Value
signal optimization	B1	approximately 2 minutes late	0.70
green extension	B2	approximately 1.5 minutes late	0.77
green extension and red truncation	B3	approximately 1 minutes late	0.85
green extension, red truncation, and queue jump	B4	approximately 0.5 minutes late	0.93

Table 5-11 Truth Values for Alternative Arrival Times

At this point all of the alternative performance measures for each criteria has been converted. The results are presented in Table 4-12.

	C_1	C_2	C_3
	Transit travel time reduction	Non-transit delay	Service reliability
A_1 (Signal optimization)	(2.00, 3.50, 5.00)	(5.00, 10.00, 10.00)	(0.70, 0.70, 0.70)
A_2 (Green extension)	(0.00, 4.90, 9.00)	(0.00, 5.00, 10.00)	(0.77, 0.77, 0.77)
A_3 (Green extension & red truncation)	(1.40, 10.70, 20.00)	(0.00, 5.00, 10.00)	(0.85, 0.85, 0.85)
A_4 (Green extension & red truncation & queue jump)	(0.00, 9.00, 18.00)	(0.00, 5.00, 10.00)	(0.93, 0.93, 0.93)

Table 5-12 Alternative Fuzzy Values

4. <u>Generate stakeholder preference-based criteria weights</u>

The stakeholder preferences are converted to the linguistic variables "not important," "important," "very important". Table 5-13 presents the results of that conversion and their associated triangular fuzzy numbers.

	Transit Travel Time Reduction	Non-Transit Delay	Service Reliability
Elected Officials	Important (0,5,10)	Very Important (5,10,10)	Very Important (5,10,10)
Traffic Representatives	Important (0,5,10)	Very Important (5,10,10)	Important (0,5,10)
Transit Representatives	Very Important (5,10,10)	Important (0,5,10)	Very Important (5,10,10)
Fire & Rescue Service Providers	Important (0,5,10)	Important (0,5,10)	Not Important (0,0,5)
Transit Riders	Very Important (5,10,10)	Not Important (0,0,5)	Very Important (5,10,10)

Table 5-13 Stakeholder Preferences and Triangular Fuzzy Numbers

The stakeholder preference-based criteria weights are generated by averaging the triangular fuzzy numbers representing stakeholder preferences in each criteria and normalizing. The results are shown in Table 5-14.

	C_1 Transit travel time	C_2 Non-transit delay	C_3 Service reliability
Elected officials	(0, 5, 10)	(5, 10, 10)	(5, 10, 10)
Traffic representatives	(0, 5, 10)	(5, 10, 10)	(0, 5, 10)
Transit representatives	(5, 10, 10)	(0, 5, 10)	(5, 10, 10)
Fire and rescue providers	(0, 5, 10)	(0, 5, 10)	(0, 0, 5)
Transit riders	(5, 10, 10)	(0, 0, 5)	(5, 10, 10)
Average	(2, 7, 10)	(2, 6, 8)	(3, 7, 9)
Normalized Weight	(0.10, 0.35, 0.50)	(0.10, 0.30, 0.45)	(0.15, 0.35, 0.45)

Table 5-14 Stakeholder Preference-Based Criteria Fuzzy Numbers

5. <u>Rank the alternatives using multi-attribute decision making methods</u>

The fuzzy WSM and the fuzzy TOPSIS methods both begin with a fuzzy decision matrix in the form:

$$
\begin{array}{c}
\begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array} \\
\begin{array}{cccc} W_1 & W_2 & \cdots & W_n \end{array} \\
D = \begin{array}{c} A_1 \\ A_2 \\ \vdots \\ A_m \end{array}
\left[\begin{array}{cccc}
x_{11} & x_{12} & \cdots & x_{1n} \\
x_{21} & x_{22} & \cdots & x_{2n} \\
\cdots & \cdots & \cdots & \cdots \\
X_{m1} & X_{m2} & \cdots & X_{mn}
\end{array} \right]
\end{array}
$$

(5-20)

The normalized fuzzy decision matrix for the illustrative example is:

$$
\begin{array}{c}
\begin{array}{ccc} \mathbf{C_1} & \mathbf{C_2} & \mathbf{C_3} \end{array} \\
\begin{array}{ccc} (0.10, 0.35, 0.50) & (0.10, 0.30, 0.45) & (0.15, 0.35, .45) \end{array} \\
D = \begin{array}{c} \mathbf{A_1} \\ \mathbf{A_2} \\ \mathbf{A_3} \\ \mathbf{A_4} \end{array}
\left[\begin{array}{ccc}
(1.00, 1.75,\ 2.50) & (5.00, 10.00, 10.00) & (7.00, 7.00, 7.00) \\
(0.00, 2.45,\ 4.50) & (0.00,\ 5.00, 10.00) & (7.70, 7.70, 7.70) \\
(0.70, 5.35, 10.00) & (0.00,\ 5.00, 10.00) & (8.50, 8.50, 8.50) \\
(0.00, 4.50,\ 9.00) & (0.00,\ 5.00, 10.00) & (9.30, 9.30, 9.30)
\end{array} \right]
\end{array}
$$

Fuzzy WSM Method

The priority score for each alternative is computed using:

$$ P_i = \sum_{i=1}^{n} a_{ij} (W_j) \qquad (5\text{-}21) $$

The priority score for P_1 is calculated as follows:

P_1 = (0.10, 0.35, 0.50) x (1.00, 1.75, 2.50) + (0.10, 0.30, 0.45) x (5.00, 10.00, 10.00) + (0.15, 0.35, 0.45) x (7.00, 7.00, 7.00)

= (1.65, 6.06, 8.90)

and similarly,

$$P_2 = (1.16, 5.05, 10.22)$$
$$P_3 = (1.35, 6.35, 13.33)$$
$$P_4 = (1.40, 6.33, 13.19)$$

The ranking of P1 is calculated using Kraufmann and Gupta's method for ranking as follows:

$$R(P_1) = (a_1 + 2a_2 + a_3)/(2)$$
$$= (1.65 + (2) \times (6.06) + 8.90)/2$$
$$= 5.67$$

and similarly,

$$R(P_2) = 5.37$$
$$R(P_3) = 6.84$$
$$R(P_4) = 6.81$$

Using fuzzy WSM, the alternatives are ranked: $A_3 > A_4 > A_1 > A_2$.

Fuzzy TOPSIS Method

A normalized decision matrix is derived using equation (5 –2);

	C_1	C_2	C_3
	(0.10, 0.35, 0.50)	(0.10, 0.30, 0.45)	(0.15, 0.35, .45)
A_1	(0.07, 0.23, 2.05)	(0.25, 0.76, 2.00)	(0.43, 0.43, 0.43)
A_2	(0.00, 0.32, 3.69)	(0.00, 0.38, 2.00)	(0.47, 0.47, 0.47)
A_3	(0.05, 0.70, 8.19)	(0.00, 0.38, 2.00)	(0.52, 0.52, 0.52)
A_4	(0.00, 0.59, 7.37)	(0.00, 0.38, 2.00)	(0.57, 0.57, 0.57)

D =

The weighted normalized decision matrix is:

$$
\begin{array}{cccc}
 & \mathbf{C_1} & \mathbf{C_2} & \mathbf{C_3} \\
 & (0.10, 0.35, 0.50) & (0.10, 0.30, 0.45) & (0.15, 0.35, .45) \\
\mathbf{A_1} & (0.01, 0.08, 1.02) & (0.03, 0.23, 0.90) & (0.06, 0.15, 0.19) \\
\mathbf{A_2} & (0.00, 0.11, 1.84) & (0.00, 0.11, 0.90) & (0.07, 0.16, 0.21) \\
\mathbf{A_3} & (0.00, 0.25, 4.10) & (0.00, 0.11, 0.90) & (0.08, 0.18, 0.23) \\
\mathbf{A_4} & (0.00, 0.21, 3.69) & (0.00, 0.11, 0.90) & (0.09, 0.20, 0.26)
\end{array}
$$

$\mathbf{D} =$ (indicated to the left of the matrix)

The ideal-positive $\mathbf{A^*}$ and ideal-negative $\mathbf{A^-}$ solutions are:

$\mathbf{A^*}$ = (0.00, 0.25, 4.10), (0.03, 0.23, 0.90), (0.90, 0.20, 0.26)

$\mathbf{A^-}$ = (0.01, 0.08, 1.02), (0.00, 0.11, 0.90), (0.06, 0.15, 0.19)

The separation measures $\mathbf{S_i^*}$ and $\mathbf{S_i^-}$ are:

$\mathbf{S_1^*}$ = (0.026, 0.173, 3.073) $\mathbf{S_1^-}$ = (0.025, 0.113, 0.000)

$\mathbf{S_2^*}$ = (0.032, 0.179, 2.253) $\mathbf{S_2^-}$ = (0.010, 0.036, 0.820)

$\mathbf{S_3^*}$ = (0.028, 0.115, 0.026) $\mathbf{S_3^-}$ = (0.014, 0.169, 3.072)

$\mathbf{S_4^*}$ = (0.026, 0.120, 0.410) $\mathbf{S_4^-}$ = (0.022, 0.136, 2.663)

The relative closeness to the ideal solution is defined by:

$$
C_i^* = \frac{S_i^-}{S_i^+ + S_i^-} \tag{5-22}
$$

$$
C_1^* = \frac{(0.026, 0.173, 3.073)}{(0.025, 0.113, 0.000) + (0.026, 0.173, 3.073)}
$$

$$
= (0.01, 0.40, 0.00),
$$

and similarly,

C_2^* = (0.00, 0.17, 19.78)

C_3^* = (0.00, 0.59, 73.77)

C_4^* = (0.01, 0.53, 55.36)

Using fuzzy TOPSIS, the alternatives are ranked: **A₃> A₄> A₁> A₂**.

Post evaluation sensitivity analysis

Results obtained from both the fuzzy WSM and fuzzy TOPSIS methods using the data set for the illustrative example rank the transit signal priority alternatives as follows: (1) green extension and red truncation; (2) green extension, red truncation and queue jump; (3) signal optimization; and (4) green extension only.

Unfortunately different multi-attribute decision making methods often produce different outcomes for selecting or ranking a set of alternatives involving multiple attributes. The fuzzy WSM and fuzzy TOPSIS methods were chosen because of their simplicity, computational efficiency and wide usage. The main difference between the two methods used lie in (1) the normalization process for comparing all performance ratings and (2) the aggregation of the normalized decision matrix and weighting vector for obtaining overall preference value for each alternative. As a result, the outcomes for the fuzzy WSM and the fuzzy TOPSIS methods may not always be consistent for a given decision matrix and weighting vector. Sensitivity analysis provides a means to examine the influence of input parameters to MADM outcomes.

5.7   Sensitivity Analysis

Sensitivity analysis will focus on the performance measures of the alternatives and the weights of the decision criteria (Triantaphyllou and Sanchez, 1997). Two techniques for sensitivity analysis will be used. First, Shannon's entropy method will be used to determine the usefulness of each attribute to the decision maker based on distribution of information within the criteria (Hwang and Yoon, 1981; Yeh and Willis, 2001).   This will address the question "how useful are the performance attributes of the alternatives to the decision maker?" Second, computational experiments will be used to examine the influence of stakeholder-based weight changes on MADM outcomes. This addresses the question "how sensitive is each method to criteria weight changes?"

5.7.1 Shannon's Entropy Method

Shannon's entropy method is based on information uncertainly within a data set. This method has it roots in information theory and was introduced in 1948 to provide a quantitative measure of the "uncertainty" represented by a discrete probability distribution (Shannon, 1948).   Today, the term "entropy" is synonymous with the term "uncertainty" (Hwang and Yoon, 1981). Entropy analysis is based on three measures: entropy (e_j), degree of divergence (d_j), and degree of influence or weight of importance (f_j).

The entropy value e_j represents the uncertainty of the criteria C_j. It is determined by (Hwang and Yoon, 1981; Yeh and Willis, 2001):

$$e_j = -k \sum_{i=1}^{m} p_{ij} \ln p_{ij} ; \qquad j = 1,2,\ldots,n. \tag{5-23}$$

where $k = 1/(\ln m)$ and

$$p_{ij} = x_{ij} / \sum_{q=1}^{m} x_{qj} ; \qquad i = 1,2,\ldots,m; \ j = 1, 2,\ldots,n. \tag{5-24}$$

e_j has a number of interesting properties (Shannon, 1948).

1. $e_j = 0$ if and only if all the p_{ij} but one are zero, this one having the value of unity. In this case, the outcome is certain and e_j vanishes. Otherwise, e_j is positive.

2. For a given n, e_j is a maximum and equal to 1 when all the p_{ij} are equal (i.e., 1/n). This is intuitively the most uncertain situation.

Entropy can be used as a tool in attribute evaluation by investigating contrasts between sets of data.   If all the alternatives have similar outcomes for that attribute, that attribute does not provide the decision maker any useful information. In the most extreme case, when all the values are the same, the attribute can be eliminated (Hwang and Yoon, 1981; Shannon, 1948).

The degree of divergence represents the inherent contrast intensity of the criterion C_j and is defined as (Hwang and Yoon, 1981; Yeh and Willis, 2001):

$$d_j = 1 - e_j; \qquad j = 1,2,\ldots,n. \tag{5-25}$$

The degree of influence (weight of importance) provides a means to order the criteria weights. The degree of influence is smaller when all alternatives of

the attribute have similar outcomes. The degree of influence is (Hwang and
Yoon, 1981; Yeh and Willis, 2001):

$$f_j = d_j / \sum_{q=1}^{n} d_q ; \qquad j = 1,2,\ldots,n. \qquad\qquad (5\text{-}26)$$

Shannon's entropy analysis was performed on the illustrative problem
data set and the results are presented in the Table 4-15:

	C_1	C_2	C_3
e_i	(0.227, 0.978, -0.407)	(0.078, 0.961, -48)	(0.996, 0.996, 0.996)
d_i	(0.773, 0.022, 1.407)	(0.922, 0.039, 49)	(0.004, 0.004, 0.004)
f_i	(0.015, 0.338, 0.828)	(0.018, 0.60, 28.85)	(0.000, 0.062, 0.0024)

Table 5-15 Shannon's Entropy Analysis Results

Relatively high entropy would indicate uncertainty among the alternative
outcomes for the criteria. This would mean the performance attributes of the
alternatives within that criterion would provide useful information to the decision
maker. Results from Table 5-15 indicate large entropy values for all three
criteria. This suggests that the fuzzy performance attributes of the four
alternatives provide useful information to the decision maker.

The importance of a criterion reflects the range of alternative outcomes in
that criterion. A criterion with similar outcomes from the alternatives will have a
smaller weight. The order of criteria importance as determined by the degree of
influence f_j is: C_2 (non-transit delay), C_1 (transit travel time reduction), C_3
(schedule reliability). This indicates that non-transit delay has the largest range
of outcomes, followed by transit travel time deduction and schedule reliability has
the most similar outcomes.

5.7.2 Computational Experiments

Computational experiments were performed to examine the influence of
stakeholder-based criteria weight changes on MADM outcomes. Three sets of
computational experiments were conducted to determine the impact of
stakeholder preference changes on MADM outcomes. . In each set, the

stakeholder preference for one criterion was varied over its entire possible range while the other two was fixed. The baseline was the data set used in the illustrative example. Figures 5-15 to 5-18 graphically displays the outcomes of computational experiments. The degree of stakeholder preference is increased along the x-axis starting with all five stakeholders considering that criteria not important (5,0,0) to all five stakeholders considering that criteria is very important (0,0,5).

The impact of changing stakeholder preferences for non-transit delay on both fuzzy MADM methods is illustrated in Figure 5-15.   Results from these indicate that stakeholder preference changes in non-transit delay have no impact on the ranking outcomes for fuzzy WSM and minimal impact for fuzzy TOPSIS.

