COMPREHENSIVE METHOD FOR EVALUATING SIGNALIZED INTERSECTIONS TREATMENTS: LEFT TURN PROHIBITION AND PARTIAL GRADE SEPARATION

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By
Xin Yu

Dissertation Committee:
Panos D. Prevedouros, Chairperson
Honglong Li
Michelle H. Teng
Peter G. Flachsbart
Roger W. Babcock

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We certify that we have read this dissertation and that, in our opinion, it is satisfactory in scope and quality as a dissertation for the degree of Doctor of Philosophy in Civil Engineering.

DISSERTATION COMMITTEE

Chairperson

UNIVERSITY OF HAWAI'I AT MĀNOA

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Part I. To be completed by the student

Name Yu, Xin (LAST, FIRST, M.I.) UH ID No. 17411167

Graduate Program Civil Engineering (INCLUDE SPECIALIZATION IF APPLICABLE.) Degree Objective PHD

I certify that I have read and understand the policies and instructions for this form.

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We certify that we have read and understand the policies and instructions for this form. We hereby approve both the content and the form of this dissertation.

Name (Print or Type)	Signature	Date
Chair Panos D. Prevedouros	[signature]	1/7/13
Member Honglong Li	[signature]	1/7/13
Member Michelle H. Teng	[signature]	1/3/13
Member Roger W. Babcock	[signature]	1/4/13
Member		
University Representative Peter G. Flachsbart	[signature]	1/7/13

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☐ Approved ☐ Not Approved By __________ Date __________

Remarks

C: Graduate Program

2540 Maile Way, Spalding Hall 352, Honolulu, Hawai'i 96822
Telephone: (808) 956-8500

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ABSTRACT

Recurring congestion at signalized intersections is caused by the inability of traffic signal controls to serve demand even in cities where advanced traffic signal timing and management systems are in operation. Left turn prohibition (LTP) and partial grade separation with low-clearance underpass (LCUP) are possible congestion mitigation actions for urban complex and congested signalized intersections that have exhausted other options for capacity enhancement such as lane addition and signal timing optimization. LTP and LCUP improve traffic signal efficiency by eliminating signal phases, increasing green splits or adding lanes. They also improve intersection safety by eliminating certain conflicts. At the same time, they necessitate traffic rerouting, may have negative impacts at downstream locations, and may have perceived or actual impacts to accessibility and neighborhood character.

A comprehensive method considering multiple objectives, stakeholders, and attributes of a proposed treatment is inherently complicated. There is currently unavailability of methods pertaining to address the lack of techniques to integrate operation, safety, economic, stakeholder objective analysis and uncertainty into multi-attribute decision-making tool. A complete set of stakeholders is also absent, including motorists, pedestrians, bicyclists, adjacent businesses and residents and responsible agencies.

This research proposes a three-level project decision-making process taking into account the planning and screening, feasibility and performance study, and evaluation

and decision-making in the development of an intersection improvement project. A planning and screening level is to quantify and compare the benefits and costs LTP and LCUP was developed to examine the potential applicability of these congestion mitigation actions by examining intersection delay using the Highway Capacity Manual 2010, accident frequency using the Highway Safety Manual, and cost-benefit analysis based on AASHTO's User Benefit Analysis for Highways Manual, prior to conducting extended data collection and detailed analysis. Feasibility and performance analysis is to examine the feasibility of a treatment by considering site-specific constraints, and if feasible, conduct detailed performance analysis using advanced analysis tools. Five-stage multiple attribute evaluation under uncertainty and fuzziness (MAFU) process is proposed in evaluation and decision-making level, which is able to assess the magnitudes of intersection treatment performance and to the fuzziness in stakeholder preference and the uncertainty in performance measurement. MAFU is designed to determinate the alternative which can best achieve a compromise between all competing objectives and conflicting interests. It features fuzzy mathematics (FAHP) to capture the stakeholder preferences, utility function theory (MAUT) to combine performance measures and describe risk sensitivity, and probabilistic approach (MCS) to model output uncertainties and conduct the tradeoff analysis.

A case study is provided to demonstrate the application of this integrated and comprehensive method and the reliability of using this method for project evaluation and decision-making.

Due to the complexity of analysis for various time periods and multiple locations, a spreadsheet-based tool was developed for the planning and screening level and the evaluation and decision-making level. The study presents and demonstrates the comprehensive evaluation and decision-making process using the left-turn prohibition and low-clearance underpass treatments, but the method itself is generic and can be further extended to other intersection treatments and transportation projects.

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
AHP	Analytic Hierarchy Process
CBA	Cost Benefit Analysis
CMF	Crash Modification Factor
FAHP	Fuzzy Analytic Hierarchy Process
FHWA	Federal Highway Administration
HCM	Highway Capacity Manual
HSM	Highway Safety Manual
ITE	Institute of Transportation Engineers
LCUP	Low Clearance Underpass
LOS	Level of Service
LTP	Left Turn Prohibition
MAFU	Multiple Attributes evaluation under Fuzziness and Uncertainty
MAUT	Multi-Attribute Utility Theory
MCS	Monte Carlo Simulation
NCHRP	National Cooperative Highway Research Program
PHF	Peak Hour Factor
ROW	Right Of Way
TRB	Transportation Research Board
UBA	User and Non-User Benefit Analysis for Highways
VMT	Vehicle Miles Traveled
VRT	Variance Reduction Techniques

CHAPTER 1

INTRODUCTION

1.1 Background

The causes and locations of traffic congestion are numerous, but recurring congestion is more frequently observed at urban intersections than other road segments. For a variety of reasons such as population, economic and auto ownership growth, increasing traffic demand can quickly exceed the carrying capacity of the intersection during certain periods. As a consequence, traffic level of service deteriorates and safety risk worsens. The sharply deteriorated traffic conditions are not restricted to a single intersection. Queues can grow long at a saturated intersection and block driveways, access roads and adjacent major intersections, so negative effects of intersection congestion can be both localized and regional.

Severe traffic congestion also causes unnecessary and excessive fuel consumption, emissions, and noise pollution. In addition, based on a nationwide statistical survey of traffic crashes, more than half (57%) of all crashes and half (54%) of all injury crashes occur at intersections [1]. Most accidents not only result in the loss of life, medical and public resources, but also have negative impacts on roadway performance. Therefore negative operational and safety effects of intersection bottleneck can affect a city's quality of life, world resources and ambient conditions.

Intersections can be classified as signalized or unsignalized. According to Federal Highway Administration, there are at least three million intersections in the United States.

Less than 10% of the intersections are signalized [1]. However, signalized intersections are typically located in urban areas and serve high motorist and non-motorist volume. The signalized intersections are often the source of congestion and accidents along urban arterials. A large amount of this congestion occurs at intersections, rather than along the links between intersections [2]. With respect to crashes, 29% of fatal crashes occurred at signalized intersections and 84% of them at signalized intersections in urban areas [3].

Signalized intersections are key elements in the urban transportation network. In large urbanized areas, they carry heavy traffic of motorized and non-motorized vehicles and pedestrians, which, in turn, generate many conflicts among crossing, turning and merging maneuvers. The importance of signalized intersections in urban transportation systems is well understood by transportation agencies. Various improvement projects have being implemented in order to enhance safety, mobility and accessibility at busy intersections in urban area. Some of the intersection treatments can be small and inexpensive, such as enhanced pavement markings, new signs, traffic signal coordination and optimization, and prohibition of turning movements. Some are more expensive and require of excavation, construction and relocation, such as traffic signal installation, underpass, right-turn channelization and additional left-turn lanes.

However, these measures applied to improve the intersection capacity and safety may not necessarily ensure the overall benefit to adjacent roads, business, and residents, particularly in the urbanized area, which has complex spatial distributions of business, resident, and industrial areas and is characterized by higher population density, various amenities and facilities. This study proposes a comprehensive method for planning, analyzing and evaluating intersection treatments with focus on major urban signalized intersections.

1.2 Current Signalized Intersection Improvement Practices

Intersection treatments for congestion mitigation are summarized in Table 1.1 along with their advantages and disadvantages. There is no "one size fits all" solution. One potential treatment that combats congestion and safety problems at intersections may have negative impacts, such as:

(1) Indirect left-turn design that can provide the safety benefits and operational improvement to traditional intersection design and operation by removing the left-turning vehicles, would cause driver confusion, require additional right-of-way, and increase vehicle operating costs and pedestrian crossing risk.

(2) Underpass or overpass, which efficiently reduces the intersection delay and increase the capacity, would be considered as an exotic and impractical alternative in most urban intersections because of the expensive construction and maintenance cost and the implication of utilities relocation like gas, sewer, telecom, electrical and so forth.

(3) Roundabout, which eliminates the potential for hazardous conflicts and direct road traffic travel in one direction around a central island, may not be feasible in some situations with limited right-of-way, because roundabout requires a large amount of land to be properly constructed.