The impact of changing stakeholder preferences for service reliability is illustrated in Figure 5-16. Results indicate that stakeholder preference changes in schedule reliability have no impact on the ranking outcomes of fuzzy TOPSIS and minimal impact for fuzzy WSM.
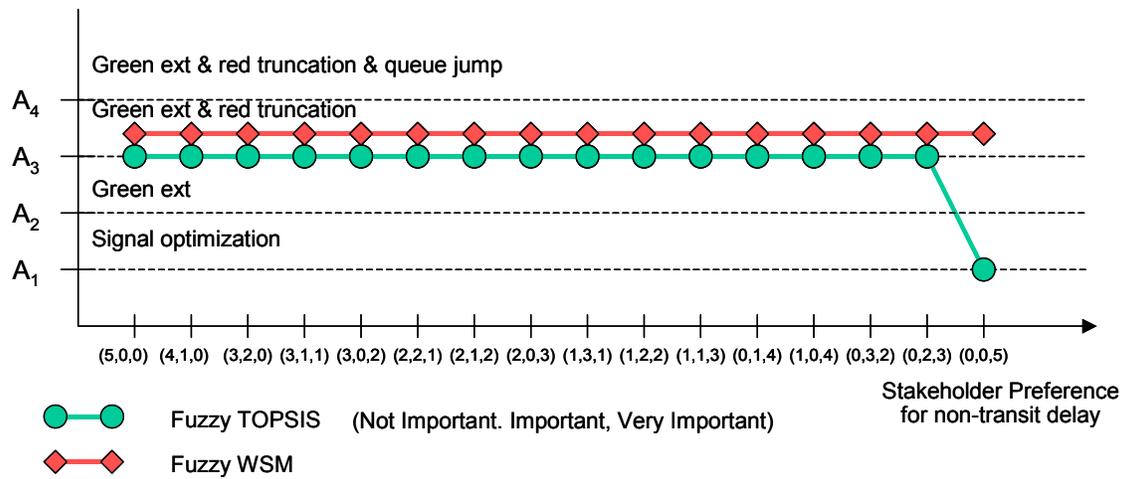
Figure 5-15 Influence of Stakeholder Preference for Non-Transit Delay on Fuzzy MADM Outcomes
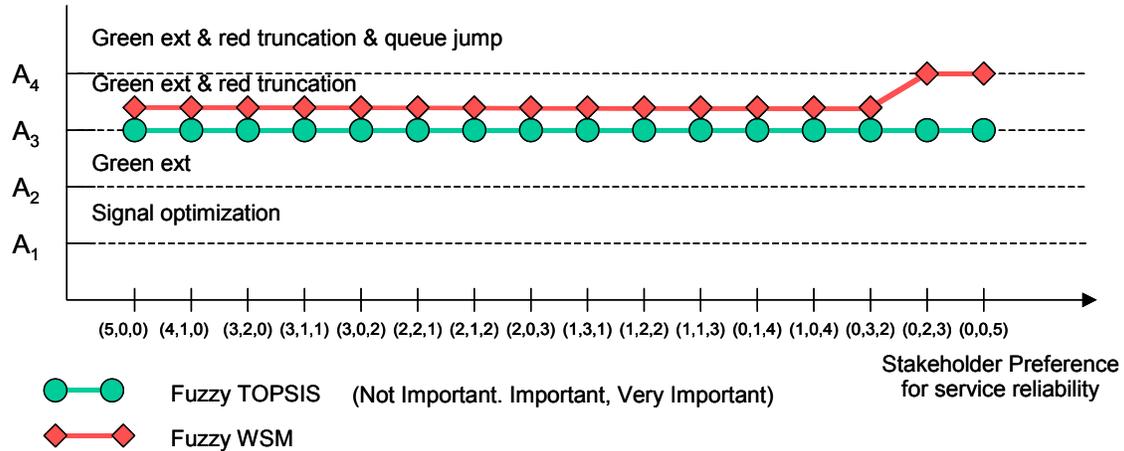
Figure 5-16 Influence of Stakeholder Preference for Service Reliability on Fuzzy MADM Outcomes

The impact of stakeholder preferences on fuzzy TOPSIS is illustrated in Figure 5-17.   When there is little or no support for transit signal priority – in the range where all stakeholders consider transit signal priority not important (5, 0, 0) to where two stakeholders consider transit signal priority not important, two stakeholders consider transit signal priority to be important, and one stakeholder deeming transit signal priority to be very important (2, 2, 1), alternative 1 (signal optimization) is selected; when stakeholder preference for transit signal priority is high – in the range where one stakeholder considers transit signal priority to be not important, three stakeholders consider transit signal priority important and one stakeholder considers transit signal priority to be very important (1, 3, 1) to all stakeholders deem transit signal priority very important (0, 0, 5), alternative 3 (green extension and red truncation) is selected.   This makes intuitive sense. When support for transit signal priority is low, then the base case, signal prioritization should be the highest ranking alternative.
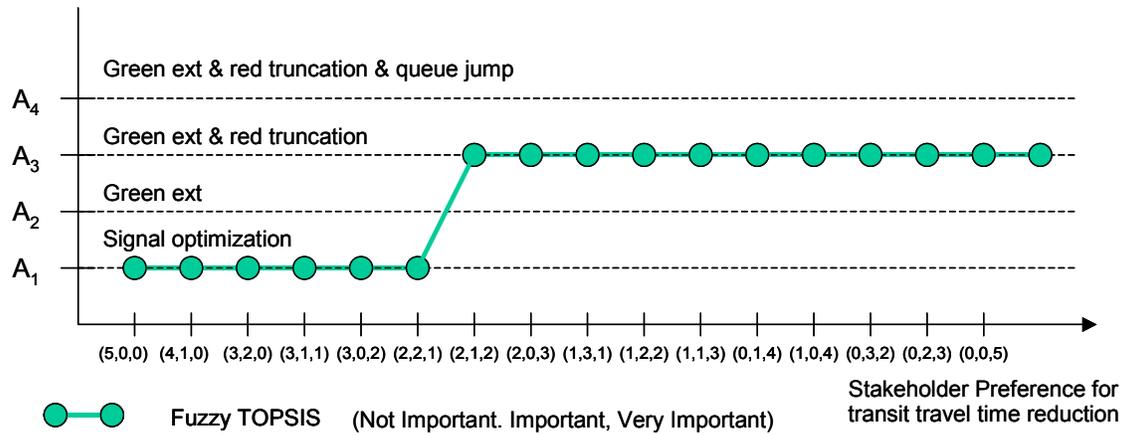
Figure 5-17 Stakeholder Preference Influence for Transit Travel Time Reduction on Fuzzy TOPSIS

The impact of stakeholder preferences on fuzzy WSM is shown in Figure 5-18.　Alternative 4 (green extension, red truncation, and queue jump) is ranked highest until preference for transit signal priority is very high, then alternative 3 (green extension and red truncation) is selected.　However, there is no change to alterative ranking at the ranges where stakeholder preference is low.
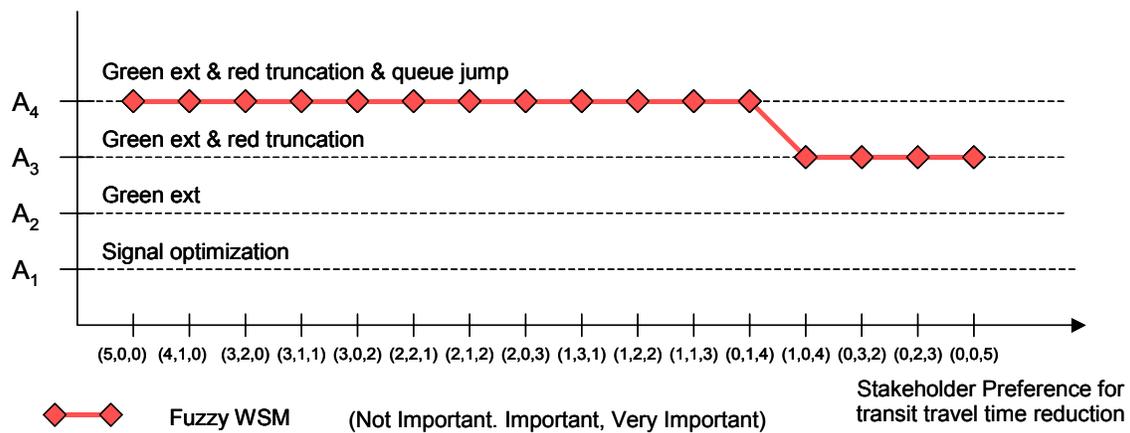
Figure 5-18 Stakeholder Preference Response for Transit Travel Time Reduction on Fuzzy WSM

5.7.3　Conclusions

Results from Shannon's entropy analysis suggest that the methodology to convert uncertain, subjective, imprecise and ambiguous performance data to the

fuzzy performance attributes for the four alternatives provide useful information to the decision maker. Computational experiments suggest that, in this application, fuzzy TOPSIS is more responsive to stakeholder preferences and best reflect the values of the decision maker.   As a result, fuzzy TOPSIS is the preferred fuzzy multi-attribute decision making method.

Chapter 6:   Summary, Conclusions and Recommendations

6.1   Summary

The research conducted for this dissertation focused on the development of a decision support system framework for emergency vehicle preemption and transit signal priority investment planning.   This research builds on and expands upon previous research on economic evaluation frameworks, evaluation of preferential treatments of emergency vehicle preemption and transit vehicle priority at signalized intersections, emergency vehicle crash characteristics, and transit travel time reduction.

This dissertation has 2 research goals: (1) to develop a decision support system framework to assess the impacts of advanced traffic signal control systems capable of integrating emergency vehicle preemption and transit signal priority operations for investment planning purposes; and (2) to develop analytical tools for incorporation into the decision support system framework.

Decision Support System Framework
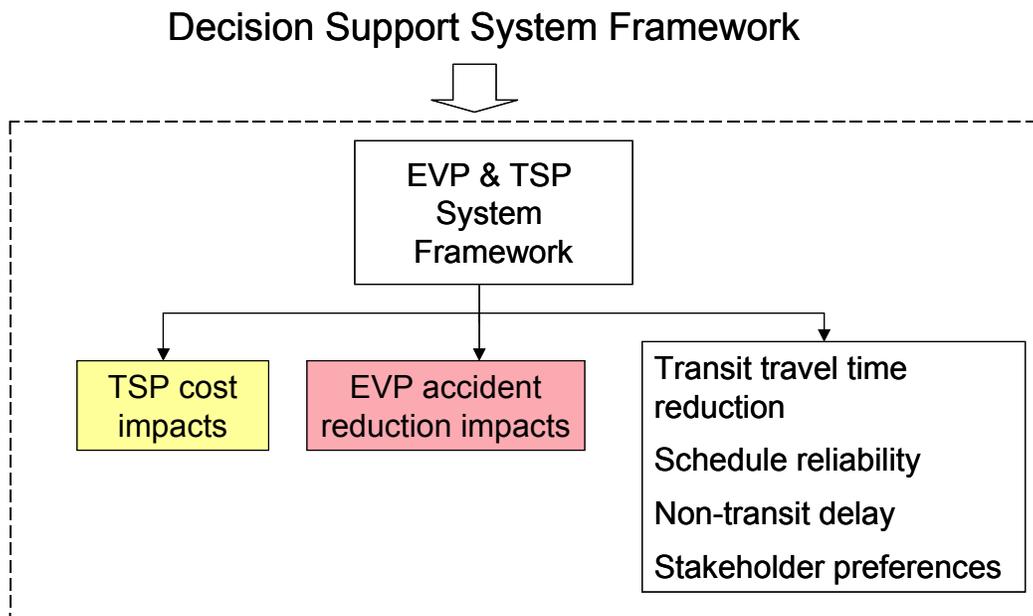
Figure 6-1 Research Products

The research products are illustrated in Figure 6-1.   They include a conceptual decision support framework, two analytical tools that assess transit

signal priority and emergency vehicle preemption impacts at the corridor level, and one analytical tool that addresses transit signal priority strategy impacts at the intersection level.

The conceptual decision support system framework was presented in Chapter 3. It provides a holistic framework that can be used to perform analytical assessments of integrated emergency vehicle preemption and transit signal priority system impacts for investment planning. An integrated emergency vehicle preemption and transit signal priority system was examined from a systems perspective. Ten travel impacts were identified and a review on the state-of-the-art of impact assessment was presented.   Finally, a conceptual decision support system framework was introduced and desired functionalities and capabilities described.

A total of three analytical tools were developed as part of this research. Two were presented in Chapter 4. These assess the impact of emergency vehicle preemption and transit signal priority at the corridor level. The first addressed the potential impact of transit travel time reduction due to transit signal priority on transit operating costs. The second addressed the potential impact of reduced emergency vehicle crashes on signalized intersection due to emergency vehicle preemption. The purpose of these two analytical tools is to aid planners and managers in assessing the cost impacts of emergency vehicle preemption and transit priority systems.

The third analytical tool integrates fuzzy sets concepts and multi-attribute decision making methods to rank order transit signal priority strategy alternatives at the intersection level. The tool also incorporates stakeholder preference-based weighting as part of the MADM method. It is presented in Chapter 5. Techniques to use fuzzy sets concepts such as triangular fuzzy numbers, linguistic variables, and intersection of fuzzy sets to convert uncertain, subjective, imprecise and ambiguous performance data for transit travel time, non-transit delay and schedule reliability was demonstrated. Performance attributes in the form of triangular fuzzy numbers were derived for four transit signal priority strategy alternatives. Fuzzy sets concepts were also used to derive stakeholder

preference-based weighting for each criterion. Two widely used fuzzy multi-attribute decision making methods, fuzzy WSM and fuzzy TOPSIS were used. Based on results from sensitivity analysis, the fuzzy TOPSIS was recommended over the fuzzy WSM because it was more responsive to changes in stakeholder preferences.

The analytical tools developed in this research outline a standardized systematic technique to assess the impacts of ITS projects for investment planning purposes.   These tools use cost factors, accident reduction factors and soft computing techniques to use transform quantitative and qualitative performance data for input into mathematical modeling methods commonly used to support decision making. These analytical tools could be incorporated into the design of a decision support system in the future.

6.2   Conclusions

This research applied soft computing concepts in the form of fuzzy sets theory to convert uncertain, subjective, imprecise and ambiguous performance data to linguistic terms and triangular fuzzy numbers that can be used in fuzzy MADM methods for transit signal priority strategy alternatives selection.

Fuzzy sets theory is a very convenient mathematical device for treating the uncertainty, subjectivity, imprecision and ambiguity often found in many transportation and traffic engineering problems. The use of fuzzy sets theory provides a means to convert qualitative data, as well as uncertain, subjective, imprecise, and ambiguous data to a form useful for application in multi-attribute decision making methods. The use of linguistic terms coupled with expert knowledge to represent otherwise difficult to measure performance attributes is especially useful in those instances where precise techniques are not applicable. Fuzzy sets theory concepts have been applied to fuzzy traffic control problems, vehicle routing and scheduling problems, vehicle dispatching problems, and choice problems (Teodorovic, 1994).

The opportunity exists to apply fuzzy sets theory concepts to aid in decision making for other branches of transportation and traffic engineering where real life

multi-attribute decision making problems usually contains a mixture of quantitative and qualitative data, with varying degrees of precision, subjectivity and certainty and criteria that usually conflict. The use of fuzzy sets theory provides a means to incorporate unquantifiable information, incomplete information, nonobtainable information and subjective information into decision models (Chen and Hwang, 1992).

One possible application is in the area of transportation safety analysis. Recommendations for safety improvements must consider multiple criteria such as: geometric designs, traffic control devices, rules enforcement, infrastructure maintenance, driver behavior and qualification, pedestrian and bicycle traffic, and population demographics (Institute of Transportation Engineers, 1999). These criteria have conflicting impacts; contain both qualitative and quantitative data of various degrees of precision and subjectivity; and often require expert knowledge to interpret. These conditions are perfect for fuzzy MADM.

6.3   Recommendations for Future Work

This research introduced a conceptual decision support system framework for planners and managers to use in making integrated emergency vehicle preemption and traffic signal priority system investment planning decisions. Analytical tools to determine the impact of transit travel time reduction on transit operational costs and the impact of reduced emergency vehicle crashes at signalized intersections were developed. Follow-on work should continue to extend that work by: (1) addressing the potential impact of reduced emergency vehicle travel time on saving lives, reducing injury and reducing property damage. The resulting algorithm may consider linking emergency vehicle responses with hospital emergency room admissions data and subsequent outcomes of the admission. (2) developing analytical tools and techniques to identify and assess system level impacts.

This research developed a fuzzy MADM framework to rank transit signal priority strategy alternatives at the intersection level using three criteria: transit travel time reduction, non-transit delay, and schedule reliability. This fuzzy

MADM framework should be expanded to include other criteria such as investment costs and safety. Cost data may include for example, infrastructure costs to modify an intersection to accommodate a queue jump or to relocate bus stops from near side to far side to accommodate a green extension. Some cost data may be expressed in terms of a range and consequently the concept of triangular fuzzy numbers could be used to represent cost data in the fuzzy MADM framework described in Chapter 5. In cases where costs are more certain and easily estimated, crisp numbers might be used instead of triangular fuzzy numbers. Crisp numbers can be represented as a singleton, a special triangular fuzzy number defined $a_1 = a_2 = a_3$. Safety impacts include both transit and pedestrian safety. Far side bus stops are preferred for green extension; however, they are more susceptible to rear end crashes. In all alternatives, the impact on pedestrian safety needs to be researched and incorporated. In this instance linguistic variables may be appropriate. However, research is required to determine the most appropriate fuzzy sets concepts to apply.

This research also introduced the use of fuzzy sets concepts to convert uncertain, subjective, imprecise and ambiguous performance information of transit signal priority strategy alternatives to fuzzy numbers. Techniques were presented to convert the criteria of transit travel time reduction, non-transit delay and service reliability. Follow-on work should apply this fuzzy MADM method to on-going research conducted at the VT/GMU/VDOT integrated emergency vehicle preemption and transit signal priority operational field test site on US 1 in Northern Virginia. Data collection, in future simulations and field measurements, should use the performance attributes utilized in the MADM methods to standardize data collection for continued analysis using fuzzy MADM methods.

This research applied fuzzy MADM to rank various transit signal priority strategy alternatives at the intersection level. Follow-on work should investigate linking a series of intersections and use dynamic programming to determine the best mix of transit signal priority strategy alternatives along a corridor.

Finally, the power of fuzzy MADM should be expanded beyond this specific application. Follow-on work should investigate the application of fuzzy

MADM methods to other branches of transportation and traffic engineering such as transportation safety analysis. This will provide decision makers with a structured analytical process to mathematically process both qualitative and quantitative data.

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Appendix A: Application of Fuzzy Sets Theory to Multi-attribute Decision Making

A.1   Introduction

This appendix supplements the information presented in Chapter 4 on fuzzy sets fundamentals used to convert uncertain and imprecise transit signal priority performance measures to triangular fuzzy numbers for use in multi-attribute decision making (MADM) methods.   This information was not included in Chapter 5 to minimize distraction from the main focus of the chapter, which was the development of the techniques to apply fuzzy sets theory concepts to transit signal priority performance characteristics. Section A.2 provides additional details on the theoretical and mathematical fundamentals pertaining to fuzzy numbers, Kaufmann and Gupta's ranking method, and linguistic terms. Section A.3 provides additional information on the weighted sum method (WSM) and the Technique for Ordered Precedence by Similarity to Ideal Solution (TOPSIS).

A.2   Fuzzy Sets Theory Fundamentals

Multi-attribute decision making (MADM) refers to making selections among some course of action in the presence of multiple usually conflicting attributes. Traditional MADM solution methods assume the values for the attributes and weights are crisp numbers.   Real life performance data is often imprecise, uncertain, subjective, and ambiguous. In some instances, performance attributes cannot be numbers, and are represented by linguistic terms such as "good," "average," and "poor." Most real world MADM problems would contain a mixture of fuzzy and crisp data (Chen and Hwang, 1992).

Fuzzy sets theory, originally introduced by Lotfi Zadeh in the1960's, resembles human reasoning in its use of approximate information and uncertainty to generate decisions. Fuzzy sets theory implements classes or groupings of data with boundaries that are not sharply defined (i.e., fuzzy). Any methodology or theory implementing "crisp" definitions such as classical set

theory, arithmetic and programming, can be "fuzzified" by generalizing the concept of a crisp set to a fuzzy set with blurred boundaries (Battelle, 2001).

Fuzzy sets theory is a convenient mathematical device for treating uncertainty, subjectivity, ambiguity and indetermination (Teodorovic, 1994). In this research, fundamental fuzzy sets theory concepts were applied to convert transit signal priority performance measures to fuzzy performance attributes in the form of triangular fuzzy numbers. These fundamental fuzzy sets concepts include: triangular fuzzy numbers, basic operations on triangular fuzzy numbers, the intersection of fuzzy sets, ranking of fuzzy sets, and linguistic terms. In Chapter 5, theoretical and mathematical details pertaining to triangular fuzzy numbers, Kaufmann and Gupta's method for comparing fuzzy numbers, and linguistic terms were deliberately excluded to not divert attention from the explanation of how to apply the fuzzy sets concept to the specific transit signal priority performance attribute. Expansion of these fundamental fuzzy set sets theory concepts follows.

Triangular Fuzzy Numbers

In the classic theory of sets, very precise bounds separate the elements that belong to a certain set from the elements outside the set. For example: element x in set **A** is described by the membership function $\mu_A(x)$ as follows:

$$\mu_A(x) \;=\; \begin{cases} 1, \text{ if and only if } x \text{ is member of } \mathbf{A} \\ 0, \text{ if and only if } x \text{ is not member of } \mathbf{A} \end{cases}$$

Central to fuzzy sets theory is the expression of fuzziness, which is defined by the membership function. For a fuzzy set **A**, the membership function $\mu_A(x)$, represents degree that an element x belongs to set **A**. Fuzzy set, **A**, may take any value from the closed interval [0,1]. Fuzzy set **A** is defined as the set of ordered pairs $\mathbf{A} = \{x, \mu_A(x)\}$, where $\mu_A(x)$ is the grade of membership of the element x in set **A**. The greater $\mu_A(x)$, the greater the truth of the statement that element x belongs to set **A** (Teodorovic and Vukadinovic, 1998). Fuzzy set **A**,

may also be defined as "a set which represents that the travel time between two points in approximately t minutes". For a particular travel time t, the degree of that it belongs to the fuzzy set **A** is expressed by the grade defined in the membership function (Teodorovic and Kikuchi, 1991).

Triangular fuzzy numbers represent a special set of fuzzy numbers. Their name is derived from the shape of their membership function. Figure A-1 shows a typical triangular number **A** = (a_1, a_2, a_3).   Where a_1 is the lower (left) boundary of the triangular fuzzy number, a_2 is the number corresponding to the highest level of presumption, and a_3 is the upper (right) boundary of the fuzzy number. The triangular representation of a fuzzy number allows simple arithmetic operations of the fuzzy number, by specifying only three control points (a_1, a_2, a_3).
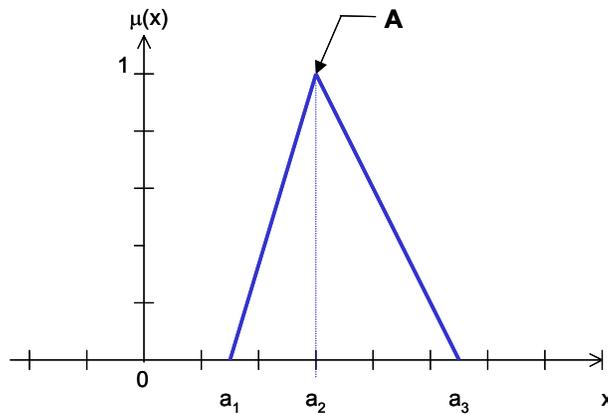
Figure A-1 Membership Function of Triangular Fuzzy Number A

The membership function of **A** is:

$$\mu_A(x) = \begin{cases} 0, & x < a_1 \\ \dfrac{x - a_1}{a_2 - a_1}, & a_1 \le x \le a_2 \\ \dfrac{a_3 - x}{a_3 - a_2}, & a_2 \le x \le a_3 \\ 0, & x > a_3 \end{cases}$$

Kaufmann and Gupta's Method for Comparing Fuzzy Numbers

When fuzzy data are incorporated in the MADM problem, the final ratings are no longer crisp numbers; they are fuzzy numbers. The ranking of fuzzy numbers has been the subject of research that has produced numerous methods or theories. Some 20 ranking methods are classified by Chen and Hwang (1992) in their monograph on fuzzy multiple attribute decision making (Chen and Hwang, 1992). The particular method used in this research is Kaufmann and Gupta's method (Teodorovic, 1994; Teodorovic and Kikuchi, 1991; Teodorovic and Vukadinovic, 1998). This method was selected because of it simplicity. Kaufmann and Gupta's method consists of three progressive steps: (1) comparing removals, (2) comparing modes, and (3) comparing divergences.

Comparing removals

The calculation of the removal of triangular fuzzy number **A** with respect to an ordinary number $k=0$ involves two concepts: left side removal and right side removal as shown in Figure A-1.

The left side removal with respect to an ordinary number, k, $R_l(A,k)$ is defined as the area between k and the left side of the fuzzy number A (shown by the diagonal hatched area in Figure A-2). The right side removal $R_r(A,k)$ is defined by the area between the right side of **A** and k (shown by the hatched area in Figure A-1).
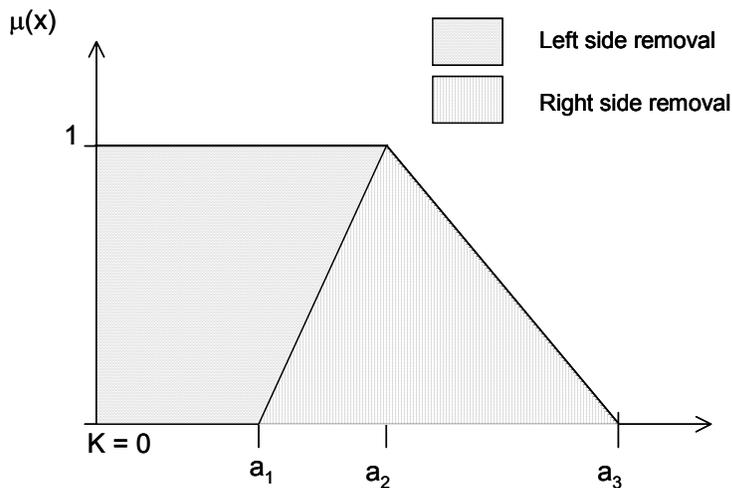
Figure A-2 Fuzzy Number A Removal Compared to Real Number *k*

The removal of the fuzzy number **A** with respect to *k* is defined as:

R(A,*k*) = (0.5)[**R$_l$(A**,*k*) + **R$_r$(A**,*k*)]

When **A** is a triangular fuzzy number, the value of removal takes the form:

R$_A$ = (a_1 + 2a_2 + a_3)/4

The fuzzy number **A** is less than fuzzy number **B** if **R$_A$** < **R$_B$.**

<u>Comparing modes</u>

This step compares the modes of the two fuzzy numbers. The fuzzy number **A** is less than the fuzzy number **B** if the highest grade of membership of **A** is less than that of **B**.

<u>Comparing divergences</u>

This step compares the divergence around the modes (or the support base of the fuzzy triangular number). The fuzzy number **A** is less than fuzzy number **B** if the divergence around the mode of **A** is less than that of **B**.

Linguistic Terms

Fuzzy data can be in the form of fuzzy numbers, fuzzy sets or linguistic terms. Linguistic terms (variables) are critical aspects of some fuzzy sets theory applications. Some attributes can be better described in terms of linguistic terms or variables than by numerical variables. For instance, if cost is one of the attributes, a possible set of linguistic variables include: {extremely expensive, very expensive, …fair,…fairly cheap, …cheap} (Chen and Hwang, 1992). Linguistic terms refer to the use of words or sentences such as "large," "medium," "small" are used to capture a range of numerical values.

Chen and Hwang (1991) first introduced a numerical approximation system that used eight conversion scales to systematically convert linguistic

terms to either crisp numbers or fuzzy numbers (Chen and Hwang, 1992). Yeh and Deng (1997) introduced a conversion scale that converted linguistic terms to fuzzy triangular numbers. Teodorovic and Vukadinovic (1998) presented additional techniques used in subsequent transportation and traffic applications (Teodorovic and Vukadinovic, 1998).

Two techniques are used in Chapter 4. The first used the linguistic preference expressions of "not important," "important," and "very important" to represent stakeholder preferences. The membership functions of these three linguistic expressions based on the technique described by Yeh and Deng (1997) are shown in Figure A-3 (Yeh et al., 2000). In this way, the linguistic expression "not important" becomes (0,0,5); the linguistic expressions "important" becomes (0,5,10); and "very important" becomes (5,10,10).
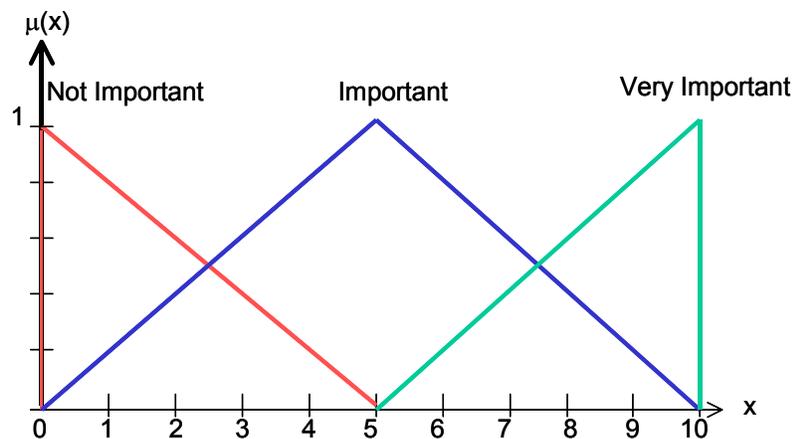
Figure A-3 Membership Function of "Not Important," "Important," and "Very Important"

The second technique used a two-step process that first converts performance variables to linguistic terms that in turn are converted to triangular fuzzy numbers.   In the first step, the linguistics terms "minimal," "moderate," and "significant" were used to describe the impact of volume to capacity ratio. These terms were derived from expert knowledge and represent subjective evaluations of the impact. Figure A-4 illustrates the conversion scale used.
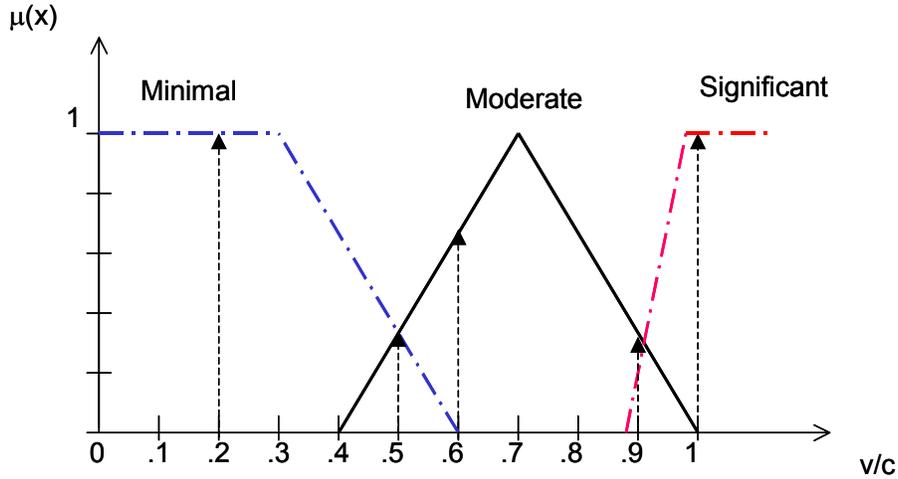
Figure A-4 Membership Function for Cross Street Non-Transit Delay

In the second step, the linguistic variable is converted to a triangular fuzzy number using the conversion scale shown in Figure A-5. This converted this set of performance measures to triangular fuzzy number that could be used in the MADM method.
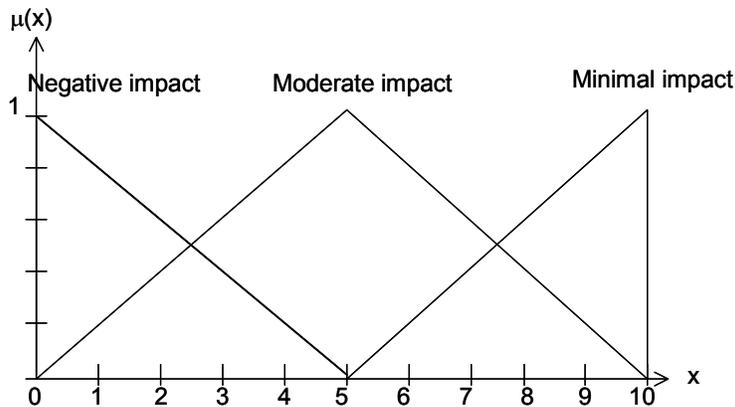
Figure A-5 Membership Functions of "Negative Impact," "Moderate Impact," and "Minimal Impact"

A.3   Fuzzy Multi-attribute Decision Making Methods

Fuzzy MADM methods are MADM methods that solve problems, which involve fuzzy data. Chen and Hwang (1991) published the monograph entitled "Fuzzy Multiple Attribute Decision Making: Methods and Applications" which provided a state-of-the art survey of methods that solve fuzzy MADM problems

and their applications. Over two dozen fuzzy ranking methods were reviewed and over a dozen fuzzy MADM methods were presented.