Table 1.1 Summary of Congestion and Safety Risk Mitigation Treatments

Treatment	Cost	Advantage	Disadvantage
Narrow Lane	Low/Moderate	1. Provides additional lanes (e.g., bike lane, bus/BRT lane or travel lane for general purpose) at intersections 2. Increases the traffic capacity of an intersection	1. May cause safety concern due to limited clearance 2. Intersection may be temporary closed
New Traffic Signs and Pavement Markings	Low/ Moderate	1. Provide information to road users 2. Lower cost of installation and easy to be removed or relocated 3. Delineate travel lanes	1. Potential Confusion to road user if traffic signs are not clear and properly placed 2. Redundant signs can cause confusion and senselessness
Add Left-turn Lanes	High	1. Increase the efficiency signal operation of signalized intersection 2. Enhance intersection safety 3. Increase capacity and reduces delay.	1. May need to narrow existing lanes, shoulder and median to attain additional pavement width. 2. A transition is required to separate turning traffic from through traffic. 3. Construction cost may be considerable
Intersection Channelization	Moderate/ High	1. Channelization islands provide a refuge for pedestrians 2. Delineate desirable vehicle paths (usually right-turn) within wide intersections 3. Raised medians restrict left turns from a driveway between two signalized intersections.	1. Left-in and left-out turns may be restricted 2. Channelization islands may block the bicycle lanes 3. Raised medians may affect the accessibility of roadside business
Left-turn Prohibition	Low/ Moderate	1. Increase signal efficiency and intersection capacity 2. Eliminate left-turn collisions 3. Reduce intersection delay	1. Alternative routes are required for left-turn vehicles 2. Inconvenient for turning vehicles 3. May not be publically welcomed
Convert into One-way Traffic	Moderate	1. Improve signal timing and accommodate odd-spaced signals 2. Reduce head-on collision and pedestrian crashes	1. Conversion may be costly 2. Increase travel distances of motorists and bicyclists 3. Can create confusion
Indirect Left-Turn Design	Moderate	1. Improve through traffic 2. Reduce intersection delay 3. Reduces total crashes at intersections	1. Unsatisfactory performance under moderate or high left-turn volume 2. Increase travel distances of turning vehicles 3. Require extra right-of-way 4. May cause confusion
Roundabout	High	1. Eliminate most of the conflict points 2. Provide greater capacity and shorter delay 3. Easy U-turns 4. Low operation and maintenance cost than signalized intersection	1. Inconvenient for pedestrians to cross the street 2. Right-of-way acquisition can be very expensive
Underpass/ Overpass	High	1. Spatially separate conflicting traffic 2. Significantly increase intersection capacity and reduce delay 3. Easy to be used for faster passage of emergency vehicles	1. Cost of construction would be prohibitive 2. High maintenance expenditure 3. Underground utilities has to be relocated
Toll/ Congestion Pricing	Low/ Moderate	1. Efficiently allocate scarce resources 2. Alleviate congestion	1. May experience strong public controversy 2. Raise a concern of traffic inequality

1.3 Problem Statement

Intersection treatments which are designed to enhance arterial traffic flow reduce intersection delays and benefit safety issues are usually evaluated in terms of operational and safety improvement. Some of the treatments have a straightforward assessment, such as optimization of signalization. Others have substantial impacts on surrounding intersections and community. For a complex intersection in urbanized area, the impacts may refer to several stakeholders with conflicting interests. For example, motorists want high speed flow and neighbors want low speed flow and long pedestrian time. Many intersection improvement measures, such as turning movement restriction, roundabout, underpass and channelization, have been generating much public objection over the years. Public controversy comes from various subgroups within the affected communities, such as residents, businesses, and road users. The concerns from residents usually focus on the safety, noise and pollution during and after the intersection improvement project. The primary concerns of transportation agencies may be the right-of-way inquiry and project budget. Much of the protests of business and property owners result from the potential loss of by-pass traffic and accessibility that are strongly related to their business profits and land value.

Different expectations and uncertain consequences of effects have made it difficult for transportation agencies, residents and business to be able to work together. In addition, the engineers, stakeholders and decision makers have limited information and understanding of the full range of effects that may be attributed to an improvement project. Although sometimes an improvement alternative has to be abandoned due to public protest, the public perceptions and options are not always reliable and stable. For example, a study conducted by the Engineering Division of City of Woodbury, Minnesota, showed that 80% to 90% of residents are against the construction of roundabouts before the construction, but after construction this quickly changes to 80% to 90% in favor [4]. A study of the effects of raised medians on business vitality conducted by Iowa State University in 1997 also indicated that business owners' perceptions of the potential for adverse impacts of access changes tend to be much worse than actual impacts based on before and after comparisons [5].

The public controversies and the potential advantages associated with intersection treatments and the potentially substantial tradeoffs and uncertainty in alternative analysis and evaluation suggest a need for research on developing a complete process to planning, analyzing and evaluating treatments, in order to assist transportation agencies in addressing public concerns and in comprehensively understanding their capabilities and risks.

There is currently unavailability of methods pertaining to assess the full development cycle of an intersection improvement project and lack of techniques that can be used to integrate the impacts of various dimensions and interpret tradeoffs between conflicting interests. With the purpose of applying the best possible methods to increase the capability of effects prediction and control, although a comprehensive method considering multiple objectives and attributes of a proposed treatment is inherently complicated, this research developed a full approach taking into account intersection treatment planning and screening, feasibility and performance analysis, and evaluation, trade-offs and decision-making.

1.4 Left-turn Prohibitions and Low Clearance Underpass

This method was developed to handle the difficult and complex mitigation assessment of Left-turn prohibitions (LTP) and partial grade separation (1 or 2 lane low clearance underpass, i.e., LCUP). It can also be used to evaluate most other mitigations.

LTP is considered as one of individual movement treatments according to FHWA Signalized Intersections: Informational Guide [6]. Permanent or temporary (usually during congested periods) restriction of left turning maneuvers of one or more directions is commonly employed as a low cost and sometimes short term measure of intersection level of service improvement. This measure is applicable to areas with high road density, available rerouting paths (if adjacent roads can accommodate the rerouting traffic) and moderately heavy turning volume. Intersections with too heavy or too light left turning traffic are not likely good candidates for left turn prohibition. Light left turn volume may yield a negligible improvement and heavy left turn volume may relocate the problem elsewhere or generate a large number of complaints. This intersection treatment is relatively easy to be implemented and can be quickly installed and removed. Level of service improvement may necessitate only a peak period prohibition of left turns. Safety improvements may necessitate the permanent prohibition of left turns. LTP may cause motorist, and resident and business complaints for “loss of access”. Rerouting may also affect local street condition.

LCUP is one type of grade separation that is described as one of the intersection reconstruction treatments [6]. The primary benefits of reconstruction treatments are the permanent reduction in conflict points and significant improvement of traffic operation at the intersection by reducing the number of phases and conflicting volume at a single location. LCUP is a bypass underpass in the form of a short cut-and-cover tunnel for one or multiple congested intersections. Unlike standard underpass which provides 4.9 m (16 ft) clearance over the entire roadway [7], the proposed underpass is “substandard” with only 2.5 m (8 ft) height clearance and cannot serve vehicles taller than 2.0 m (6.6 ft). An overpass would be the same in terms of functionality (and likely cheaper) but aesthetics make it less desirable for central city locations. Low-clearance is necessary to minimize the length of approach ramps, which in turn minimizes the length of the underpass and make it more suitable for major intersections.

Typically a very small proportion of urban traffic consists of vehicles taller than 2 m. According to NCHRP Report 599, the average percentage of truck, buses and recreational vehicles within a city (population size not less than 50,000) falls within a range of 2.5% to 3.5% [8]. These tall vehicles can use the at-grade lanes of the intersection or switch to alternate routes. Underpasses are suited to wide intersections (e.g., a cross section of seven or more lanes is ideal for two way streets).

Underpass capacity benefits come from the fact that 1 or 2 lanes pass through the intersection at effectively 100% green time. As a result, demand decreases on the subject direction and its actual green (at grade) is reduced. Within the same cycle length, the saved green is reallocated to other movements, so other approaches are also benefitted. One to four thousand vehicles per hour may use the underpass instead of the surface junction thereby reducing conflicts and accident risk with other vehicles, bicycles and pedestrians.

These two treatments are not arbitrarily selected in this study, but by considering the following attributes:

(1) Treatment requiring minimal Right-of-Way (ROW)

The most direct and intuitive approach to alleviate the increasing congestion is to cope with the peak period disparity between the total travel demand and limited capacity of major intersections by expanding intersection capacity. The addition of lanes by expanding the street ROW is often impractical in build-up cities and the provision of more and narrower lanes or reversible lanes has often been exploited. Some high-flow intersection treatments such as unconventional intersection designs require an amount of space which is typically unavailable in dense urban areas; they also tend to generate heavy U turns and a pedestrian unfriendly environment [9].

Because LTP requires slight road work and doesn't modify intersection layout and LCUP adopts small and substandard structural dimension, both treatments may improve traffic and safety with little or no need for additional ROW for urban signalized intersection experiencing severe congestion and safety issues. Another capacity improvement suitable to the problems and conditions specified above is the subterranean double decking of arteries or the addition of express tunnels, both of which have been done is several cities. These are relatively massive regional capacity enhancement alternatives. However, our selection of treatments focuses on maximizing the capacity of intersections with localized treatments.

(2) Absence of methodology for planning and analyzing LTP and LCUP

LTP and LCUP are not new solutions for addressing intersection operation and safety issues and are currently in use by various organizations. However, there is a clear absence of methodology for assessing the significant tradeoffs in the benefits and impacts of these treatments. The absence of methodologies and guidelines may also have played a role in the relatively suppressed use of these solutions for intersection capacity enhancement

According the surveys on guides and methods of left turn prohibition conducted by ITE Technical Council in 1981[10] and Virginal DOT in 1994 [11], little information could be used to evaluate the LTP at signalized intersections and few operating agencies have a method to establish prohibitions. Because of the complication and uncertainty in defining the redistribution of turning vehicles and the possible negative consequences including increase of travel time and distance and relocation of congestion after left turn restriction, most of the left turn removal plans are determined based on traffic engineers' "empirical judgment" or "trial deployment" rather than a systematic and scientific process.

LCUP may be the most effective but most expensive countermeasure to cope with a dangerous and congested arterial intersection. However, the underpass are not as popular in the US compared with Asian and European countries, since massive investment on a transportation project with substantial construction work, long-term expected return period and considerable impacts on surrounding areas may trigger a large-scale public dispute. In addition, there may be concerns on ROW demand and underground utility relocation, possible visual and obstruction impacts to the adjacent residents. Due to potential lower maintenance and liability costs, and limited ROW requirement compared with other grade separation alternatives, LCUP is selected as a more promising treatment for urban intersections. Although the potential application of the smaller dimension separation structures on mitigating urban congestion and safety risk has been proposed in several recent research [12][13], there remains many questions about addressing social and economic impacts, determining its feasibility and comparing with other alternatives.

(3) LTP and LCUP evaluation under uncertainty and trade-offs

Although these solutions offer a way to make a significant transportation improvement in a congested area with limited ROW for roadway expansion, the analysis and evaluation of both treatments have to concern the uncertainties in performance measures (such as fluctuation of traffic volume and internal rate of return (IRR)) and tradeoffs among conflicting interests of various stakeholders. The variables and the uncertainty of variables that control the selection of alternatives and determine the impacts of alternatives are not well documented.

For LTP, on the one hand, perceived negative consequences include increase of travel time and travel distance associated with more fuel consumption and air pollution due to rerouting left turn traffic, potential rise in accidents and conflicts as a result of increased vehicle miles of travel and detour driving tasks, and loss in patronage and property value due to restriction of left turn accessibility and business attraction.

On the other hand, if the detour route is adjacent and short, and remaining capacity of the detour route is sufficient to accommodate the turning traffic, the increased travel time of rerouting traffic could be even shorter than the delay of waiting for oncoming traffic or protected signal phase at intersection. The left-turn restriction could also likely realize net safety benefits for the intersections at urban commercial and central areas where many pedestrian crossings are present [14].Where the direct left-turns are restricted, some previous customers may change their driving courses to continue patronizing specific establishments. In some cases, business sale and property value tend to enhance as overall mobility and safety improves [15].

For LCUP, although direct benefits of significantly improved intersection capacity, safety and signal efficiency, enhancement of air quality and reeducation of fuel usage and traffic noise would be apparent and undoubted, grade separation may be opposed by road owners and investors because of the expensive construction and maintenance cost, substantial impacts on traffic during construction, and underground utility relocation. However, their benefits in terms of delay saved (cumulative wasted time valued at minimum wage), energy saved and emission reduction (fuel consumption and emission in stop-and-go traffic) have the potential to surpass their costs in a reasonable period. Especially, if the congestion relief tunnel is tolled, the period of investment return could be considerably shortened. In addition, the low clearance 1-2 lanes underpass is associated with lower cost and is applicable at congested urban intersection where the majority of vehicle classes are passenger vehicles.

(4) LTP and LCUP work similarly in the way they improve signalized intersection operation

Signalized intersection capacity is determined by the cycle length and total lost time including start-up and clearance lost time for each signal phase. The major cause of intersection accidents is the existence of conflict points at the intersection. By reducing the number of signal phases (or cycle length) and conflict points through the removal or relocation of certain movements, the intersection capacity and safety improves. Although the implementation, design and applicability of LTP and LCUP are different, both work similarly in the way they improve intersection Level of Service (LOS) and safety.

1.5 Scope and Objectives of the Research

Retrofitting intersection improvements, particularly in urban area with heavy traffic and complex land use, have long been a cause of friction between traffic engineers and communities. In order to select the best intersection treatment, the range of impacts, the factors of impacts and the quantification of the impacts are necessary to be accurately measured and assessed. In urban areas, they are not only related to the intersection level of service but also significant to the quality of life of residents and development of local communities. This study is conducted to address these issues.

The consideration of improvement measures primarily relates to those intersections at which excessive traffic delay or above-normal traffic accidents are experienced. The study scope is restricted to the complex signalized intersection on urban arterials and highways. Note that the alternatives associated with intersection modification, movement restriction and grade separation should not be adopted until other low costs and low impact alternatives have been exhausted.

The proposed method is a three-level process including treatment planning, analysis, and treatment evaluation. Planning and analysis processes consist of preliminary screening, feasibility study and quantification of effectiveness. **An innovative multiple attribute process under preference fuzziness and variable uncertainty is developed for evaluating and decision-making of LTP and LCUP.** The method is designed to provide an analytical tool for comprehensive project selection and programming by incorporating the inherent uncertainty of performance measures and fuzzy preference on alternative selection.

The study presents and demonstrates the methodology using the LTP and LCUP treatments. However, the process itself is generic and can be extended to other intersection treatments (e.g., lane addition or lane width reduction). The method consists of three levels and four modules and is demonstrated using a case study containing field data. The method process, along with the solution algorithm, have also be formulated and coded in the Excel spreadsheet and *R Project* for statistical computing.

The key research issues investigated include the following:

- Estimation of after-treatment intersection operational and safety performance.
- Establishment of preliminary planning level assessment model.
- Determination of feasibility conditions and definition of measurement of effectives.

- Development of evaluation models for integrating performance indicators and tradeoffs and incorporating risk, fuzziness and uncertainty.
- Development of decision-making model along with solution algorithm for treatment selection and programming.
- Development of a computerized tool to facilitate the application of this method.

1.6 Dissertation Outline

The dissertation is comprised of eight chapters. The first two chapters discussed the introduction and background regarding this research. The following four chapters detail the method, which is the core of this dissertation including the complete set of the methodology and discussion. The last two chapters are case study and conclusion designed to demonstrate the application of the proposed method and to provide a qualitative assessment on the findings and a perspective for future work.

Chapter 1 discusses the increasing need for a complete and inclusive analytical and assessment tool for addressing the intersection treatment selection and programming characterizing risk and uncertainty, as well as the scope and objectives of the research. Chapter 2 summarizes the existing literature on the development of treatment analysis and use of uncertainty methods in traffic project evaluation. It also provides background information and recent research on methods for the valuation of intersection performance measures, performance indicators and modeling, improvements and effects analysis, uncertainty and risk analysis, and multiple criteria decision-making. Chapter 3 briefly presents the overview and structure of the proposed methodology. Chapter 4 is the first module of the methodology. It details the planning and screening assessment of intersection treatments used to conduct preliminary operational, safety and economic analysis by assuming isolated intersection layout. The process presented in this chapter is designed to quick evaluate of the application possibility and determine the prerequisite for further analysis. Chapter 5 introduces the second and third modules in the method, concentrating on the feasibility and performance study of applying intersection treatments by considering localized conditions, legal restrictions, and construction supplies. The performance analysis introduced in this Chapter considers the study intersection in urban road network and combines existing performance measures tools. Chapter 6 discusses the fourth module and it establishes the evaluation and decision-making procedure with multiple objectives, attributes and stakeholders and estimates the marginal effects of performance criteria uncertainty in achieving on project utility computation and models. Tradeoff analysis on selection and programming, risk behaviors and mathematical amalgamation are also provided in this chapter. Chapter 7 begins with a brief introduction of case study location and field data collection, then follows to validate the proposed methodology and study findings. Chapter 8 provides a summary of the study findings, the potential exploration of the proposed method in other transportation areas and in future research. The outline of the dissertation is shown in Figure 1.1.

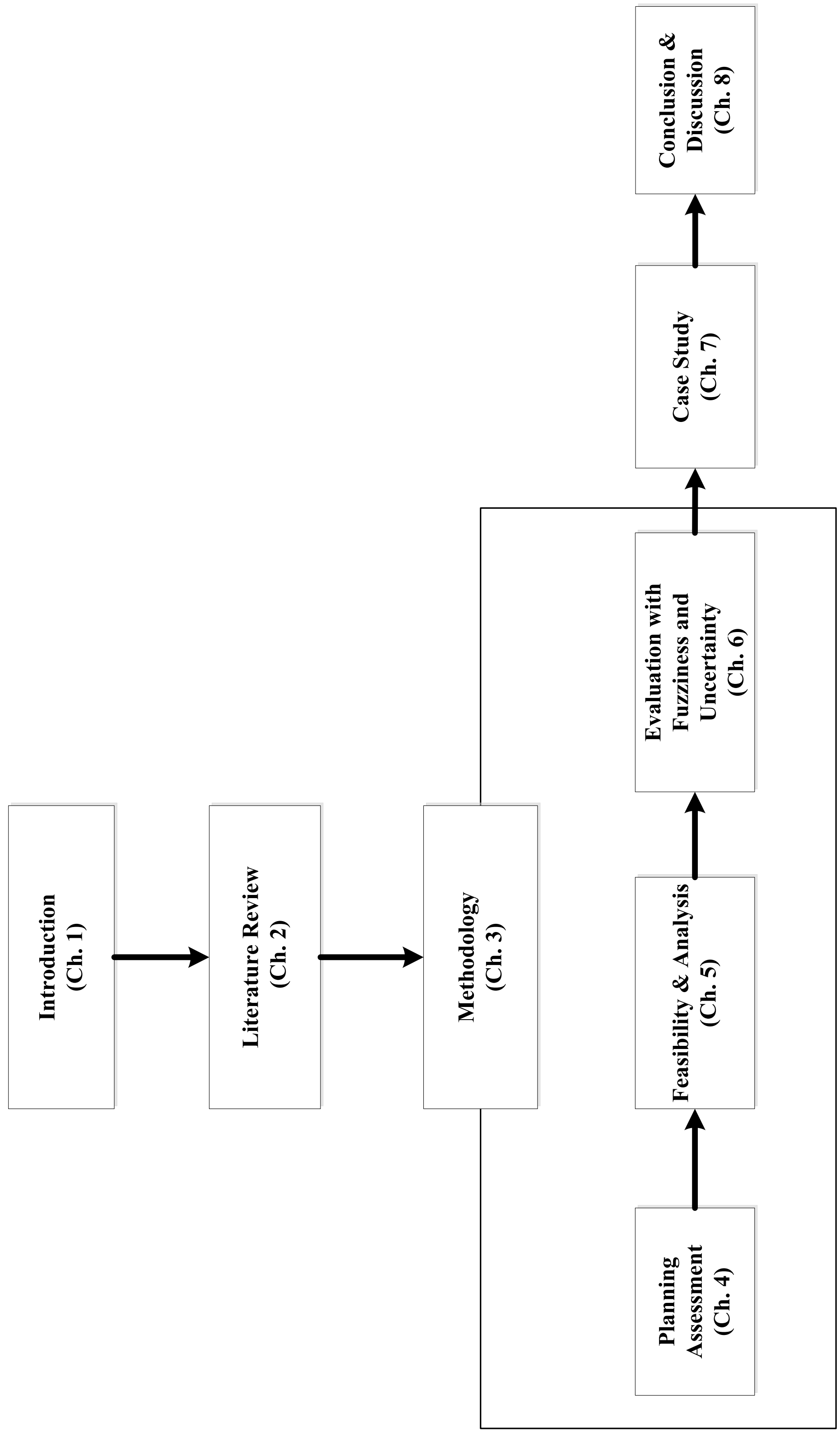


Figure 1.1 Dissertation Outline

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Over 200 references related to the analysis and evaluation of signalized intersection treatments were found in Science Direct, TRB publications database, University of California online, Texas Transportation Institute (TTI) and other transportation journals. A large portion of the research emphasizes the analysis of turning movements, such as left-turn prohibition, indirect left-turn and intersection channelization, and the installation of roundabouts and underpasses. However, a comprehensive method considering the full development cycle, uncertainty and risk factors have received only limited attention. Only a small proportion of studies on improving established project analysis and assessment methods were found.

This chapter present literature reviews on the existing methods of intersection treatment analysis. Additional literature reviews on downstream queuing effects are presented in Chapter 4 where the planning and screening analysis is introduced. Additional literature review can also be found on uncertainty algorithmic, fuzzy and risk theory discussed in Chapter 6.