This research uses two fuzzy MADM methods, the fuzzy WSM and the fuzzy TOPSIS, to rank order the transit signal priority alternatives. A summary description of these two methods follows.

Fuzzy Weighted Sum Method

The fuzzy WSM is based on the simple additive weighting method (SAW). The WSM is the best known and most widely used MADM method mainly because it is simple to use and understand. The method requires the attributes to be non-complementary. In this method, the overall score of an alternative is computed as the weighted sum of the attribute values. The procedure is straightforward:

(1) for each alternative, compute a score by multiplying the rating of each attribute by its importance weight and summing these products over all attributes.

(2) Select the alternative with the highest score. Mathematically,

$$A^* = \left\{ A_i \middle| \max \sum_{j=1}^{N} x_{ij} w_j \middle/ \sum_{j=1}^{N} w_j \right\}$$

Where x_{ij} is the outcome of the ith alternative about the jth attribute, and w_j Is the importance weight of the jth attribute.

Since the fuzzy WSM uses triangular fuzzy numbers for attributes and weights, the final results are triangular fuzzy numbers. To rank order these results require the use of fuzzy ranking methods to determine the highest ranking alternative. In this research, Kaufmann and Gupta's method, described previously, is used to rank these fuzzy numbers.

Fuzzy Technique for Ordered Precedence by Similarity to Ideal Solution

The Technique for Ordered Preference by Similarity to Ideal Solution (TOPSIS) was developed by Hwang and Yoon in 1981 based on the concept that

the preferred alternative should have the shortest distance from the ideal solution and the farthest distance from the negative-ideal solution in a geometric (Euclidean) sense. The procedure consists of six steps:

Step 1 Construct the normalized decision matrix

Step 2 Construct the weighted normalized decision matrix

Step 3 Identify the positive-ideal and negative-ideal solutions

Step 4 Calculate the separation measures

Step 5 Calculate the relative closeness to the ideal solution

Step 6 Rank the alternatives

The fuzzy version of TOPSIS uses triangular fuzzy numbers for attributes and weighting. Illustrative examples to demonstrate fuzzy TOPSIS are presented by Triantaphyllou and Lin (1996) and Teodorovic and Vukadinovic (1998). Basic arithmetic operations on fuzzy triangular numbers are defined as follows:

Addition: $A (+) B = (a_1, a_2, a_3) + (b_1, b_2, b_3) = (a_1 + b_1, a_2 + b_2, a_3 + b_3)$

Subtraction: $A (-) B = (a_1, a_2, a_3) - (b_1, b_2, b_3) = (a_1 - b1_3, a_2 - b_2, a_3 - b_3)$

Division: $A (\div) B \cong (a_1, a_2, a_3) \div (b_1, b_2, b_3) = (a_1/b_3, a_2/b_2, a_3/b_1)$

Natural logarithm: $\ln (A) \cong (\ln (a_1), \ln (a_2), \ln (a_3))$

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Appendix B: TRB Paper

This appendix contains the paper entitled: Evaluating the Impacts of Advanced Traffic Signal Control Systems: The Effect of Transit Signal Priority Strategies on Transit Operating Costs." This paper was submitted and accepted for presentation at the 2004 Annual Meeting of the Transportation Research Board and published in the Compendium of Papers CD-ROM.

This paper presents an overarching evaluation framework to assess the efficiency and cost effectiveness of advanced traffic signal control systems capable of emergency vehicle preemption and transit priority and presents an analytical approach to assess the impact of reduced transit travel time on transit operation and maintenance cost.

The paper identifies the many recipients of an integrated emergency vehicle preemption and transit priority system. They include the general public, transit riders, non-transit users, fire and rescue service providers and transit operators. These recipients are the system stakeholders.

Also presented is the notion of distributing investment costs and operating costs among three entities: the owner of the traffic signal system, fire and rescue service providers, and transit operators. These three entities are separate functions with separate missions and usually make investment decisions independently from each other. Treating integrated emergency vehicle preemption and transit signal priority as a system provides planners and managers a different perspective for economic analysis for investment planning.

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Evaluating the Impacts of Advanced Traffic Signal Control Systems: The Effect of Transit Signal Priority Strategies on Transit Operating Costs

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ABSTRACT

An overarching evaluation framework has been developed to assess the efficiency and the cost effectiveness of advanced traffic signal control systems that can provide emergency vehicle preemption and transit priority capabilities. In addition, an analytical approach within this framework has been included that assesses the impact of reduced transit travel time on transit operating and maintenance costs. This methodology is intended to assist traffic managers, planners, engineers and other professionals in evaluating the impacts of integrated emergency vehicle preemption and transit priority systems. Initial application of the methodology indicates that the values for both efficiency and cost effectiveness of the adopted transit priority strategies and preferential treatment solutions are a function of many variables, such as the magnitude of transit travel time delay; the transit fleet size, the labor rules; the apportionment of preemption and priority system costs among transit operators, emergency service providers and the municipality; and the cost of money.

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INTRODUCTION
Background
Urban congestion is a major problem across the United States. In many of our Nation's cities, the congested peak travel periods are normally three to four hours in duration. This phenomenon increases commuter travel time, contributes to reduced air quality, increases noise pollution, adds to driver stress, and impacts the ability of municipalities to provide efficient and timely essential public services such as fire and rescue services and public transit.

Intelligent Transportation Systems (ITS) can help ease this strain through the application of modern information technology and communications to improve the transportation system to make it more effective, efficient and safer (*1*). Advanced traffic signal control is an ITS application that can potentially ameliorate the impacts of congestion. Traffic signal systems can be adapted to provide preferential treatment for emergency vehicles and qualified transit vehicles in the form of emergency vehicle preemption and transit priority. Advances in microcomputer and communications technologies are making it possible for many jurisdictions to use advanced traffic signal controllers and vehicle detection technology to accommodate both emergency vehicle preemption and transit priority strategies.

Emergency vehicle preemption unconditionally interrupts the normal signal operation process to facilitate the safe passage of emergency vehicles by providing a green signal in the direction needed by the emergency vehicle. This will potentially reduce response time, emergency personnel stress, and possible crashes involving emergency vehicles (*2*). Emergency vehicle preemption has been widely deployed in the U.S. and abroad. Experience from these deployments have demonstrated increased safety and reduced response time to emergencies (*3*). Emergency vehicle preemption enjoys universal support for deployment because virtually everybody understands the need for fast response to an incident, when lives are at risk.

Transit priority modifies the normal signal operation process to move qualified transit vehicles through signalized intersections. The objective of transit priority is to improve transit efficiency and improve rider convenience. Experience from deployments in Europe and the U.S. indicate transit priority can potentially improve transit travel time, increase service reliability and reduce bus driver stress with minimal impact on other traffic (*4*).

Problem Identification
The benefits of transit priority are simple to enumerate: i) decrease transit travel time to reduce emissions; ii) improve transit operational efficiency to reduce costs; iii) and improve service reliability to attract more riders. A collateral benefit may be increased transit ridership, which could reduce automotive usage and emissions. Unfortunately, transit priority does not enjoy the level of support enjoyed by emergency vehicle preemption. Elected officials are not supportive and the public is ambivalent (*5*). Some transit agencies and city traffic engineers are resistant to implementing transit priority. Implementation barriers include institutional issues, operational issues, and human factors issues (*6*). Major concerns of elected officials and transportation professionals include potential negative impacts on traffic and concerns on cost effectiveness (*7*).

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The potential impacts of transit priority on traffic can be derived from operational experience and from analytical modeling. Experience from operational tests and from simulation applications in the U.S. and abroad indicate that side street impact is minimal and in most cases, traffic traveling in the same direction of the bus receiving priority also experience reduced travel times *(4)*. For planned deployments, simulation tools such as VISSIM, INTEGRATION, CORSIM, PARAMICS and MITSIM have been used to assess impacts such as side street delay and total delay model along potential corridors *(8)*.

Limited work has been reported in the literature on the economic impact of transit signal priority strategies on transit operating cost from a **cost effectiveness** perspective. The question is - "can we afford to implement transit priority?" Traditional Benefit/Cost (B/C) analysis provides a framework for the comparison of alternatives in order to make rational choices. It assesses the **efficiency** of a project and answers the question, "are total net benefits received by society as a whole greater than the project costs?"*(9)*. In a fiscally constrained environment operating agencies are concerned about financial feasibility or **cost effectiveness.** There is a requirement for a simple evaluation approach to assess whether the implementation of transit priority will produce sufficient benefits to justify the investment.

The purpose of this paper is to present an overarching evaluation framework to assess the efficiency and cost effectiveness of advanced traffic signal control systems that are capable of providing emergency vehicle preemption and transit priority; and to present an analytical approach within this framework that assesses the impact of reduced transit travel time on transit operating and maintenance costs. The applicability of the framework and analytical approach will be demonstrated using results from an on-going Virginia Tech/Virginia Department of Transportation (VT/VDOT) emergency vehicle preemption and transit priority operational field test along U.S. 1.An underlying aim of this analytical approach is to aid in the assessment of the potential impact of integrated emergency vehicle preemption and transit priority systems on transit operating and maintenance costs, and thus facilitate the investment planning and decision-making by transit agencies..

LITERATURE REVIEW
 The review of literature is presented under two categories: (1) economic analysis of ITS investments with an emphasis on financial feasibility analysis and (2) travel time impacts of various transit priority strategies.

Economic Analysis
Transit Cooperative Research Program Report 78 entitled "Estimating the Benefits and Costs of Public Transit Projects: A Guidebook for Practitioners" provides an analytical framework that helps transit planners at all levels of government to evaluate transit investments. It groups impacts into five categories: (1) travel impacts; (2) environmental impacts, (3) impacts on economic development, (4) land use and development impacts, (5) distribution of transit impacts *(10)*.

The Federal Highway Administration developed the spreadsheet analysis tool SCRITS (**SCR**eening for **ITS**), to allow practitioners to obtain an initial indication of the possible benefits of various ITS applications. SCRITS contains 16 different ITS

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applications. One of them is Signal Priority Systems for Buses. This SCRITS application focuses on two elements: time savings for buses that are given priority and additional delay for side street traffic. SCRITS is intended as a sketch-level or screening-level analysis tool because there is a great deal of uncertainty regarding the effects of ITS applications. The answers produced by SCRITS are approximate and are recommended for general planning purposes only *(11)*.

Khasnabis, Rudraraju and Baig, suggested a variation of benefit-cost-analysis in which the maximum possible investment for a transit priority project is set by the magnitude of passenger delay savings. They determined, through simulation, that passenger delay savings was significantly large enough, to offset the maximum investment threshold *(12)*.

Lee and Carroll presented a practical and intuitive benefit-cost evaluation framework to evaluate ITS projects that includes benefits accrued to transit users, other users and transit providers. This framework linked potential impacts to actions in an A-causes-B-causes-C series of impact linkages. Algorithms were developed to bind the range of magnitude of each of these linkages and their dollar validations. Spreadsheet models were used to compute the total benefits and costs *(9)*.

Morlok, Brunn and Blackman introduced how a transit agency might evaluate the feasibility or the desirability of an ITS project as a subset of a comprehensive benefit-cost evaluation approach *(13)..* They posited that if an evaluation demonstrated that the ITS project was desirable from a purely financial perspective; it would be even more desirable from a more comprehensive perspective. The bus transit cost model, a widely used and accepted model for the total cost of operating a bus fleet, was adapted to relate the investment cost to a change in transit operating cost. That model is presented in equation 1:

$$\text{Investment Cost} = A(\text{Revenue-hr}) + B(\text{Revenue-mi}) + C(\text{Fleet size}) \qquad (1)$$

where:

A = Unit cost associated with revenue-hours
  = (Vehicle operations expense %) x (Total expense)/ (Total Revenue-hours);
B = Unit cost associated with revenue-miles
  = (Material & utilities per vehicle-mile) + (Vehicle maintenance per vehicle-mile);
C = Unit cost associated with fleet size
  = [(Non-vehicle maintenance %) + (General admin %)] x (Total expense/fleet size) +
  (bus cost) x (CRF);

Traffic Priority Strategies
Preferential treatments are used to improve transit system performance. They include transit priority, infrastructure improvements, and new equipment acquisitions. Transit priority modifies traffic signals to move qualified buses through signalized intersections. Infrastructure improvements include bus stop relocation, bus stop consolidation, bus only exclusive lanes, and curb extensions. New equipment acquisition solutions include low floor buses, electronic fare collection, automatic vehicle locators, and passenger counters. Determining the proper combination of preferential treatment solutions that can produce the most effective and efficient transit priority system requires a detailed analysis and assessment of operational impacts.

There are two classes of transit priority strategies, passive priority and active priority *(14)(15)*. Passive priority strategies use static signal settings to favor transit vehicles to reduce delay to transit passengers. Common passive priority strategies include: preprogrammed signal timing of coordinated signals at average transit vehicle speed instead of average automobile speed, reducing cycle length along transit corridors, increasing green time along the transit route, and providing transit by-passes at metering locations. Unfortunately, passive priority strategies typically make the intersection operate less efficiently overall.

In contrast, active priority strategies dynamically alter signal settings only when necessary, making real time signal timing adjustments to minimize delay to approaching transit vehicles. Active priority strategies require devices to detect transit vehicles approaching the intersection, advanced traffic signal controllers to alter the signals and a communication link between the traffic signal controller and transit vehicles. Signal phases are modified upon detection of the transit vehicle. Active priority strategies are further classified into two types: conditional and unconditional. Conditional priority grants priority status based on criteria such as lateness of the vehicle relative to its schedule and passenger load. Unconditional priority gives priority status to every transit vehicles detected.