2.2 Intersection Treatments Analysis

2.2.1 Left-Turn Prohibition

Left turns prohibition at intersection can be found in many states and cities as a countermeasures to traffic operational and safety issues. According to a survey conducted in 1996 [16], most transportation agencies at one time for another have prohibited left turns and the common methods for prohibition are signing (temporary) and raised islands (permanent). About twenty years ago, ITE Technical Council planned to generate specific guidelines or warrants for left-turn prohibition at urban signalized intersection, but the attempt was unsuccessful due to insufficient data and samples. Based on their survey on fifty States, and counties and cities with urban areas over 50,000 population, 79% of local and regional traffic engineers didn't specifically consider the effects of the diverted left-turn traffic on the surrounding streets and communities [10]. A study on identifying traffic and road conditions for installing No Left Turn signs was conducted by Virgina DOT [11] in 1994 by sending a questionnaire to nationwide state, city and county traffic engineers. The results also showed that 86% of the respondents did not have a written policy, and installed these signs on a case-by-case basis using "engineering judgment". In 1984, research sponsored by Federal Highway Administration (FHWA) developed a delay prediction tool to describe the effect of left-turn prohibition on the through and right turn traffic at urban signalized intersections [14]. The principal focus of research was the qualitative discussion of left-turn restriction on traffic system and safety. It contained little information about the safety assessment of left-turn removal and didn't produce an estimation of quantified benefits to the abutting communities.

A set of turning prohibition design criteria was provided in NCHRP Reports 348 [17] and 457 [18]. It recommended that left turn related delay, conflicts or crash frequency, availability of alternative routes, and the location of the intersection should be carefully studied for LTP cases. The potential effects of left turn removal are uncertain. On the one hand, possible negative consequences include increase of travel time and distance for rerouting left turn traffic which come with more fuel consumption and air pollution, potential rise in accidents and conflicts as a result of increased travel (detour), and relocation of operational or safety problems [7][10][11]. In addition, some loss in business patronage and property values may be attributed to LTP due to potentially reduced accessibility and exposure [19].

NCHRP Project 25-4 attempted to analyze the economic impacts resulting from restricting left turns. The scope of this research was to determine and quantify the effects on tenants and property owners through a series of field studies and surveys [16]. However, the insufficiency of study sites, the lack of community participation and interviews, and unreliability of business sales and employment data precluded the development of a quantitative model for the estimation of impacts. NCHRP Research Digest No. 231 summarizes the findings from the final report of project 25-4. The key findings based on the surveys and limited statistical analysis were" 1) Attitudes and perceptions were mixed, some business owners reported a loss in business, while others felt the congestion alleviation expanded their market area. 2) Gas stations, food stores and personal service business appeared to be the most adversely affected by left-turn prohibition.

Many alternative routes are adopted to divert left turn traffic, such as right turn, followed by U turn or a loop of three right-turns. ITE research in 1981[10] concluded that the installation of three right turns to eliminate left turn will simultaneously increase the driving task, vehicle miles of travel, fuel consumption, air pollution, traffic noise and vehicle operating costs. Accident potential may also increase for vehicles and pedestrians. In contrast to ITE's conclusion, UPS announced that they employed a "package flow" software program which will give the best pre-designated route for package delivery by minimizing the need for left turns. This "no left turn" policy annually saved 3 million gallons of gas, and reduced emissions by 31,000 metric tons of CO_2 [20]. Based on an interview with UPS chief operating officer Dave Abney (Atlanta, GA), engine idling and waiting for oncoming traffic to clear is wasteful. Actually, the "three right turns makes a left" loop dispatch is an efficient way to run UPS delivery network [21]. In addition, FHWA's study on the effects of prohibiting left-turns at signalized intersections showed that left-turn pedestrian accidents occur much more frequently than right-turning accidents. The left-turn replacement by a loop of right turns could likely realize net safety benefits at school crossing and urban commercial areas [14].

A research on impacts of raised median was conducted by TTI for Pleasanton Baytown, and San Antonio in Texas in 1964 [22]. The results showed that the total left-turn volume at intersection was significantly reduced after construction of raised median, but the change of gross business sales at the three cities was inconsistent, ranging from -14% to +5%. A similar but more comprehensive study on the economic impacts of raised median was completed by TTI in 2001 [23], which involved personal interviews and mail-out survey of business owners and customers in eight cities of Texas. The research indicated the differences in perceived impacts from those business owners present before, during and after the raised median installation. The business owners had harsher prior perceptions of impact than after construction. Although the surveys provide insight into the perceptions of business owners and customers regarding an improvement measure, the methodology developed in this research only provide a research work plan instead of a tool for impacts estimation and comparison in general.

Transportation Research Center at the University of Florida assessed the impacts of raised median projects at a 2.25 mile commercial section of Oakland Park Boulevard in 1993, which includes 4 signalized and 33 unsignalized intersections and median openings [24]. The researchers conducted surveys on the affected road section in order to obtain resident, customer and trucker's attitudes before and after the construction: 44% of residents and customers surveyed felt increased inconvenience in visiting business. Most business owners reported no change in the patronage and property value, and 6% reported an increase in business sale. A study by Levinson summarized previous studies of impacts of installing medians and concluded a simplified empirical approach to estimate the impacts of movement removal on business profits based on quantification of pass-by traffic and the likelihood of left turns for various business activities [25]. Based on Levinson's approach, NCHRP Report 420 [26] developed a software program "IAMT CALCULATOR" to estimate the economic impacts of access management (intersection channelization and turning restriction). The algorithm of IAMT CALCULATOR for economic impacts is used to estimate the maximum revenue loss after left-turn restriction based on percentage of pass-by traffic and left turn volume, and business types. This software is not widely adopted by transportation engineers to estimate the economic impacts because this calculation simplified the economic effects of various improvement alternatives and ignored the potential benefits of traffic improvement to business.

2.2.2 Grade Separation

The most effective but most expensive countermeasure to fix a dangerous and congested arterial intersection is to construct an underpass s. However, there are many concerns about feasibility and availability of grade-separation at urban intersection, such as right-of-way and underground utilities. Underpasses are more popular in Asian and European countries. Thailand's study on application of underpass in urban area inspected the widely adopted underground structures in urban areas of Thailand for the last 20 years and concluded that the use of vehicular underpasses at major intersection become more popular and accepted by engineers and residents because it mitigates traffic congestion and yields more environmentally friendly results [27].

Underground construction can be expensive. Dehnert and Prevedouros designed a substandard underpass (low clearance) for urban intersections [12]. Underpass design was modeled with INTERGRATION along a congested arterial in Honolulu. The results showed the substandard underpasses effectively reduce the travel time, fuel consumptions and air pollution. The cost of construction would also be significantly less than regular underpasses. In the City of Wuhan, China, substandard underpass has been applied to several major intersections on urban arterials. This project is sponsored by The World Bank [28] in order to reduce the serious intersection congestion of mixed traffic flow.

A general guideline which descriptively introduces the design and operation criteria for installing interchanges and grade separations is provided by AASHTO's "Green Book" [7]. Underpass retrofit at urban arterial streets has been difficult because of cost concerns, disruption due to construction, underground utility relocation, etc. [6] [29]. On the other hand, an underpass may significantly improve intersection capacity, safety and signal efficiency, and also enhance air quality and reduce fuel usage and traffic noise.

Underpass benefits in terms of uninterrupted access, delay and energy saved and noise and emission reduction have the potential to surpass their costs in a reasonable period [12] [30] [31], especially if it is tolled [32].

2.3 Methodologies for Treatment Assessments

FHWA report HRT-04-091 describes a standard process for conducting an intersection design/redesign project assessment including identification of stakeholder interests and objectives, establishment and summary performance measures and criteria, and determination of costs and implementation issues. NCHRP Report 457 [18] provides a guide for the engineering study process of operational effectiveness evaluation of various intersection treatments. However, it only shows a guideline on assessing the operational impacts of the treatments by using capacity analysis and traffic simulation models. The assessment of an alternative's safety and other effects is not addressed.

Most previous studies attempted to collect information about effects on business sales, employment, property value and resident quality of life and to define stakeholders and their interests through surveys or interviews. NCHRP Project 25-4 [16] focused on the qualification of overall changes in population, employment and income and travel patterns within the affected corridor region.

TTI's research in 2001 [23] administrated several surveys in different cities to assess the residents and businesses' opinions on the raised median. Changes of gross business sales and property value were selected as the effect indicators to evaluate the potential impacts of the project. A research that designed to estimate the business owner's view on safety improvements after conversion into one-way was administrated by Texas Transportation Institute's research in 1987 [33].

Habib's research sponsored by FHWA [14] contained an assessment to evaluate change of safety value and traffic delay due to left-turn prohibition. Its method required field measurements to calibrate traffic simulation model, which was then used to generate results for a variety of traffic volumes, approach widths, and traffic delay. An investigation on assessing attitudes of road users regarding two-way and one-way roads was employed and its results indicated that the enhanced safety associated with one-way roads is widely recognized and many real estate or business owners vary in their views.

A case study on the application of low-clearance underpass at unban intersections was conducted to assess the benefits of implementing substandard underpass at the intersections along a congested urban arterial network in Honolulu [12]. Traffic simulation model was used to examine the traffic performance of four intersections and to compare the benefits of travel time and fuel consumption with and without grade separation. The construction costs of underpass and savings in travel time and gasoline were monetized and included in economic comparisons. The research showed that the expected benefits would outweigh the costs of construction and implementation after two to five years of operations for three of the four candidate locations in the case study.

Miller presented a research on the costs and benefits of roadway pavement markings in 1993[34]. This analysis considered the costs and benefits due to pavement marking on different classes of road and land use, including the unit costs of fast-dying paint or thermoplastic materials, the environmental costs of high-solvent paint and the benefits from crash reduction and travel speed increase. Those indicators were assessed based on the empirical assumptions or the conclusions of related published literature. In addition, sensitivity analysis was conducted and showed the estimation of benefit-cost ratios is robust.

2.4 Treatment Evaluation and Selection

Cost-benefit analysis (CBA) is a common and simple tool employed to evaluate transportation projects. It provides a set of values that are useful to determine the feasibility of a project from an economic standpoint [35]. However, results of cost / benefit analyis may be inaccurate and have enduring bias, if large infrastructure projects have high risk of cost overruns, uncertain return period and conflicting interests. The FHWA recommends that full range of reasonable alternatives and effects need to be considered for a proper CBA [36]. However, since CBA has to convert different types of non-monetary performance criteria in dollar term and CBA is unable to explore uncertainty and tradeoffs in costs and benefits.

Concerns with current evaluation methods are they have a myopic focus on only a few impacts. If they focus on many impacts, then difficulty in interpreting those results during decision-making if attributes and interests are equally combined the built-in uncertainty and risk are simply ignored. More advanced and complete evaluation by integrating probabilistic and uncertainty analysis techniques into decision-making in transportation engineering or other domains have received increasing attention past decade. Attempts to mitigate these issues are summarized below:

Hans-Jürgen Zimmermann's book "Fuzzy Set Theory-And Its Applications" introduced several operations research principles that can help in the selection of the most appropriate method for solving a specific multi-criteria decision-making in ill-structured situations by using the popular decision-making approach analytic hierarchy process [37]. Sjoerd and Huibert's research explored the application of fuzzy set theory to solve multiple-attribute decision problems under uncertainty. Their study proposed the concept of membership level to fuzzify the inherent uncertainty of preference (ratings or weights).It provided a basic method to establish preference fuzzy set to quantify the uncertainty of rating and weighting among different attributes or stakeholders [38]. Turan Arslan conducted a research on decision support model to consider public opinion in forming transportation policy or selecting transportation project by using fuzzy logic and analytical hierarchy process [39]. Xiaojin Ji 's research introduced that a probabilistic method with comprehensive view and more realistic and robust results of the LOS evaluation of a signalized intersection. The probabilistic analysis provides a control delay and LOS results varying from simple upper and lower values to a comprehensive output with mean values, standard deviations, confidence intervals and distribution of delays by investigating the integration of variable uncertainty (represented by probabilistic distributions) [40].

A design technique of Aerospace Systems (MATE) developed by Diller applies the Joint Probabilistic Decision-making (JPDM) technique for multi-objective optimization and product selection [41]. The technique can account for the uncertain values of the uncontrollable variables because of its ability to transform disparate objectives into a single figure of merit. This technique further evolved into a multi-attribute tradespace exploration method to capture decision maker preferences and use them to generate and evaluate a multitude of space system designs. Through multi-attribute utility theory for the aggregation of preferences to create a common metric for evaluation in those models, the process provides a common metric that can be easily communicated throughout the design enterprise and enables the engineer to discover better value designs for multiple stakeholders [42]. In 2010, the MATE was extended to the area of transportation planning. It addressed multiple stakeholder structure and several cost types for the purpose of the transportation system analysis and highlighted the application of tradespace exploration in determining trade-offs between alternatives in transportation domain by proving expected benefits, variability and patron optimal values [43].

2.5 Summary

According to the study of current literature, the deficiencies of previous studies may be summarized as follows:

1. Most of the research on intersection treatment analysis focuses only on the impacts on safety and operations and defines the road users as the primary beneficiary of intersection improvement project and transportation agencies as the only decision maker.

2. The effects of a proposed improvement project on a community's social and economic welfare are usually estimated based on questionnaires, interviews, or public hearings. Researchers also found survey may be an effective tool in descriptively collecting the attitudes of all interest groups, but the results from survey can hardly be

used in quantifying the effects and further integrating into the decision-making process because personal preference is fuzzy and complicated to be measured, and the responses from various stakeholders can be conflicting and inconsistent. In addition, weak community participation was experienced by the researchers.

3. Comparison of business sale, employment data, and property values prior to and after the intersection treatments was utilized to assess the economic impacts. However, these data are not available or are difficult to access. Furthermore, the change of business profits may result from the combination of traffic condition and other factors, such as local economic conditions and variation of product demand. The portion of change in business profits due to traffic improvement at intersection cannot be accurately separated and individually estimated. Previous research only estimated the short term after-treatment performance improvement at an intersection. The impacts during the construction period, the side-effects on surrounding areas and the long-term impacts on traffic demand and pattern are usually not taken into consideration.

4. Many researchers have acknowledged that CBA can only be applied if all of the relevant effects of a project can be measured as monetary equivalents and only if decision makers fully agree on those measurements. The evaluation of some intersection treatments (the LTP and LCUP discussed in this study are the typical) are naturally manifold, politically controlled and public related, so that technical decisions cannot be made without considering the best balance between conflicting interests. Proposed transportation project that generates substantial and conflicting concerns, involves many uncertain and non-monetary performance measures, and has multiple objectives and

attributes, the reduction of multi-criteria judgments to a single net aggregate benefit in CBA raises a large number of concerns and inaccuracy.

According to recent studies on addressing this issue, the structured technique of Analytic Hierarchy Process (AHP) is widely used to organize and analyze complex decisions containing multiple criteria. A quantitative uncertainty Monte Carlo simulation and probabilistic methods are recommended to apply for capturing the variety of performance measures and examining the confidence level and conclusion robustness. The multiple attribute utility theory with sampling based replication calculation across the design variable enumeration range is employed to generate tradespace to determine the optimal solution and assess the tradeoffs.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter outlines the entire methodology for planning, analyzing and evaluating LTP and LCUP for urban signalized intersections. It discusses the process that was adopted to address the multitude of tasks involved in the improvement of a major intersection. These tasks include treatment screening and planning, feasibility study, selection of traffic performance indicators, application of analysis tools and models, fuzzifiness of stakeholder preferences or perceptions, uncertainty and tradeoff analysis, and project selection and decision-making. This chapter discusses the structure of the methodology and explains the interrelations and interactions among the main modules in each level of the method. This chapter is followed by three chapters that detail each level as well as provide definitions and measurements of the indicators and criteria used in this method.

The proposed method is designed to:

1. Provide a completed, robust and systematic approach for planning and analyzing the application of LTP and LCUP treatments at an urban signalized intersection. It addresses two treatments which generate public controversy, but have no methods, tools and techniques that can be used to analyze and justify their applicability.

2. Develop multiple-objective evaluation and selection approach featuring fuzzy mathematics (FAHP) to capture the tradeoffs of stakeholder preferences, utility function theory (MAUT) to describe risk sensitivity, and probabilistic approach (Monte Carlo) to model criteria uncertainties.

3.2 Structure of Methodology

This methodology is designed to be used throughout the project development cycle of an intersection improvement project including treatment screening, planning, feasibility study, detailed traffic and performance analysis, and evaluation and decision-making. The method consists of three levels which are:

- **Level 1** - Planning and screening level assessment including preliminary and intersection-wide operational, safety and cost-benefit analysis. Level 1 is detailed in Chapter 4.
- **Level 2** - Feasibility and analysis level. It includes 1) the identification of project objectives and stakeholders' concerns, project budgeting and scheduling, and construction impacts assessment and 2) detailed traffic and performance analysis including traffic, environmental and other impacts analysis on adjacent intersections, roadways, and surrounding communities within a defined influence area. This level also develops and identifies the performance attributes and indicators for the appraisal of treatments. Level 2 is detailed in Chapter 5.
- **Level 3 -** If substantial uncertainties involved in performance analysis and/or conflicting interests involved in stakeholder perceptions, multiple-objective

assessment with fuzziness and uncertainty should be employed in project evaluation and decision-making, which includes Measure of Effectiveness (MOE) weighing and scaling, uncertainty and tradeoff analysis and project decision-making. Level 3 is detailed in Chapter 6.

The complete method including planning, analysis and evaluation is shown in Figure 3.1. It is designed to assist in robust and reliable analysis and decision-making among candidate alternatives. The comprehensive processes maximize consistency, accuracy and validity for selecting the best treatment. As indicated in Figure 3.1, the method is applied at three processing levels using four modules. Level 1 is a planning level proceeded within Module 1. Level 2 is analysis level including feasibility and traffic analysis that are programmed in Module 2 and Module 3. Level 3 is an evaluation and decision-making process completed in Module 4. The first two levels are planning and engineering studies focusing on generalized planning and screening, feasibility of proposed treatments, and measuring direct and indirect traffic and other impacts by using existing models or tools. The third level is an evaluation and programming procedure. This level is designed to answer whether the proposed treatments which the stakeholders are funding, implementing, voting for, receiving or objecting to are actually having the intended effects. This method proposed a comprehensive multiple-objective decision-making process in this level, which collects and integrates the performance measures, stakeholder preferences, and uncertainty/risk factors from the previous phases and external resources. This process uses to generate scenario for tradeoff analysis in order to select the best alternative based on effectiveness and efficiency. If uncertainty and risk factors in measuring treatment performance and public perceptions are not taken into account, a traditional decision-making process using basic cost-benefit and sensitivity analysis can be used at this level.

As shown in Figure 3.1, this method has three conditional tests (A, B and C) at each level where a judgment is necessary (Yes/No question). A positive answer would lead the flow to advance to the next level or module, but a negative answer could end further consideration of these treatments for a given intersection. The stratification of the method is designed to filter out unprofitable and infeasible treatments or locations prior to conducting extensive and expensive analysis and evaluation. The detailed data collection, microsimulation and performance assessment can be cumbersome, often time consuming, and labor intensive. Most of current practice initiates a detailed traffic study without conducting the preliminary planning and feasibility study. However, a planning and feasibility study is essential for determining whether such effort should be expended. They are also important for developing a prioritized list of LTP and LCUP deployments at major intersections. Especially for a city-wide improvement project involving numerous intersections, this layered method can assist in selecting only the most promising treatments or locations for detailed analyses and minimize the expenditure of resources.