The four basic active transit priority strategies are: green extension, red truncation, phase insertion, and queue jump. **Green Extension** extends the duration of the green phase time to allow a qualified bus to clear an intersection. Upon request from a qualified bus, additional green time up to a preset maximum (usually 10 seconds) is "borrowed" from the side street. As a result, side street traffic will experience a longer red interval. **Red Truncation** shortens the red phase to expedite the return to green. Upon request from a qualified bus, an early green is provided after meeting minimum cross street green times (such as pedestrian crossing time). Again, the green time is "borrowed" from the side streets. **Phase Insertion** inserts a green phase into a red phase to provide a bus early entry into the traffic flow with the controller returning to normal operations once the bus has cleared. Finally, **Queue Jump** provides buses an exclusive phase to by-pass queues at signalized intersection.

Travel Time Impacts of Transit Priority Strategies
The City of Portland performed a detailed operational analysis of the effect of transit preferential strategies on five corridors. They found that on the average, only 34% of the total bus travel time was attributable to driving. The remaining 66% was distributed as follows: 22% at traffic signals, 16% at bus stops, and 28% in traffic congestion *(16)*. These results are consistent with findings from Wilshire and Whittier Boulevards in Los Angeles where traffic signal delay was 20% and bus stop delay was 25% *(17)*. These results suggest that the maximum transit travel time reduction attainable by transit priority alone is in the order of 20%.

A limited number of past deployments and computer simulations were analyzed to assess the travel time impact of various transit priority strategies. Evaluating travel time impacts of transit priority strategies is hard to accomplish. Because most transit priority projects have only been deployed in the U.S. within the past few years, and the results from operational evaluations are not applicable across the board since performance measures are not well defined in a standardized framework and the used

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terminology is not consistent. In some cases, combinations of several preferential treatments were simultaneously implemented making it difficult to isolate the impact of a particular transit priority strategy. Additionally, the degree of impact is influenced by the specific conditions of the corridor. These conditions may include: frequency and direction of travel for vehicles requesting priority, roadway characteristics, travel demand, presence and frequency of pedestrian phases, transition strategy, cycle characteristics, and intersection spacing and progression strategy *(18)*. Results from this assessment are presented in TABLE 1. Because the underlying data is collected from various sources, using different measurement standards, and under different traffic conditions, caution should be exercised in interpreting and applying these results. However, these results provide a rough order of magnitude estimate that can be used as a benchmark for the expected outcomes of various strategies. These results suggests the following:

(1) Signal optimization should be a part of any transit priority project.
(2) Transit travel time reduction is greatest when a combination of strategies is utilized and each intersection is optimized according to its specific characteristics.
(3) Transit time reduction from deployments is greater than those projected by computer simulations, which indicates that simulations may provide conservative estimates.

EVALUATION FRAMEWORK
Advanced traffic signal control systems can provide preferential treatment to both emergency vehicles and buses. Emergency vehicles can use high priority requests for preemption while buses use the low priority requests for priority. Today there is not a simple evaluation framework and analytical approach available to assess the efficiency and cost effectiveness of advanced traffic signal control systems using emergency vehicle preemption and transit priority strategies.

An advanced traffic signal control evaluation framework that links system preemption and priority functionalities to performance impacts is presented in FIGURE 1. The framework follows a systems approach and draws from an analytical framework presented in past work for estimating the impacts of public transportation projects *(10)*. The framework groups impacts into the five categories as shown on the right hand side of FIGURE 1. The system will be assessed from three perspectives: the impact of emergency vehicle preemption, the impact of transit priority and the combined effects of both. A comprehensive benefit-cost analysis would evaluate all five impacts. This paper will focus on travel impacts because they are the most significant.

Expected Impacts
The travel impacts of emergency vehicle preemption are shown in FIGURE 2. Preemption permits emergency vehicles to travel at a higher rate of speed. This can reduce emergency vehicle travel time and potentially save lives, reduce injury, and minimize physical damage. This can also potentially reduce crashes involving emergency vehicles and reduce accident costs *(3)*. However, recovery from preemption may disrupt the normal traffic flow in all directions. This could potentially increase travel times for non-transit and transit users.

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The possible travel impacts of transit priority are shown in FIGURE 3. Transit priority may reduce bus delays at signalized intersections. The resulting transit travel time reduction could potentially benefit transit operators by reducing operating costs. Transit passengers may benefit by spending less time traveling. Traffic in the direction of priority may benefit from the additional green time, while traffic on cross streets may experience some delay. Lastly, transit priority may improve bus service reliability, a key measure transit agencies use to assess route performance *(19)*. Improved schedule reliability may improve the quality of transit service and potentially increase ridership *(20)*.

Logical rules, based on preemption recovery strategies, contribute to the severity of the impact of emergency vehicle preemption on transit priority operations. For instance, if the recovery strategy is to return to normal operations in five cycles, then transit signal priority may not be granted until the sixth cycle. Thus, frequent preemption calls may reduce anticipated transit travel time reductions.

TABLE 2 illustrates the distribution of system impacts. Beneficiaries include the general public, transit passengers, non-transit users, emergency service providers and transit operators.

Analysis of Impacts

An assessment of financial feasibility examines the impact of reduced transit operation and maintenance (O&M) costs and whether that reduction is sufficient to warrant the investment costs. It answers the question "can we afford to do this investment". Ideally, operating cost and capital cost savings should cover the cost for the improvement. A simple three-step spreadsheet model to determine financial feasibility is presented in TABLE3.

Step 1 computes the operating cost savings based on the total transit travel time reduction using the simple relationship:

$$\Delta \text{Operating Cost} = (A+BY)(\Delta \text{Revenue-hr}) \qquad (2)$$

where Y= Revenue hr/Revenue-mi

The coefficients A, B and Y can be determined using data from the transit agency's operational database or estimated using data from the National Transit Database and the National Transit Summaries and Trends Report. *(21)(22)*. Average operating cost per vehicle revenue-hour, and vehicle revenue-miles can be found in the National Transit Profile. Annual vehicle revenue miles and vehicle revenue hours, and total operating expenses for a select number of transit agencies can be found in Table 28 and Table 31 of the National Transit Database. The average values of expense functions (vehicle operations, vehicle maintenance, non-vehicle maintenance, and general administration), and object class (salaries, fringe benefits, services, materials and supplies, utilities, and other) can be found in Tables 11 and 12 of the National Transit Database. .

Revenue-hr savings for a particular bus corridor can be determined by using:

$$\Delta \text{ revenue-hrs} = \sum_{i=1}^{n} (N_i)(TTT_{ib} - TTT_{ia}) \qquad (3)$$

where: N_i = number of trips on route n.

TTT_{ib} = transit travel time on route n before priority.

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TTT_{ia} = transit travel time on route n after priority.

Step 2 computes the investment costs and annual costs associated with this deployment. The capital costs can be subdivided into two categories: roadside equipment such as detectors, controllers, and onboard equipment such as emitters. A capital cost model that can be used for both categories is *(23)*:

$$TCC = [(\sum_{i=1}^{n} (UC_i)(q_i))(1+x_{PS} + x_{IC} + x_{ESPM})] (1 + y_C) \tag{4}$$

where: TCC = Total capital costs;
UC_i = unit cost of nth equipment ;
q_i = quantity of nth equipment;
x_{PS} = non-recurring parts and services expressed as percent of the equipment costs;
x_{IC} = non-recurring installation and construction costs expressed as percentage of the equipment costs;
x_{ESPM} = non-recurring engineering, software and project management costs expressed as percentage of the equipment costs;
y_C = contingency costs

Determining cost estimates for advanced traffic signal control systems is complicated for a number of reasons. First, the technology is relatively immature so there is a lack of a universal standard, and competing manufacturers have different cost structures. Second, desired system functionalities will impact cost; thus, a complex system will cost more. Third, the existing traffic signal control system may be inadequate to execute preferential treatment. Replacement will increase implementation cost. And, fourth there is a paucity of published information on the costs of operational deployments. Data from deployments indicate per-intersection costs range from \$5,000 to \$11, 000 *(24)*.

Step 3 provides the result of two assessments methodologies: payback period analysis, and net present value analysis. Payback period analysis evaluates how quickly the investment can be recovered based on savings in operating costs associated with the transit priority system. The formula for payback period analysis is *(23)*:

$$x = TCC/[(Operating\ cost)*(\Delta Revenue\text{-}hrs) - (O\&M\ costs)] \tag{5}$$

where: x = payback period
TCC = Total capital cost

Net present value analysis evaluates the time required to recover the investment cost based on operating costs savings taking into account the compounding interest of money. An interest rate of 7% is used. The number of years required to recover the investment can be found by first determining the capital recovery factor (CRF) *(23)*:

$$CRF = [(Operating\ cost)*(\Delta Revenue\text{-}hrs) - (O\&M\ costs)]/(TCC) \tag{6}$$

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And then determine number of years using the CRF at the 7% interest rate in the standard interest tables.

TABLE 3 presents an illustrative assessment of a ten-mile long bus route with ten signalized intersections that is being serviced by 30 buses during the peak periods. The displayed operating cost parameters represent average bus operations values extracted from the 2001 National Transit Database. In addition, bus travel times of 35 minutes and potential transit travel time reduction of 9% (average travel time reduction for green extension and /or red truncation combination strategy) are used. Investment costs are assumed to be $8,000 per intersection (average value for the range) and $750 per emitter. The results indicate a payback period of 3 years and capital recovery period of 3.4 years.

CASE STUDY: U.S. ROUTE 1 NORTHERN VIRGINIA
Virginia Tech in collaboration with George Mason University and supported by the Washington Regional Council of Governments and the Virginia and Maryland Departments of Transportation has been conducting an operational field test to assess the impact of deploying an advanced traffic signal control system capable of emergency vehicle preemption and transit priority along U.S. 1 from the Prince William Country Line to I-495 in Northern Virginia. U.S. 1 is a major arterial that carries over 2700 vehicles per hour as it winds along one of the most densely populated areas in Northern Virginia. Two transit agencies operate four bus routes and three fire and rescue facilities provide emergency service along the corridor.

The operational test site is a 1.3-mile long segment of U.S. 1 that includes seven signalized intersections. It is located within close proximity to a Washington Metropolitan Area Transit Agency (WMATA) terminal subway station, a natural trans-loading point, and along the travel route of one the fire companies that provide emergency services to the community. As part of the study, 3M Opticom systems were installed at the seven signalized intersections within the test site and pole-mounted video cameras were positioned to record traffic conditions.

VISSIM, a microscopic, time-based, and behavior based simulation tool was used to model the impacts of a 10 second green extension and unconditional priority strategy along this site. This followed VDOT guidance to minimize potential disruption to vehicular traffic flow. The model was calibrated using 2002 weekday peak hour traffic data from SYNCHRO data supplied by VDOT, and operational site characteristics (traffic speed, control delay and number of stops) obtained using the "floating car" technique. Data on bus service reliability (measured as the standard deviation of elapsed time between end points), bus service efficiency (measured as the average run time between end points), and queue lengths on side streets (measured queue length) were obtained. Results from 30 pairs of "before" and "after" simulations indicated bus service reliability increased by 3.6%, bus travel time decreased by 2.64%, and side street queue length increased by less than one car length *(25)*.

These results were extrapolated to assess the financial feasibility of deploying an advanced traffic signal control system along a 13-mile long 22-intersection corridor under three investment cost allocation scenarios. FIGURE 4 depicts the trace of that corridor and the location of the test site within the corridor.

The distribution of benefits shown in TABLE 2 suggests that apportioning the investment costs of an integrated emergency vehicle preemption and transit priority system among the municipality, emergency service providers, and transit providers is appropriate. Three funding allocation cases were considered:

Case 1: The transit agency pays 100% of the roadside equipment cost. This represents the tradition method of analysis in which the transit provider assumes the cost of the system.

Case 2: The transit agency shares the cost of the roadside equipment with the emergency service providers. This recognizes the shared nature of an integrated system.

Case 3: The County or VDOT pays the cost of the roadside equipment. The emergency service provider and the transit provider would cover the cost to connect to the system and their share of the O&M costs.

Operational experience and simulations suggests that the choice and combinations of transit priority strategies will impact transit travel time reductions. TABLE 1 results indicate that strategies that employ combinations of green extension, red truncation and queue jump provide progressively better transit travel time reductions. This in turn would impact the payback period. FIGURE 5 shows the impact on payback period as a result of increased transit travel time reductions. Model inputs used Fairfax Connector Transit operating costs from the 2001 National Transit Database; route times from Fairfax Connector bus schedules, measured route lengths, and actual test site investment costs. FIGURE 5 suggests there are threshold levels from a payback period perspective where the incremental improvement may not be worth the incremental cost. For example: for Case 1 a payback period of 11 years can be realized with a transit travel time reduction of 10%. That same payback period can be realized with a transit travel time reduction of 7% for Case 2. In Case 3 a payback period of less than 3 years can be realized with a transit travel time reduction of 8%. This suggests that modest transit travel time reductions may be sufficient to justify the investment depending on the strategy (e.g., green extension only versus a combination of green extension and/or red truncation) and the financial apportionment scheme chosen.

CONCLUSIONS AND RECOMMENDATIONS

The impact of transit priority strategies on transit operating costs is influenced by a number of variables**.** First consideration is the impact various combinations of green extension, red truncation, queue jump, and phase insertion have on transit travel time. Next is the impact of simultaneously implementing other possible preferential treatment solutions. Third, the number of buses on a route must be sufficient to provide the necessary revenue-hrs to make a difference. Since driver salaries determine operating costs per revenue hr, labor rules will play a significant role in transit operating costs.

How the investment cost is apportioned is also an important consideration. Cost sharing of investment costs would reduce the cost to both service providers. In addition to the obvious fiscal advantage, an integrated system would capitalize on the popular support for the deployment of emergency vehicle preemption systems. Since the major beneficiary of the emergency vehicle preemption and transit priority is among the general population, a case can be made for the municipality to treat the advanced traffic signal controller system as an upgrade to the existing traffic signal system. The service

providers will bear the cost of connecting to the system and their share of the annual operating and maintenance cost.

The evaluation framework and the first part of a four-part analytical approach presented in this paper represent initial results from research at Virginia Tech on integrated emergency vehicle preemption and transit priority traffic control systems. The evaluation framework and four-part analytical approach will become the basis of a decision support system that is under development. The purpose of that decision support system is to provide transportation planners and engineers, and other professionals a standardized framework to evaluate the impacts of emergency vehicle preemption and transit priority for investment decision-making purposes.

Recommendations for further research include: (1) expanding VISSIM modeling to the entire 13-mile 22 intersection corridor to obtain a better estimate for transit travel time impacts, (2) use VISSIM to examine the impacts of green extensions greater then 10 seconds, and (3) explore the application of fuzzy inference (fuzzy decision-making) techniques and linguistically formulated expert knowledge in the selection of transit priority strategies at intersections to overcome the imprecise nature of transit priority strategies and their uncertain consequences on traffic flow *(26)*.