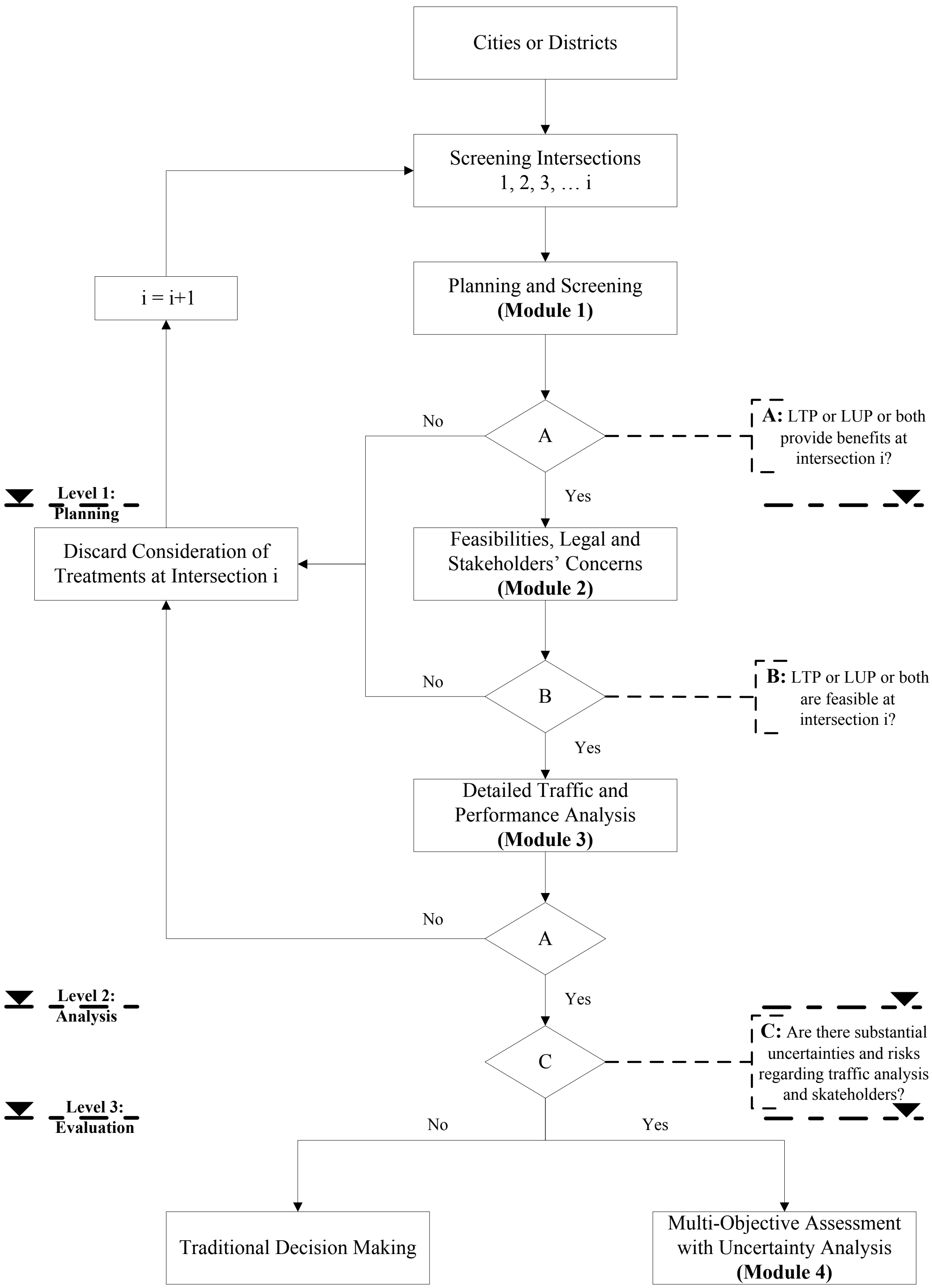


Figure 3.1 Methodology Structure

3.3 Levels and Modules of Methodology

An extended layout of methodology summarizing main tasks in the levels and modules is shown in the Figure 3.2. The complete set of this method has three levels used to identify and to further assess the candidate treatments. The levels are arranged in order of complexity and the logic of this sequence, from intersection-wide planning, to site-specific feasibility and traffic study, and end with alternatives comparison and selection.

The planning and screening module in the planning level maximizes the use of default settings in Highway Capacity Manual 2010 (HCM), Highway Safety Manual 2010 (HSM) and User and Non-User Benefit Analysis for Highways (AASHTO Redbook, abbreviated as UBA herein) in order to minimize requirements and to expedite the assessment of treatments at multiple locations. The locations and treatments that passed this level may be further analyzed in the second level. The second level includes feasibility and analysis modules. The feasibility module examines the construction, budget, local and legal constraints for a special project to produce additional verification of the applicability of the proposed treatment. If a project passes the feasibility examination, a detailed analysis on traffic and other impacts (e.g, energy consumption, emissions and impacts on accessibility, and businesses and property values) will be conducted in the analysis module. The third level is used to evaluate, compare and select the most deliverable alternative. The evaluation module in this level proposed a stochastic multiple-objective evaluation approach for a comprehensive alternative selection by addressing issues of measurement uncertainty, conflicting interests and inherent risk. In some cases, HCM, HSM and microsimulation analysis may need to be rerun with more refined inputs or additional MOEs based on the evaluation results, so feed-back loops have been included in Figure 3.2.

As shown in Figure 3.2, this is a level-independent method. Although the full cycle of analysis is recommended for major intersection projects in urbanized area, each level can lead to decision-making depending on the characteristics of the project. For example, the planning level assessment may be sufficient to determine a suitable project if project budget, land use limitations, and construction and traffic impacts are not the primary concerns. If there are limited uncertainties regarding the estimation of performance indicators and the conflicts among stakeholders are not considerable, a planning level assessment used in preliminary screening and detailed feasibility and traffic analysis used in project selection would likely be acceptable. In addition, although the evaluation level collects the performance attributes and indicators defined and estimated in the previous levels, the evaluation level is not always necessary and may be negligible if the proposed treatment is the only alternative for a site. The key ideas and main tasks of three levels are discussed below.

Figure 3.2 Levels of the Proposed Method

3.3.1 Level 1 – Planning

The planning level answers whether the proposed treatment is promising by presenting fundamental technical and economical results. The process begins with a planning level analysis by only considering intersection-wide impacts and the primary performance criteria: Operations and Safety. By assuming that the study intersection is isolated and controlled by pre-timed signals and fixed phases, the expected benefits due to deploying the treatment are estimated. The process in planning analysis is developed for the proposed two treatments LTP and LCUP in this study because there is a clear absence of methodology in current practice to guide the early stage of analysis and screening for these two treatments. However, this planning assessment can be easily modified to be applicable for other treatments, because the methods used in the assessment of operational, safety and cost-benefits are extracted from widely adopted manuals (HCM, HSM and UBA).

Planning and screening module (Module 1) is applied in this level, which starts with the identification of intersection conditions and collection of treatment related information, followed by three analysis procedures: operational analysis, safety analysis and preliminary economic analysis. This level ends with a judgment on whether or not the alternative potentially provides benefits for the study intersection. The operational analysis focuses on the changes in intersection delay and level of service. The number of predictive annual traffic collisions by vehicle classes, accident severities and movements is estimated in the safety analysis. The economic analysis integrates the direct costs from project design, planning, construction and maintenance and direct benefits from travel time savings and safety risk mitigation in order to estimate the benefit/cost ratio and expected years to payoff. Because estimating the effects of a transportation improvement project requires forecasting transportation and land use for a 20 year period [44], a cost benefit analysis over 20-year project life is conducted. The planning process only measures for the intersection as a whole and optimizes the potential benefits. If the positive measures for an intersection as a whole are nil or negative, or the expected B/C ratio and year of return cannot be satisfied, the proposed treatment could safely be rejected for the intersection.

A quick estimation tool has been programmed into a spreadsheet to automate the planning and screening module of potential solutions based on limited and often readily available data and standard engineering parameters. Level 1 is detailed in Chapter 4.

3.3.2 Level 2 – Analysis

This level starts with the identification of project objectives and affected stakeholders, then proceeds in two modules: Feasibility Analysis and Performance Analysis. The main tasks in this level are to examine the feasibility of treatments by considering site-specific constraints, and if feasible, to conduct detailed traffic and performance analysis.

The feasibility analysis module (Module 2) brings in a series of practical and localized constraints by asking whether the selected alternative can be implemented given time, financial, legal, environmental and social constraints. For example, if considering a turning removal option (e.g., LTP), the availability of rerouting roads and potential legal restrictions on removing the accessibility to some important buildings (e.g., fire station or hospital) should be carefully taken into account before proceeding with the detailed traffic analysis and simulation. The dimension and optimum size of LCUP are most likely restricted by project budgets. The construction impacts, sightline blockage, and the difficulty of underground utility relocation and accommodation can also limit the potential of this alternative.

According to the TELOS principle in feasibility study [45], five common factors in feasibility study are technological feasibility, economic feasibility, legal feasibility, operational feasibility and construction/scheduling feasibility. The planning module and following performance analysis module are designed to address the technological and operational conditions. The feasibility analysis module emphasizes economical, legal and scheduling feasibility.

A set of feasibility indicators based on local conditions are examined in the module of feasibility study. A checklist is provided to facilitate this analysis. The treatments that were justified in the planning assessment are further examined to ensure they are actually feasible given site-specific conditions. This information is used for justifying the feasibility of application under different site conditions in order to determine whether to initiate the labor-intensive detailed analysis and measurement on traffic and other environmental and socio-economic impacts.

The third Performance Analysis module in Level 2 should not proceed until the feasibility of an alternative is justified. The performance of intersection traffic would affect and be affected by adjacent intersections, and driveways. In addition, the treatment may also have potentially significant impacts on environmental, ecological and socio-economic systems. The direct and indirect effects have to be carefully studied and will be used to generate a reliable evaluation and comparison among other alternatives.

In this performance analysis module, the study intersection is treated as its function in the real world: isolated or interconnected intersection. Vehicular flow has to be modeled individually within a road corridor or network and their movements are studied based on car following and gap acceptance theory for the most critical operational and mobility analysis. This module would employ advanced traffic modeling or simulation tools in order to provide detailed information. Microsimulation tools are usually capable of modeling relatively complex geometric and operational situations for a non-isolated intersection. This level also measures other impacts such as vehicle emissions, energy consumption, accessibility, land valuation, and visual impacts by using suitable models and tools. This module enables identification and quantification of the performance attributes and indicators for subsequent evaluation. Level 2 is presented Chapter 5.

It is important to note that the planning and analysis levels (level 1 and level 2) have conditional tests similar to a decision- making process. The proposed treatment may be abandoned if the results of conditional tests appeared to be negative. Although the project alternatives may also be chosen or discarded in these two levels, unlike the decision-making at Level 3, the judgments made in level 1 and level 2 are on the basis of objective analysis results and local conditions. They do not involve uncertainty, risk or trade-offs.