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TABLE 1 Transit Priority Strategy Impacts

| Strategy	Deployment	Simulation
Signal Optimization	2% - 5% [1][2][3]	None
Green Extension Only	0% - 9.7% [2][3][4]	0% - 6% [4][15][16][17][18]
Red Truncation Only	None	1% - 10.6% [18]
GE + RT	1.4% - 20% [1][2][3][4][5][6][7][8][9]	1.6% - 14.2% [4][18]
GE + RT + Queue Jump	0% - 18% [10][11][12]	None
Combinations	1.8% - 28% [3][7][11][13][14]	2.7% - 17.6% [18][19]

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Adapted from
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FIGURE 1 Advance Traffic Signal Control Evaluation Framework
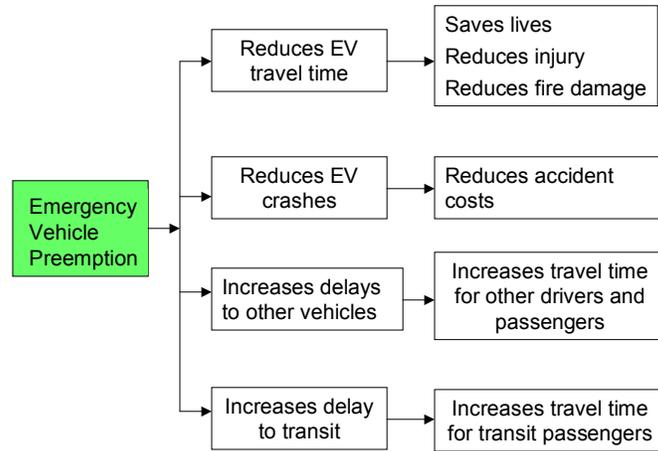
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Adapted from
Lee, D. & Carroll, A., *Benefit-Cost Evaluation of a Highway-Railroad Intermodal Control System, January 2003 (9)*

FIGURE 2 Emergency Vehicle Preemption Travel Impacts
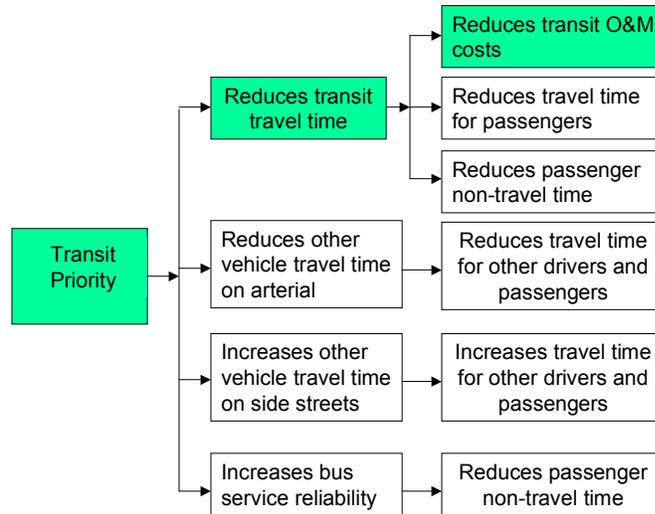
Adapted from
Lee, D. & Carroll, A., *Benefit-Cost Evaluation of a Highway-Railroad Intermodal Control System, January 2003 (9)*

FIGURE 3 Transit Priority Travel Impacts

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TABLE 2 Emergency Vehicle Preemption and Transit Priority System Impact Distribution

Impact	Recipient
Saves lives, reduces injury, reduces fire damage	General public
Reduces accident costs	Emergency service provider
Increases travel time for other drivers and passengers	Motorist
Increases travel time for transit passengers	Transit passengers
Reduces transit O&M costs	Transit operator
Reduces transit passenger non-travel time	Transit passengers
Reduces transit passenger travel time	Transit passengers
Reduces travel time for other drivers on arterial	Motorist
Increases travel time for drivers on side streets	Motorist
Reduces passenger non-travel time	Transit passengers

TABLE 3 Transit Operating Cost Module

| | 2001National Average | |
	Input	Output
Step 1		
Operating cost parameters		
Operating expense per vehicle revenue-hr	$82.79	
vehicle revenue-hrs (millions)	2452.4	
vehicle revenue-miles (millions)	1821.2	
material and utilities ($millions)	$128.5	
vehicle maintenance ($millions)	$238.1	
vehicle operations %	0.60	
Y = (revenue-hrs)/(revenue-miles)		1.35
A = (vehicle operations %)*(operating expense/veh-hr)		$50.07
B = (mat & Util + veh maint)/(vehicle revenue-miles)		0.20
BY		0.27
(A+BY)		$50.34
Revenue hour savings		
Miles on which priority treatment is implemented	10	
Number of buses per weekday during peak period	60	
bus travel time (minutes)	35	
Annual revenue hrs		8750.00
Estimated bus travel time savings	0.09	
Δ Revenue hours		787.50
Operating cost savings		
operating cost savings = (A+BY)*(Δ revenue-hrs)		$39,644.68
Step 2		
Determine investment cost		
Roadside equipment		
Cost per intersection	$8,000	
Number of intersections	10	
Roadside equipment cost		$80,000
Onboard equipment cost		
Cost per emitter	$750	
number of buses	35	
Onboard equipment cost		$26,250
Determine annual system costs		
Annual O&M costs	$3,000	
Other	$500	
Annual system cost		$3,500
Step 3		
Financial Feasibility Assessment		
payback period (yrs)		
(Total investment cost)/Annualized savings		2.94
number of years @ 7% interest		
Capital Recovery Factor =		0.3402
(operating cost)(Δ Revenue hours) - System O&M		
Total Investment cost		
determine n from 7% interest table		3.4

Adapted from: Washington Metropolitan Area Transit Authority Virginia Metrobus Service Map

FIGURE 4 U.S. Route 1 Northern Virginia Case Study Corridor
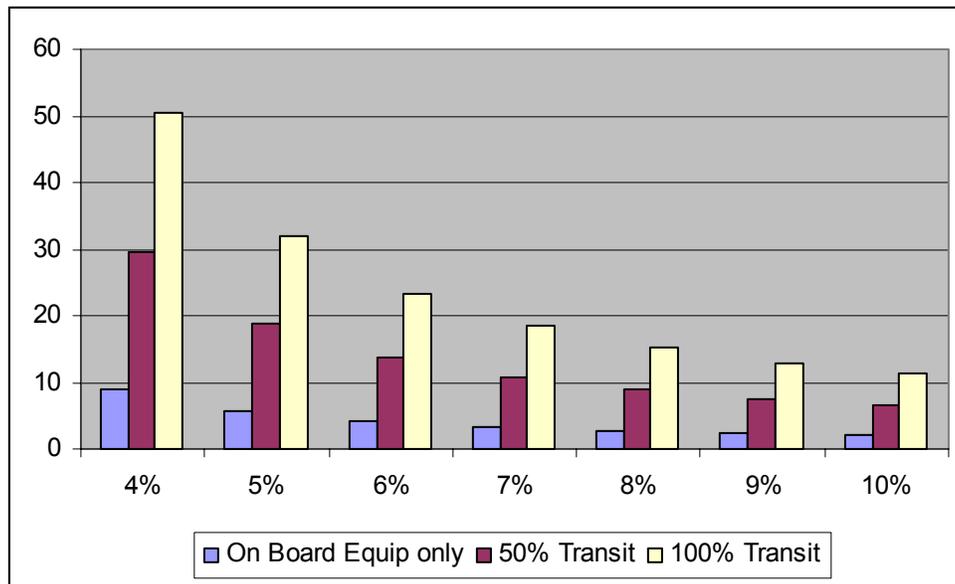
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Inputs:
Operating Costs parameter (A+BY) = $35.20
Annual Revenue-hrs = 4375 hrs
Roadside Investment Costs = $5,000/Intersection x 22 Intersections = $110,000
Onboard equipment costs (transit) = $750/vehicle x 32 transit vehicles = $24,000
Annual O&M costs = $3,500

FIGURE 5 Impact of Transit Travel Time Reductions on Pay Back Period

Appendix C: ITSA Paper

This appendix contains the paper entitled: An Analytical Framework for Evaluating the Impacts of Advanced Traffic Signal Control Systems for Emergency Vehicle Preemption and Transit Priority." This paper was submitted and accepted for presentation at the 2004 Annual Meeting of the Intelligent Transportation Systems of America and published in the Journal of Proceedings.

This paper presents an overarching evaluation framework to assess the efficiency and cost effectiveness of advanced traffic signal control systems capable of emergency vehicle preemption and transit priority. Two analytical approaches are presented to assess: (1) the impact of reduced emergency vehicle crashes at signalized intersections on fire and rescue operation and maintenance costs; and (2) the impact of reduced transit travel time on transit operating and maintenance cost.

The paper identifies the recipients of integrated emergency vehicle preemption and transit priority system. They include the general public, transit riders, non-transit users, fire and rescue service providers and transit operators. They are the system stakeholders.

Also presented is the notion of distributing investment costs and operating costs among three entities: the owner of the traffic signal system, fire and rescue service providers, and transit operators. These three entities are separate functions with separate missions and usually make investment decisions independently from each other. Treating integrated emergency vehicle preemption and transit signal priority as a system provides planners and managers a different perspective for economic analysis for investment planning.

An Analytical Framework for Evaluating the Impacts of Advanced Traffic Signal Control Systems for Emergency Vehicle Preemption and Transit Priority

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ABSTRACT

The purpose of this paper is two fold: (1) to present an overarching evaluation framework to assess the efficiency and the cost effectiveness of advanced traffic signal control systems that can provide emergency vehicle preemption and transit priority capabilities; (2) to present two parts of a four-part analytical approach within this framework that assess: (a) the impact of reduced emergency vehicle crashes on fire and rescue operation and maintenance costs; and (b) the impact of reduced transit travel time on transit operating and maintenance costs. This methodology is intended to assist traffic managers, fire and rescue providers, planners, engineers and other professionals in evaluating the impacts of integrated emergency vehicle preemption and transit priority systems. Initial results indicate: (1) that emergency vehicle preemption has the potential to reduce fire and rescue operational and maintenance costs; and, (2) that the values for both efficiency and cost effectiveness of the adopted transit priority strategies and preferential treatment solutions are a function of many variables, such as: the magnitude of transit travel time delay; the transit fleet size, the labor rules; the apportionment of preemption and priority system costs among transit operators, emergency service providers and the municipality; and the cost of money.

INTRODUCTION

Background

Increasing population growth, urban sprawl, and automobile ownership is taxing our Nation's transportation capacity. Today, urban congestion is a major problem across the United States. In many of our Nation's cities the congested peak travel periods are normally three to four hours in duration. Congestion increases commuter travel time, contributes to reduced air quality, increases noise pollution, and adds to driver stress. It also impacts on the ability of municipalities to provide efficient and timely essential public services such as fire and rescue services and public transit.

Intelligent Transportation Systems (ITS) can help ease this strain through the application of modern information technology and communications to improve the transportation system to make it more effective, efficient and safer (*1*). Advanced traffic signal control is an ITS application that can potentially ameliorate the impacts of congestion. Traffic signal systems can be adapted to provide preferential treatment for emergency vehicles and qualified transit vehicles in the form of emergency vehicle preemption and transit priority.

Emergency vehicle preemption unconditionally interrupts the normal signal operation process to facilitate the safe passage of emergency vehicles by providing a green signal in the direction needed by the emergency vehicle. This will reduce the potential for crashes at signalized intersections and reduce response times to emergencies such as traffic accidents, medical emergencies, industrial and residential fires and even terrorist attacks *(2).* Experience from emergency vehicle preemption deployments in the U.S. and abroad have demonstrated increased safety and reduced response times *(3).*

Transit priority modifies the normal signal operation process to move qualified transit vehicles through signalized intersections. The objective of transit priority is to improve transit efficiency and improve rider convenience. Experience from deployments in Europe and the U.S. indicate transit priority can potentially improve transit travel time, increase service reliability and reduce bus driver stress with minimal impact on other traffic *(4).*

Problem Identification

Advances in microcomputer and communications technologies are making it possible for a common system using advanced traffic signal controllers and vehicle detection technology to accommodate both emergency vehicle preemption and transit priority strategies. This has the potential to reduce the cost of procuring and operating advanced traffic signal systems capable of both emergency vehicle preemption and transit priority. This in turn, has stimulated many jurisdictions to consider investing in advanced traffic signal control systems that can provide both emergency vehicle preemption and transit priority.

Emergency vehicle preemption enjoys universal support for deployment because virtually everybody understands the need for fast response to an incident, when lives are at risk. Transit priority, unfortunately, does not enjoy a similar level of support. Elected officials are not supportive and the public is ambivalent *(5)*. Some transit agencies and city traffic engineers are resistant to implementing transit priority. Implementation barriers include institutional issues, operational issues, and human factors issues *(6)*. Major concerns of elected officials and transportation professionals include potential negative impacts on traffic and concerns on cost effectiveness *(7)*.

Until recently, the planning and deployment of emergency vehicle preemption systems and transit priority systems have been pursued separately. Researchers in their respective fields have developed distinctly different evaluation methodologies and data collection methods. Published research on both emergency vehicle preemption and transit priority is focused on quantifying travel time impacts. There is not much published on the efficiency and cost effectiveness of preemption and priority on service providers. In today's austere public funding environment, there is a requirement for a simple and standardized framework for planners to assess potential reductions in operating cost from advanced traffic signal controller systems capable of emergency vehicle preemption and transit priority.

The purpose of this paper is to present an overarching evaluation framework to assess the efficiency and cost effectiveness of advanced traffic

signal control systems that are capable of both emergency vehicle preemption and transit priority; and to present two parts of a four-part analytical approach that assess the impact on operation and maintenance costs of reduced emergency vehicle crashes and reduced transit travel time. The applicability of this framework and the analytical approach will be demonstrated using results from an on-going Virginia Tech/Virginia Department of Transportation (VT/VDOT) emergency vehicle preemption and transit priority operational field test along U.S. 1 in Northern Virginia. An underlying aim of this evaluation framework and analytical approach is to aid in the assessment of potential impacts of integrated emergency vehicle preemption and transit priority systems and thus facilitate investment planning and decision-making.

LITERATURE REVIEW

A state-of-the-art literature review was conducted to establish background information on (1) economic analysis of ITS investments with an emphasis on financial feasibility analysis; (2) operating cost impacts of emergency vehicle preemption; and (3) travel time impacts of various transit priority strategies.

Economic Analysis

Transit Cooperative Research Program Report 78 entitled "Estimating the Benefits and Costs of Public Transit Projects: A Guidebook for Practitioners" provides an analytical framework and solid foundation for evaluating transportation projects. It was written for transit planners at all levels of government to evaluate transit investments. It groups impacts into five categories: (1) travel impacts; (2) environmental impacts, (3) impacts on economic development, (4) land use and development impacts, (5) distribution of transit impacts *(8)*.

The Federal Highway Administration developed the spreadsheet analysis tool SCRITS (**SCR**eening for **ITS**), to allow practitioners to obtain an initial indication of the possible benefits of various ITS applications. SCRITS contains 16 different ITS applications. One of them is Signal Priority Systems for Buses. This SCRITS application focuses on two elements: time savings for buses that are given priority and additional delay for side street traffic. SCRITS was

intended as a sketch-level or screening-level analysis tool because there is a
great deal of uncertainty regarding the effects of ITS applications. The answers
produced by SCRITS are approximate and are recommended for general
planning purposes only *(9)*.

Khasnabis, Rudraraju and Baig, suggested a variation of benefit-cost-
analysis in which the maximum possible investment for a transit priority project is
set by the magnitude of passenger delay savings. They determined, through
simulation, that passenger delay savings was significantly large enough to offset
the maximum investment threshold *(10)*.

Lee and Carroll presented a practical and intuitive benefit-cost evaluation
framework to evaluate ITS projects that includes benefits accrued to transit
users, other users and transit providers. This framework linked potential impacts
to actions in an A-causes-B-causes-C series of impact linkages. Algorithms were
developed to bind the range of magnitude of each of these linkages and their
dollar validations. Spreadsheet models were then used to compute the total
benefits and costs *(11)*.

Morlok, Brunn and Blackman introduced how a transit agency might
evaluate the feasibility or the desirability of an ITS project as a subset of a
comprehensive benefit-cost evaluation approach *(12)*. They posited that if an
evaluation demonstrated that the ITS project was desirable from a purely
financial perspective; it would be even more desirable from a more
comprehensive perspective. The bus transit cost model, a widely used and
accepted model for the total cost of operating a bus fleet, was adapted to relate
the investment cost to a change in transit operating cost. That model is
presented in equation 1.

Investment Cost = A(Revenue-hr) + B(Revenue-mi) + C(Fleet size)   (1)

where:
A = Unit cost associated with revenue-hours
  = (Vehicle operations expense %) x (Total expense)/ (Total Revenue-hours)
B = Unit cost associated with revenue-miles
  = (Material & utilities per vehicle-mile) + (Vehicle maintenance per vehicle-mile)
C = Unit cost associated with fleet size

= [(Non-vehicle maintenance %) + (General admin %)] x (Total expense/fleet size) + (bus cost) x (CRF)

Louisell and Collura identified the need for a standardized framework and analytical methodology to evaluate the impact of integrated emergency vehicle preemption and transit priority systems from a holistic perspective. They presented a system level evaluation framework that treated preemption and priority together as components of preferential treatment based on shared characteristics such as roadway use, implementation hardware and software, interaction with the traffic flow, integration of operational strategies, and the resulting interdependence performance *(2)*.

Operating Cost Impacts of Emergency Vehicle Preemption

In the 5-year period from 1997 to 2001, more than 554 emergency vehicle crashes involving one or more fatalities were recorded in the 2003 Fatality Analysis Reporting System (FARS) *(13)*. Operational experience suggests that the deployment of emergency vehicle preemption may decrease the number and severity of accidents involving emergency vehicles and other vehicles at signalized intersections. The ITS Benefits Database contains a 1977 report from the Fire Chief from the City of St. Paul, Minnesota that describes the impact of emergency vehicle preemption deployment on emergency vehicle crash reduction. This report spanned a 9-year period of time from 1968 to 1976 in which the City of St. Paul incrementally deployed 285 3M Opticom systems on 308 intersections. The report indicated a decrease in emergency vehicle crashes in spite of an overall increase in the total number of emergency alarms and in the volume of traffic on St. Paul roadways. In 1968, prior to the deployment of emergency vehicle preemption, there were 7 emergency vehicle crashes among the 7,594 total emergency alarms. After the initial deployment of 28 3M Opticom systems, there were 6 emergency vehicle crashes among 8,300 total emergency alarms. This suggests that the initial introduction of preemption reduced emergency vehicle crashes by approximately 22% *(3)*.

Research on emergency vehicle crashes in Northern Virginia indicates that: approximately 31% of emergency vehicle crashes occurred at signalized

intersections; crash damage at intersections are more severe at intersections than at non-intersections; and crash damage cost ranged between $500 and $10,000 with the average around $6,330 *(14)*.

Travel Time Impacts of Various Traffic Priority Strategies

Preferential treatments are used to improve transit system performance. They include transit priority, infrastructure improvements, and new equipment acquisitions. Transit priority modifies traffic signals to move qualified buses through signalized intersections. Infrastructure improvements include bus stop relocation, bus stop consolidation, bus only exclusive lanes, and curb extensions. New equipment acquisition solutions include low floor buses, electronic fare collection, automatic vehicle locators, and passenger counters. Determining which combination is the most effective and efficient requires detailed analysis to assess operational impacts.

There are two classes of transit priority strategies, passive priority and active priority *(15)(16)*. Passive priority strategies use static signal settings to favor transit vehicles to reduce delay for transit passengers. Common passive priority strategies include: preprogrammed signal timing of coordinated signals at average transit vehicle speed instead of average automobile speed, reducing cycle length along transit corridors, increasing green time along the transit route, and providing transit by-passes at metering locations. The problem with passive priority strategies is that they typically make the intersection operate less efficiently overall.

In contrast, active priority strategies dynamically alter signal settings only when necessary, making real time signal timing adjustments to minimize delay to approaching transit vehicles. Active priority strategies require devices to detect transit vehicles approaching the intersection, advanced traffic signal controllers to alter the signals and a communication link between the traffic signal controller and transit vehicles. Signal phases are modified upon detection of the transit vehicle. Active priority strategies are further classified into two types: conditional and unconditional. Conditional priority grants priority status based on criteria

such as lateness of the vehicle relative to its schedule and passenger load. Unconditional priority gives priority status to every transit vehicles detected. The four basic active transit priority strategies are: green extension, red truncation, phase insertion, and queue jump. **Green Extension** extends the duration of the green phase time to allow a qualified bus to clear an intersection. Upon request from a qualified bus, the traffic signal control system provides additional green time up to a preset maximum (usually 10 seconds) to allow the bus to pass through the intersection. The additional green time is "borrowed" from the side street. Side street traffic will experience a longer red interval. Green extension is best used for far side bus stop locations. **Red Truncation** shortens the red phase to expedite the return to green. To initiate this strategy, the bus must arrive near the end of the red interval. Upon request from a qualified bus, the traffic signal control system will provide an early green after meeting minimum cross street green times (such as pedestrian crossing time). Similar to green extension, the green time is "borrowed" from the side streets, and side street traffic will experience a quicker green. **Phase Insertion** inserts a green phase into a red phase to provide a bus early entry into the traffic flow. When a qualified bus arrives at the signal near the end of the red interval and other phases need to be serviced before the normal return to green, a short phase for transit can be inserted, with the controller returning to normal operations once the bus has cleared. Finally, **Queue Jump** is a strategy that provides buses the opportunity to by-pass waiting queues of traffic at signalized intersections. An exclusive phase within the traffic signal sequence allows the bus to proceed through the intersection without any conflict from other vehicles. Queue jump is best suited for near side bus stop locations.

The City of Portland performed a detailed operational analysis of the effect of transit preferential strategies on five corridors. They found that on the average, only 34% of the total bus travel time was attributable to driving. The remaining 66% was distributed as follows: 22% at traffic signals, 16% at bus stops, and 28% in traffic congestion *(17)*. These results are consistent with findings from Wilshire and Whittier Boulevards in Los Angeles where traffic signal

delay was 20% and bus stop delay was 25% *(18)*. These results suggest that the maximum transit travel time reduction attainable by transit priority alone is in the order of 20%.

A limited number of past deployments and computer simulations were analyzed to assess the travel time impact of various transit priority strategies. Evaluating travel time impacts of transit priority strategies is hard to accomplish because most transit priority projects have only been deployed in the U.S. within the past few years and results from operational evaluations are not applicable across the board because performance measures are not well defined in a standardized framework and the terminology used is not consistent. In some cases, combinations of several preferential treatments were simultaneously implemented making it difficult to isolate the impact of a particular transit priority strategy. Additionally, the degree of impact is influenced by the specific conditions of the corridor. These conditions may include: frequency and direction of travel for vehicles requesting priority, roadway characteristics, travel demand, presence and frequency of pedestrian phases, transition strategy, cycle characteristics, and intersection spacing and progression strategy *(19)*. Results from this assessment are presented in Table 1. Because the underlying data is collected from various sources, using different measurement standards, and under different traffic conditions, caution should be exercised in interpreting and applying these results. However, these results provide a rough order of magnitude estimate that can be used as a benchmark for the expected outcomes of various strategies. These results suggests the following:

(1) Signal optimization should be a part of any transit priority project.

(2) Transit travel time reduction is greatest when a combination of strategies is utilized and each intersection is optimized according to its specific characteristics.

(3) Transit time reduction from deployments is greater than those projected by computer simulations, which indicates that simulations may provide conservative estimates.

EVALUATION FRAMEWORK

Advanced traffic signal control systems can provide preferential treatment to both emergency vehicles and buses. Emergency vehicles can use high priority requests for preemption while buses use the low priority requests for priority. Today there is not a simple evaluation framework and analytical approach available to assess the efficiency and cost effectiveness of advanced traffic signal control systems using emergency vehicle preemption and transit priority strategies.

An advanced traffic signal control evaluation framework is developed in this paper that links system preemption and priority functionalities to performance impacts. This evaluation framework is presented in Figure 1. The framework follows a systems approach and draws from an analytical framework presented in past work for estimating the impacts of public transportation projects *(10)*. The framework groups impacts into five categories as shown on the right hand side of Figure 1.   The system will be assessed from three perspectives: the impact of emergency vehicle preemption, the impact of transit priority and the combined effects of both. A comprehensive benefit-cost analysis would evaluate all five impacts. This paper will focus on travel impacts because they are the most significant.

Expected Impacts

The travel impacts of emergency vehicle preemption are shown in Figure 2. Preemption permits emergency vehicles (first responders) to travel at a higher rate of speed. This may reduce emergency vehicle travel time and potentially save lives, reduce injury, and minimize physical damage. This may also reduce crashes involving emergency vehicles and potentially reduce accident costs *(3)*. Recovery from preemption may disrupt the normal traffic flow in all directions. This could potentially increase travel times for non-transit and transit users.

The possible travel impacts of transit priority are shown in Figure 3. Transit priority may reduce bus delays at signalized intersections. The resulting transit travel time reduction could potentially benefit transit operators by reducing operating costs. Transit passengers may benefit by spending less time traveling. Traffic in the direction of priority may benefit from the additional green time, while

traffic on cross streets may experience some delay. Lastly, transit priority may improve bus service reliability, a key measure transit agencies use to assess route performance *(20).* Improved schedule reliability may improve the quality of transit service and potentially increase ridership *(21).*

Logical rules, based on preemption recovery strategies, contribute to the severity of the impact of emergency vehicle preemption on transit priority operations.   For instance, if the recovery strategy is to return to normal operations in five cycles, then transit signal priority may not be granted until the sixth cycle. Thus, frequent preemption calls may reduce anticipated transit travel time reductions.

Table 2 illustrates the distribution of system impacts. Beneficiaries include the general public, transit passengers, non-transit users, emergency service providers and transit operators.

Analysis of Impacts

Fire and Rescue Operating Costs Impacts

Reduced emergency vehicle crashes at signalized intersections will reduce the cost to fire and rescue providers to repair emergency vehicle damaged in crashes, reduce cost of vehicle insurance, and reduce non-availability time awaiting repairs. The number of emergency vehicle crashes and their distribution on signalized and non-signalized intersections and non-intersections can be determined from fire and rescue operational data or from regional accident report databases. A simple spreadsheet model that can be used to assess average savings is presented in Table 3. . The illustrative example shown in Table 3 examines the impact of a 22% crash reduction to a fire and rescue provider that has 10 signalized intersection crashes per year and an average repair cost of $6,330.

Transit Operating Costs Impacts

An assessment of financial feasibility examines the impact of reduced transit operation and maintenance (O&M) costs and whether that reduction is sufficient to warrant the investment costs. It answers the question "can we afford to do this investment". Ideally, operating cost and capital cost savings should

cover the cost for the improvement. A simple three-step spreadsheet model to determine financial feasibility is presented in Table 4. Step 1 computes the operating cost savings based on the total transit travel time reduction using the simple relationship:

$$\Delta \text{Operating Cost} = (A+BY)(\Delta \text{Revenue-hr}) \tag{2}$$

where Y= Revenue hr/Revenue-mi

The coefficients A, B and Y can be determined using data from the transit agency's operational database or estimated using data from the National Transit Database and the National Transit Summaries and Trends Report *(22)(23)*. Average operating cost per vehicle revenue-hour, and vehicle revenue-miles can be found in the National Transit Profile. Annual vehicle revenue-miles and vehicle revenue-hours, and total operating expenses for a select number of transit agencies can be found in Table 28 and 31 of the National Transit Database. The average values of the expense functions (vehicle operations, vehicle maintenance, non-vehicle maintenance, and general administration), and the object class (salaries, fringe benefits, services, materials and supplies, utilities, and other) are found in Table 13 of the National Transit Database.

Revenue-hr savings for a particular bus corridor can be determined by using:

$$\Delta \text{ revenue-hrs} = \sum_{i=1}^{n} (N_i)(TTT_{ib} - TTT_{ia}) \tag{3}$$

where: N_i = number of trips on route n.
$\quad$ TTT_{ib} = transit travel time on route n before priority.
$\quad$ TTT_{ia} = transit travel time on route n after priority.
$\quad$ Step 2 computes the investment costs and annual costs associated with this deployment. The capital costs can be subdivided into two categories: roadside equipment such as detectors, controllers, and onboard equipment such as emitters. A capital cost model that can be used for both categories is *(24)*:

$$TCC = [(\sum_{i=1}^{n} (UC_i)(q_i)(1+x_{PS} + x_{IC} + x_{ESPM})](1 + y_C) \tag{4}$$

where: TCC = Total capital costs;
$\quad$ UC_i = unit cost of nth equipment ;
$\quad$ q_i = quantity of nth equipment;

x_{PS} = non-recurring parts and services expressed as percent of the equipment costs;

x_{IC} = non-recurring installation and construction costs expressed as percentage of the equipment costs;

x_{ESPM} = non-recurring engineering, software and project management costs expressed as percentage of the equipment costs;

y_C = contingency costs

Determining cost estimates for advanced traffic signal control systems is complicated for a number of reasons. First, the technology is relatively immature so there is a lack of a universal standard and manufacturers with different competing technologies have different cost structures. Second, desired system functionalities will impact cost; thus, a complex system will cost more. Third, the existing traffic signal control system may be inadequate to execute preferential treatment Replacement will increase implementation cost. And, fourth there is a paucity of published information on the costs of operational deployments. Data from deployments indicate per-intersection costs range from $5,000 to $11, 000 *(25)*.

Step 3 provides the result of two assessments methodologies: payback period analysis, and net present value analysis. Payback period analysis evaluates how quickly the investment can be recovered based on savings in operating costs. The formula for payback period analysis is *(24)*:

$$x = TCC/[(Operating\ cost)(\Delta Revenue\text{-}hrs) - (O\&M\ costs)] \qquad (5)$$

where: x = payback period
TCC = Total capital cost

Net present value analysis evaluates the time required to recover the investment cost based on operating costs savings taking into account the compound interest of money. An interest rate of 7% used based on guidance from the Office of the Management and Budget to use that discount rate for Federal Transit Administration analysis *(26)*. The number of years required to recover the investment can be found by first determining the capital recovery factor (CRF) *(24)*:

$$CRF= [(Operating\ cost)(\Delta Revenue\text{-}hrs) - (O\&M\ costs)]/(TCC) \qquad (6)$$

And then determine the number of years using the CRF at the 7% interest rate in the standard interest tables.

Table 4 presents an illustrative assessment of a ten-mile long bus route with ten signalized intersections that is being serviced by 30 buses during peak periods. The displayed operating cost parameters represent average bus operations values extracted from the 2001 National Transit Database. In addition, bus travel times of 35 minutes and a potential transit time reduction of 9% (average travel time reduction for green extension and /or red truncation combination strategy from Table 1) are used. Investment costs are assumed to be $8,000 per intersection and $750 per emitter. Results indicate a payback period and capital recovery period of less than 3.5 years.

CASE STUDY: U.S. ROUTE 1 NORTHERN VIRGINIA

Virginia Tech in collaboration with George Mason University and supported by the Washington Regional Council of Governments and the Virginia and Maryland Departments of Transportation has been conducting an operational field test to assess the impact of deploying an advanced traffic signal control system capable of emergency vehicle preemption and transit priority along U.S. 1 from the Prince William Country Line to I-495 in Northern Virginia. U.S. 1 is a major arterial that carries over 2700 vehicles per hour as it winds along one of the most densely populated areas in Northern Virginia. Two transit agencies operate four bus routes and three fire and rescue facilities provide emergency service along the corridor.

The operational test site is an 1.3-mile long segment of U.S. 1 that includes seven signalized intersections. It is located within close proximity to a Washington Metropolitan Area Transit Agency (WMATA) terminal subway station, a natural trans-loading point, and is along the travel route of one the fire companies that provide emergency services to the community. As part of the study, 3M Opticom systems were installed at the seven signalized intersections within the test site and pole-mounted video cameras were positioned to record traffic conditions.

Regional FARS data reported 11 emergency vehicle crashes on signalized intersections on U.S. 1 in Northern Virginia over the 5-year period from 1997 to 2001. Analysis of that data indicated that approximately 31% of emergency vehicle crashes on U.S. 1 in Northern Virginia occurred at signalized intersections *(14)*. Based on the above, Table 5 uses 2.2 crashes per year along with the default inputs of 22% for anticipated crash reduction and an average accident cost of $6,330. Results indicate a potential of avoiding 0.484 emergency vehicle crashes per year as a result of initial emergency vehicle preemption deployment. So, in a two-year period there is the potential to avoid one crash. This translates into a potential annual operating cost savings of $3,165 to fire and rescue providers.