3.3.3 Level 3 – Evaluation

The multiple criteria and objectives in decision-making environments, the difference in attribute preferences, and the uncertainty in performance measures are the primary characteristics defined in the evaluation level. Increasing operational and safety benefits and minimizing project costs and adverse impacts may be some of the main project criteria. However, it is unusual to find an inexpensive treatment for a major urban intersection that offers maximal in safety, energy, environmental and other benefits. The existence of conflicts in stakeholders between their perceptions and preferences leads to more difficulty of yielding the highest benefit values and the lowest cost values. Most of the solutions in changing intersection conditions can only be a Pareto optimality, which means a change to a different alternative cannot make any one or more individual stakeholder better off without making any other individuals worse. Therefore, the evaluation level is designed to seek the alternative which can best achieve a compromise between all competing objectives and conflicting interests.

The intersection treatment selected by the decision-making process would have influences on the future development of surrounding road network and neighborhood communities. Because of significant uncertainties and risks in the measurement of traffic and socio-economic conditions, this level features quantitative uncertainty and risk analysis to make a technical contribution to the decision-making through the quantification of uncertainties in variables and the sensitivity to risk among stakeholders.

There are various benefits of considering uncertainty and risk in the evaluation level. The decision-making would be more scientific and robust by admitting uncertainty in the results. The involvement of uncertainty in performance measurements can be more realistic and would promote rational decision-making. By increasing the awareness of underlying uncertainty and conflicting interests, it also provides a better understanding of the stochastic nature of transportation project evaluation and decision-making process.

The advanced and state-of-the-art evaluation module (Module 4) was developed to incorporate uncertainties of measuring performance and vagueness of multiple stakeholder conflicting interests into an overall decision-making framework, which is also one of the major contributions of our research.

A tradeoff scenario across the multiple dimensions of evaluation attributes was carried out by integrating fuzziness in preference weights, uncertainty in performance measurements, and risks in combination of evaluation criteria. More specifically, evaluation and selection were made on the basis of overall benefits and goals resulting from project implementation in terms of variance of utility values, expected utility values, and possible maximal and minimal benefits. A solution algorithm was also developed accordingly to assist in selecting a subset from all candidate projects in an optimal manner under different stakeholder and/or decision maker priority.

This module is the last but most important module defined in this method. The information defined and quantified in previous module is integrated in this comprehensive evaluation module. The evaluation of intersection treatments may also need additional external inputs such as daily changes of intersection entering volume, turning vehicles and heavy vehicle proportions in order to determine the appropriate restriction period for temporary treatments (e.g., LTP) or reasonable fee scale for tolling or pricing treatments (e.g., tolled LCUP). This additional information provides a complete evaluation scenario rather than only peak period scenario. In addition, the selection of performance MOEs and analysis tools may need to be modified based on the outcomes from the evaluation or feedbacks from decision makers (shown by a dash line in Figure 3.2).

While unique in terms of influence areas and relevant stakeholders, urban intersection improvement project exhibiting a number of common characteristics shared with other transportation projects suggest that the proposed evaluation method can be applicable to general transportation projects and may be even applied across domains. More details about this level are discussed in Chapter 6.

3.4 Chapter Summary

This chapter provided a summary of the methodology structure and brief description of each level and module in the entire methodology. A block chart overview of the study methodology was first provided, followed by the technical details of the three-level methodology including treatment screening and planning, feasibility and performance analysis, and multiple attribute evaluation under fuzziness and uncertainty.

The method is aligned with the project's mission, vision, values and strategic objectives. Approaches and models for valuation and computation of the factors in the analysis and evaluation process were briefly discussed in this chapter as well as a summary of the significance and objectives of each level that deal with key components of project planning, analysis, evaluation and selection.

CHAPTER 4

PLANNING ASSESSMENT

4.1 Introduction

Urban intersections characterized by heavy movements generate many conflicts involving maneuvers, such as crossing, turning, merging between different road users, such as vehicle-vehicle, vehicle-pedestrian, and vehicle-bicycle conflicts. In this research, LTP and partial grade separation (one lane LCUP) are proposed for a properly timed and complex multiphase urban intersection whose traffic handling capacity has been reached or some serious safety issue has developed.

This chapter presents the planning level assessment which is the critical first step for determining whether additional investigation is warranted for LTP and LCUP. Because subsequent levels have intensive data collection and analysis requirements, a careful planning level analysis is essential for determining whether such effort should be expended. This analysis is also important and helpful for developing a prioritized list of LTP and LCUP potential deployments for major intersections. For example, in the primary urban center of Honolulu with population of approximately 600,000, about three dozen major intersections should be investigated. This planning process assists in selecting only the most promising locations for detailed analyses and minimizes the expenditure of resources.

The planning process is designed to provide with a quick estimation of the direct impacts on traffic operation and safety conditions after implementing the proposed LTP or LCUP. As presented in Figure 3.2 in the Chapter 3, the planning process for LTP and LCUP treatments starts with the identification intersection conditions and the applicable LTP and LCUP characteristics and proceeds to operation analysis, safety analysis and economic analysis. The operations analysis focuses on the changes in intersection delay and LOS. The safety analysis estimates the number of annual traffic collisions by vehicle class, accident severity and movement. The expected years to pay off the cost are estimated in the economic analysis. The planning assessment considers intersection delays using the Highway Capacity Manual 2010, accident frequency using the Highway Safety Manual, and cost-benefit analysis based on AASHTO's User Benefit Analysis for Highways Manual. The planning level method uses nationally accepted default values and conservative assumptions to expedite assessment by minimizing the number of required inputs. Due to the complexity of analysis for two treatments (LTP and LCUP) at various time periods and for multiple locations, a spreadsheet-based tool was developed.

Due to limited scope of this planning-level method, traffic impacts on surrounding roads and other secondary impacts, such as emissions and energy are not specifically considered. The study intersection is assumed to be isolated from effects of adjacent intersections. However, downstream effects are considered for the underpass treatment because the queue interactions and spillback between intersections resulting from the significant increase of traffic throughout may reduce the benefits of an underpass.

4.2 Intersection Condition Determination

Intersection characteristics include traffic conditions such as traffic volumes, pedestrian characteristics, and signal timing, safety conditions such as crash frequency, crash type, and crash severity, geometry conditions such as intersection alignment, approach grade, and intersection orientation, design conditions such as number of lanes, traffic signs, pavement marking, crosswalk, curb height, channelization, lighting and street parking, and geographic conditions such as nearby intersections, establishments, schools, and freeway accesses.

Determining an intersection condition and collecting the necessary information are part of prerequisite and essential considerations when initiating the planning analysis of intersection treatments. This process maximized the usage of default standard, authoritative guidance and commonly adopted engineering manual (i.e., HCM, HCS, AASHTO). The data required has been minimized and are most liked readily available or easily obtained. The required inputs are summarized in Table 4.1 respectively for each analysis module.

Table 4.1 Summary of Required Data for Planning Analysis

Analysis Module	Data Required
Operational Analysis	*Traffic Volume*
	% Left Turn on Each Approach
	% Heavy Vehicles on Each Approach
	Lane Configuration
	Existing Turning Phase
	*Left Turn Rerouting Distance**
	*Rerouting Speed**
	*Distance to Nearest Downstream Signalized Intersection***
	*Downstream Approach Green/Cycle Ratio***
	*Downstream Approach Lane Configuration***
Safety Analysis	*Pedestrian Volume*
	Lighting
	*Number of Bus Stops****
	*School Present****
	*Alcohol Store Present****
	*Left Turn Rerouting Distance**
Cost-Benefit Analysis	*Accident Cost*
	Travel Time Value
	Average Vehicle Occupancy
	Planning, Design and Construction Cost
	Annual Operation and Maintenance Cost
	Other Direct Costs
	Annual Interest Rate

* Only required for LTP

** Only required for Downstream Effects Analysis of LCUP

*** Within 1,000 ft of the intersection

Parameters including Peak Hour Factor (PHF), K-Factor, Saturation Flow Rate, and Loss Time per Phase for applying the HCM delay estimation method and the HSM crash prediction models for urban signalized intersections are also required. If specified local parameters are unavailable, default values provided in HCM 2010 [46] for urban areas are suggested to be used (i.e., PHF = 0.9, K-Factor = 0.09, Saturation Rate = 1710 veh/hr, and Loss time = 4 sec/phase).

4.3 Operational Analysis

The operational performance and the quality of transportation services directly measure the applicability and effectiveness of the proposed treatment and have a great influence on project development. In this analysis, intersection conditions and parameters defined in the data and information collection process are used to estimate the optimal cycle length, minimum pedestrian time, green allocation, traffic delay and LOS based on HCM 2100 signalized intersection method.

The critical challenge for conducting the operations analysis for LTP and LCUP is the redistribution of traffic volumes caused by these treatments. Once this is complete, the HCM 2010 procedure for estimation of delay and LOS can be conducted. In addition, the safety analysis also needs the traffic information with and without LTP or LCUP. The traffic redistribution principles are different for LTP and LCUP and are described in subsections below.

4.31Traffic Distribution with LTP

For permanent or temporary left turn restriction treatment, this analysis method of traffic redistribution was established with the following assumptions and conditions:

1. None of left turning vehicles choose to detour until they arrive at the study intersection.

Since left turn removal on one approach can result in an increase of through traffic at that approach, in order to maximally assess this impact, this study assumed that none of left turning vehicles will change their routes prior to arriving at intersection. The left turning traffic subject to LTP is combined into the through traffic. See item 2.

2. The prohibited left turn is replaced by a series of right turns and all of the original left turn volume does this.

Restricted left turning vehicles may have to enter the intersection twice to complete their movement. The double entering volume will generate redundant entering volume. This study assumed that restricted left turning traffic first passes through the intersection and loop around the shortest path of a right turn loop as shown in Figure 4.1.