To determine the impact of transit priority on transit operating costs, results from a VISSIM simulation was used. VISSIM is a microscopic, time-based, and behavior based simulation tool. VISSIM was used to model the impacts of a 10 second green extension and unconditional priority. This followed VDOT guidance to minimize potential disruption to vehicular traffic flow. The model was calibrated using 2002 weekday peak hour traffic data from SYNCHRO data supplied by VDOT, and operational site characteristics (such as traffic speed, control delay, and number of stops) obtained using the "floating car" technique. Results from 30 pairs of "before" and "after" simulations provided data on bus service reliability, bus service efficiency and queue lengths on side streets were obtained. Bus service reliability was measured as the standard deviation of elapsed time between the end points of the corridor. Bus service efficiency was measured as the average run time between the end points of the corridor. And queue lengths on side streets were measured.   Simulation results indicated bus service reliability increased by 3.6%, bus travel time reduced by 2.64% and side street queue length increased by less than one queue length.

These results were extrapolated to assess the financial feasibility of deploying an advanced traffic signal control system along a 13-mile long 22-intersection corridor under three investment cost allocation scenarios. Figure 4

depicts the trace of that corridor and the location of the test site within the corridor.

The Table 2 distribution of benefits suggests that apportioning the investment costs of an integrated emergency vehicle preemption and transit priority system among the municipality, emergency service providers, and transit providers is appropriate. Three funding allocation cases were considered:

Case 1: The transit agency pays 100% of the roadside equipment cost. This represents a method of analysis in which the transit provider assumes the cost of the system.

Case 2: The transit agency shares the cost of the roadside equipment with the emergency service providers. The total investment cost is divided between the two major users.

Case 3: Fairfax County pays the cost of the roadside equipment. In this scenario, the County or VDOT installs the advanced traffic signal controller system to up grade the traffic signal system with general funds. The emergency service provider and the transit provider would pay with funds from their respective budgets to connect to the system and their share of the O&M costs.

Operational experience and simulations suggests that the choice and combinations of transit priority strategies will impact transit travel time reductions. Table 1 results indicate that strategies that employ combinations of green extension, red truncation and queue jump provide progressively better transit travel time reductions. This in turn would impact the payback period. Figure 5 shows the impact on payback period as a result of increased transit travel time reductions. Figure 5 suggests there are threshold levels from a payback period perspective where the incremental improvement may not be worth the incremental cost. For example: for case 1 a payback period of 11 years can be realized with a transit travel time reduction of 10%. That same payback period can be realized with a transit travel time reduction of 7% for case 2. In case 3 a payback period of less than 3 years can be realized with a transit travel time

reduction of 8%. This suggests that modest transit travel time reductions may be sufficient to justify the investment depending on the strategy (e.g., green extension only versus a combination of green extension and/or red truncation) and the financial apportionment scheme chosen.

CONCLUSIONS AND RECOMMENDATIONS

An overarching evaluation framework for evaluating the impacts of integrated emergency vehicle preemption and transit priority systems has been developed. Two parts of a four-part analytic approach within this framework, an emergency vehicle accident reduction cost assessment and a transit operating cost assessment, were presented. The evaluation framework and analytical approach are intended to aid in the assessment of potential impacts of integrated emergency vehicle preemption and transit priority systems on fire and rescue and transit operating and maintenance costs, and thus facilitate investment planning and decision-making.

The impact of reduced emergency vehicle crashes at signalized intersections in fire and rescue provider O&M costs can be assessed using the methodology presented. The magnitude of that saving is a function of the number of emergency vehicle related crashes at signalized intersections and the average cost of repair. The impact of transit priority strategies on transit operating costs is also influenced by a number of variables.   First is the impact various combinations of transit priority strategies have on transit travel time. Next is the impact of simultaneously implementing other possible preferential treatment solutions. Third, the number of buses on a route must be sufficient to provide the necessary revenue-hrs to make a difference. And lastly, driver salaries determine operating costs per revenue hr, so labor rules will play a significant role in transit operating costs.

How the investment cost is apportioned is also an important consideration. Cost sharing of investment costs would reduce the cost to both service providers. In addition to the obvious fiscal advantage, an integrated system would capitalize on the popular support for the deployment of emergency vehicle preemption systems. Since the major beneficiary of the emergency vehicle preemption and

transit priority is among the general population, a case can be made for the municipality to treat the advanced traffic signal controller system as a upgrade to the existing traffic signal system. The service providers will bear the cost of connecting to the system and their share of the annual operating and maintenance cost.

The evaluation framework and the two parts of the analytical approach presented in this paper represent initial results from research at Virginia Tech on integrated emergency vehicle preemption and transit priority traffic control systems. The evaluation framework and four-part analytical approach will become the basis of a decision support system that is under development. The purpose of that decision support system is to provide traffic managers, planners, engineers and other professionals a standardized framework to evaluate the impacts of emergency vehicle preemption and transit priority in their decision making process.

Recommendations for further research include: (1) expanding VISSIM modeling to the entire 13-mile 22 intersection corridor to obtain a better estimate for transit travel time impacts, and to examine the impacts of other transit priority strategies. (2) applying fuzzy set theory to determine the best combination of preemption recovery strategies and transit priority strategies for each intersection on the network.

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List of Tables

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Table 1 Transit Signal Priority Strategy Impacts

| Strategy	Deployment	Simulation
Signal Optimization	2% - 5% [1][2][3]	None
Green Extension Only	0% - 9.7% [2][3][4]	0% - 6% [4][15][16][17][18]
Red Truncation Only	None	1% - 10.6% [18]
GE + RT	1.4% - 20% [1][2][3][4][5][6][7][8][9]	1.6% - 14.2% [4][18]
GE + RT + Queue Jump	0% - 18% [10][11][12]	None
Combinations	1.8% - 28% [3][7][11][13][14]	2.7% - 17.6% [18][19]

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┌─────────────────────────────┐        ┌──────────────────────────────┐
│      EVP & TSP System        │        │        Travel Impacts         │
│                              │        └──────────────────────────────┘
│  ┌───────────┐               │
│  │ Emergency │  Preemption   │        ┌──────────────────────────────┐
│  │ Vehicle   │  Impacts      │        │    Environmental Impacts      │
│  │ Preemption│               │        └──────────────────────────────┘
│  └───────────┘               │
│                              │        ┌──────────────────────────────┐
│                              │        │       Land use Impacts        │
│  ┌───────────┐  Priority     │        └──────────────────────────────┘
│  │ Transit   │  Impacts      │
│  │ Priority  │               │        ┌──────────────────────────────┐
│  └───────────┘               │        │ Economic Development Impacts  │
│                              │        └──────────────────────────────┘
└─────────────────────────────┘
                                        ┌──────────────────────────────┐
                                        │      Distributive Effects     │
                                        └──────────────────────────────┘
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Adapted from
TCRP Report 78, *Estimating the Benefits and Costs of Public Transit Projects: A Guidebook for Practitioners (8)*

Figure 1 Advanced Traffic Signal Control Evaluation Framework
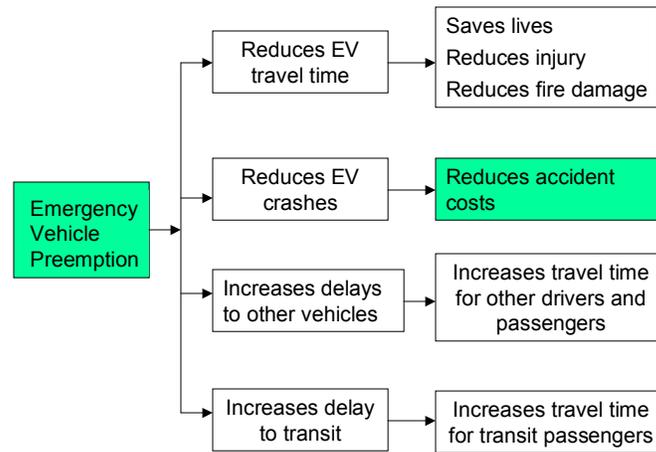
Adapted from
Lee, D. & Carroll, A., *Benefit-Cost Evaluation of a Highway-Railroad Intermodal Control System, January 2003 (11)*

Figure 2 Emergency Vehicle Preemption Travel Impacts
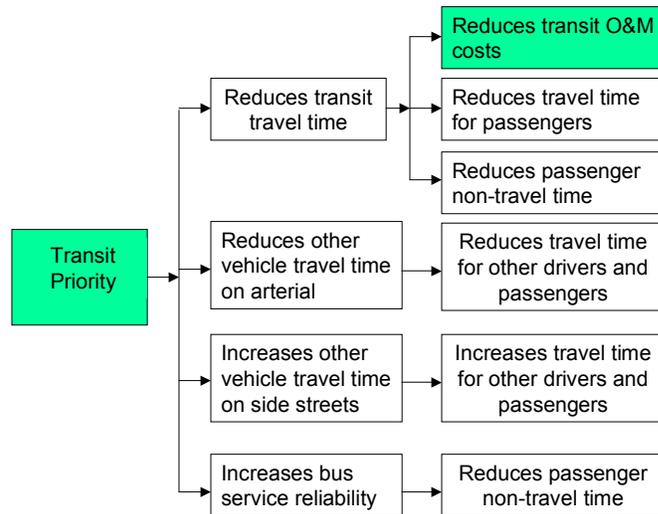
Adapted from
Lee, D. & Carroll, A., *Benefit-Cost Evaluation of a Highway-Railroad Intermodal Control System, January 2003 (11)*

Figure 3 Transit Priority Travel Impacts

Table 2 Emergency Vehicle Preemption and Transit Priority System Impact Distribution

| Impact	Recipient
Saves lives, reduces injury, reduces fire damage	General public
Reduces accident costs	Emergency service provider
Increases travel time for other drivers and passengers	Motorist
Increases travel time for transit passengers	Transit passengers
Reduces transit O&M costs	Transit operator
Reduces transit passenger non-travel time	Transit passengers
Reduces transit passenger travel time	Transit passengers
Reduces travel time for other drivers on arterial	Motorist
Increases travel time for drivers on side streets	Motorist
Reduces passenger non-travel time	Transit passengers

Table 3 Fire and Rescue Accident Cost Reduction Assessment

	Average	
	Input	**Output**
Number of crashes per year at signalized intersections	10.00	
Average cost to repair	$6,330.00	
Crash Prevention Estimate	22%	
Number of potentially avoidable crashes		2.2
Potential accident savings		$12,660.00

Table 4 Transit Operating Cost Assessment

|	2001National Average	
	Input	Output
Step 1		
Operating cost parameters		
Operating expense per vehicle revenue-hr	$82.79	
vehicle revenue-hrs (millions)	2452.4	
vehicle revenue-miles (millions)	1821.2	
material and utilities ($millions)	$128.5	
vehicle maintenance ($millions)	$238.1	
vehicle operations %	0.60	
Y = (revenue-hrs)/(revenue-miles)		1.35
A = (vehicle operations %)*(operating expense/veh-hr)		$50.07
B = (mat & Util + veh maint)/(vehicle revenue-miles)		0.20
BY		0.27
(A+BY)		$50.34
Revenue hour savings		
Miles on which priority treatment is implemented	10	
Number of buses per weekday during peak period	60	
bus travel time (minutes)	35	
Annual revenue hrs		8750.00
Estimated bus travel time savings	0.09	
Δ Revenue hours		787.50
Operating cost savings		
operating cost savings = (A+BY)*(Δ revenue-hrs)		$39,644.68
Step 2		
Determine investment cost		
Roadside equipment		
Cost per intersection	$8,000	
Number of intersections	10	
Roadside equipment cost		$80,000
Onboard equipment cost		
Cost per emitter	$750	
number of buses	35	
Onboard equipment cost		$26,250
Determine annual system costs		
Annual O&M costs	$3,000	
Other	$500	
Annual system cost		$3,500
Step 3		
Financial Feasibility Assessment		
payback period (yrs)		
(Total investment cost)/Annualized savings		2.94
number of years @ 7% interest		
Capital Recovery Factor =		0.3402
(operating cost)(Δ Revenue hours) - System O&M		
Total Investment cost		
determine n from 7% interest table		3.4

Adapted from: Washington Metropolitan Area Transit Authority Virginia Metrobus Service Area

Figure 4 U.S. Route 1 Northern Virginia Case Study Corridor

Table 5 U.S. 1 Emergency Vehicle Accident Cost Reduction

	Input	Output
Number of crashes per year at signalized intersections	2.20	
Average cost to repair	$6,330.00	
Crash Prevention Estimate	22%	
Number of potentially avoidable crashes		0.484
Potential accident savings		$3,165.00
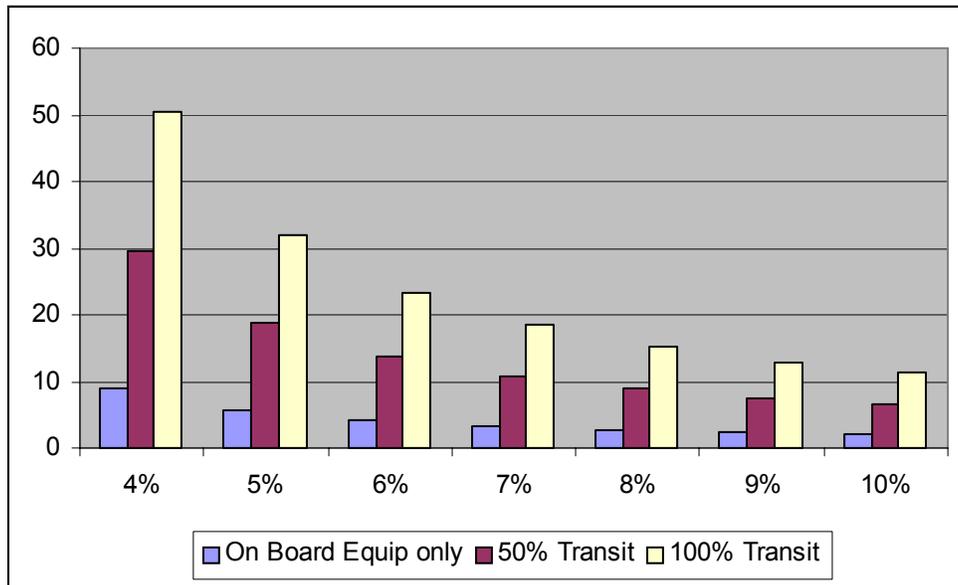
Inputs:
Operating Costs parameter (A+BY) = $35.20
Annual Revenue-hrs = 4375 hrs
Roadside Investment Costs = $5,000/Intersection x 22 Intersections = $110,000
Onboard equipment costs (transit) = $750/vehicle x 32 transit vehicles = $24,000
Annual O&M costs = $3,500

Figure 5 Impacts of Transit Travel Time Reductions on Pay Back Period

VITA

Houng Y. Soo was born in Kowloon, Hong Kong in 1949. He moved to the United States in 1952 and grew up in Brooklyn, New York. He graduated from The Polytechnic Institute of Brooklyn in 1971 with a Bachelors of Science in Electrical Engineering and was commissioned as a Second Lieutenant in the United States Army Corps of Engineers.

Houng served in a variety of command and staff assignments in airborne, mechanized and combat heavy engineer units in the Continental United States, Turkey, Federal Republic of Germany, and the Republic of Korea until his retirement from the United States Army in 1999. His commanded the Engineer Brigade, 2nd Infantry Division, forward deployed in the Republic of Korea from 1994 to 1996; and the 544th Engineer Battalion, Fort Belvoir, Virginia and Fort Leonard Wood, Missouri, from 1988-1990. He also served at the Defense Nuclear Agency where he managed research and development programs focusing on pulsed power applications for high-power above ground laboratory weapons effects simulation. His last assignment was in the Office of the Assistant Deputy Chief of Staff for Operations and Plans, Force Development, Headquarters, U.S. Army, where he was responsible for planning, programming, and budgeting of U.S. Army research, development and acquisition programs.

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