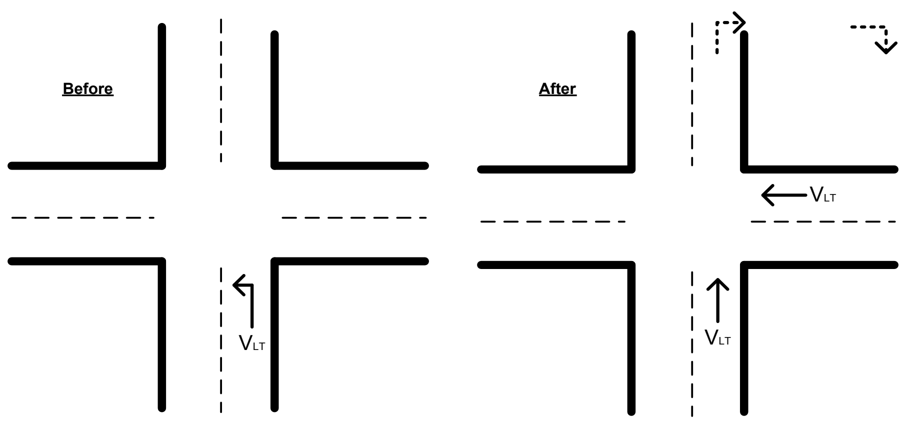


Figure 4.1 Northbound Left Turn Traffic Redistribution

For example, the peak through and left turn volumes for each approach of a four-leg intersection are V_{NBTH} and V_{NBLT}, V_{SBTH} *and* V_{SBLT}, V_{WBTH} and V_{WBLT}, and V_{EBTH} and V_{EBLT}. If left turn is removed at two opposing approaches (e.g. northbound and southbound), the redistribution of intersection volume of four approaches (V'):

$$V'_{NBTH} = V_{NBTH} + V_{NBLT}$$

$$V'_{SBTH} = V_{SBTH} + V_{SBLT}$$

$$V'_{WBTH} = V_{WBTH} + V_{NBLT}$$

$$V'_{EBTH} = V_{EBTH} + V_{NBLT}$$

This is a conservative assumption that accentuates the impacts on the through lanes of the subject intersection, the rerouting left turn traffic and the neighboring intersections. It also maximizes the safety impacts along the loop that replaces the existing left turn.

3. The number of through lanes remains the same after LTP. Exclusive left turning lane is not re-assigned to serve other movements.

Based on the fundamental intersection design rule, the number of lanes exiting an intersection should not exceed the number of available receiving lanes at the intersection [47]. LTP may be a temporary action and the intersection layout and lane configurations remain intact, unless the LTP is proposed as permanent treatment and/or the intersection lane configurations is specially modified to covert the left turning lane into a through lane. Therefore the exclusive left turn lanes subject to LTP are assumed to have no role at intersection. However, in some cases, the space of left turn lane may be used as a priority lane or queue jumper for transit or HOV vehicles, but this is a special case that may be analyzed and tested in the simulation stage.

4. Rerouting routes and distance are determined by a mapping tool if designated, or by standard city block size.

A mapping tool may be used to estimate the length of the rerouted left turn volume (length of the detour loop). For example, the ruler/path function in Google Earth should provide a sufficiently accurate estimation of the length of the loop for the planning level assessment. However, if a mapping tool is not available or if multiple alternative rerouting routes are available, a simple method using the average city block size may be employed. If the area of a city block is square miles and the average rerouting speed (V_{re}) are known, then the rerouting travel time (T_{re}) can be easily estimated. V_{re} is 15 mph if the rerouting contains one or more signalized intersections [48], and 5 mph higher (20 mph) if the rerouting route contains no signalized intersections.

A city block is defined as the smallest area that is surrounded by local streets [49]. If designated detour is not provided, left-turn drivers would choose their preferred rerouting depending on their familiarity with the surrounding area, perception of road conditions and personal preference. Because the individual choice of alternative routes is hard to track and compare (later stages employ network models for traffic assignment includes the option for dynamic traffic assignment, DTA), this study estimates the average rerouting distance by using the city block size concept in urban planning. Standard block size is an element in urban planning and design and may differ in every city. The city block is typically a regular pattern of square or rectangular but not always.

It can also be triangle or trapezoid. For example, there are many city blocks in Tribeca, New York appears as a triangle (Tribeca actually standards for Triangle below Canal Street). City block is surrounded by local streets or collectors. However, the neighborhood paths and community internal roads cannot be used to divide the city block.

The information of block size in some US cities, average value and engineering default are summarized in the Table 4.2 [49]. Although the size of block within cities varies and appears not to be generic, a city's standard block size is usually determined by urban planning and design policies. It can also be estimated by consulting the map and counting how many blocks within one mile of the area where the study intersection is located.

Table 4.2 Downtown Standard City Block Size in US Cities

City	Block Length (ft)	Block Width (ft)	Block Area (mile^2)	Average Side Length (mile)
Portland	260	260	0.002	0.05
Houston	330	330	0.004	0.06
Sacramento	410	410	0.006	0.08
Manhattan	264	900	0.009	0.09
Chicago	465	465	0.008	0.09
U.S. Cities Standard Blocks	600	600	0.013	0.11
Typically Used Default	316	316	0.004	0.06

Left-turn prohibition measures may also be deployed at unsignalized intersections for addressing safety concerns or as an alternative treatment if there is no space available for exclusive left turn lane which has been warranted.

The benefits of LTP to intersection operation for urban signalized intersection are anticipated to be realized when protected left turn phases are removed, because the number of signal phases and the cycle length may be reduced after LTP, depending on the types of pervious left turn phase (permitted or protected), traffic volume, and the number of LTP approaches. Left turn movement is usually prohibited in a pair of opposing approaches. LTP at single approach is unusual in mitigate intersection congestion, but it might be a possible deployment for safety purpose.

4.32 Traffic Distribution after LCUP

One underpass lane can be equivalent to several at-grade lanes on the basis of hourly throughput. LCUP treatment for signalized intersection does not restrict or modify previously existing movements at the intersection. Although there is no rerouting for a LCUP treatment, the challenge is the volume assignment per lane because all motorists would prefer the stop-free flow of the underpass. Due to the compact dimension and limited height of the LCUP , it can only allow for vans, automobiles, light to medium sized trucks, and vans to fit (8 ft clearance). Therefore heavy vehicles and turning vehicles have to use the surface lanes through the intersection. Both the flow capacity and dimension restrictions affect the volume distribution on each approach lane.

The assumptions underlying the traffic redistribution analysis for LCUP treatment as follows.

1. All through vehicles eligible to use LCUP would tend to use the underpass when the at-grade traffic signal displays yellow or red.

Since the partial grade separated (underpass) lanes at a signalized intersection theoretically enjoy a 100% green time and allow for the uninterrupted movement of through vehicles for the approach on which the treatment is deployed, all light duty vehicles would want to use it when the at-grade traffic signal displays yellow or red. However, there is one exception which should be further studied in the simulation and detailed analysis in Level 2 and Module 3. On a multi-lane arterial approach, all eligible through traffic volume may not be able to merge onto the lane leading to the underpass . Simulation with various intersection condition inputs is recommended to be employed to test whether the upstream entering distance and downstream leaving distance are sufficient.

The distance of proposed underpass entrance from the traffic signal and the designed sight distance for signal visibility at the study intersection need to be measured. In addition, a large vehicle ahead may block sight. Under some unusual special design or geographic conditions, such as rolling approach in a mountainous area, the driver may be unable to see the signal indicator while he/she is approaching the underpass entrance and encountering a decision of choosing underpass or surface lane. The Table 4.3 summarizes the minimal signal visibility distance under various 85^{th} percentile speed required based on MUTCD 2009 [50], the minimal distance visibility is applied under low visibility or extreme conditions (e.g, darkness and inclement weather). If the underpass entrance (decision point of drive) is not within sight distance of signal visibility, all eligible through vehicles are assumed to use underpass regardless of the traffic signal at the intersection.

Table 4.3 Minimum Sight Distance for Signal Visibility [50]

85th-Percentile Speed (mph)	Minimum Sight Distance (ft)
20	175
25	215
30	270
35	325
40	390
45	460
50	540
55	625
60	715

2. Through traffic arriving on green will not change lanes.

Drivers will remain on their through lane (at-grade or underpass) if they can expect to clear the intersection prior to the signal display turning red. A green time countdown counter may be fitted upstream near the LCUP entry to facilitate motorist choice.

LCUP lane volume (Vu) and at-grade volume (Vg) are estimated separately for the effective green and effective red time. During the red interval for the through movement, all eligible through traffic is expected to use the LCUP until its capacity is reached and merging onto the underpass lane becomes impossible. This planning process does not consider the discrepancies between the utilization of underpass and at grade through lanes, so all eligible through traffic is assumed to be equally distributed on LCUP and at-grade lanes during green for the through movement. The formulas at left side of the plus in both equations are the volume distribution during effective red and the right side is for the effective green period.

During the red interval for through movement, all eligible through traffic is expected to use the underpass until its capacity is reached and merging onto the underpass lane becomes impossible.

$$V_u = \min[c_{u,} V_{TH}(1-HV\%)](1-P) + \frac{\min[c_{u,} V_{TH}(1-HV\%)]P}{N_{TH}} \quad (4.1)$$

$$V_g = V_{TH} - V_u \quad (4.2)$$

Where

$\boldsymbol{V_{TH}}$ = total approach through volume

$\boldsymbol{N_{TH}}$ = number of through lanes (sum of at-grade and underpass lanes)

HV% = proportion of ineligible (over-height) vehicles in the approach through traffic

P = percentage of vehicle arrivals on green estimated by $P = R_p g/C$ in which R_p is the signal progression factor, g is the effective green time for through movement, and C is the intersection cycle length.

$\boldsymbol{c_u}$ = underpass lane effective capacity. The queuing interactions between closely spaced intersections are substantial. The determination of c_u is subject to downstream queuing as detailed below.

Three steps and the following data are involved in the estimation of c_u as explained in section 4.3 which details the downstream effects. This three step process adds considerable complexity, but it is necessary because it avoids the potential fallacy that the LCUP is assumed to operate continuously at capacity which, in turn, would result in unrealistically favorable results.

4.4 Downstream Queue Interaction

4.4.1 Introduction

Intersection treatments that substantially expand intersection capacity such as adding lanes and grade separation may not realize the expected benefits of relieving congestion and reducing delay, because the traffic conditions at downstream intersections may deteriorate by increased upstream arrivals. Additionally, the extended queue generated from downstream intersections can spill back into the upstream intersection and diminish the performance of the upstream treatment. This phenomenon is frequently observed in large urban areas where the traffic volume is heavy, intersection spacing is short and cycle length is long. Although this planning level analysis technically treats the study intersection as an isolated junction without considering interactive impacts from road network and surrounding area, adverse downstream effects have great potential to offset the project benefits and cannot be ignored in the early stage analysis.

The method provides traffic engineers with a step-by-step process to identify the occurrence and the type of queue spillback (Cyclic and Sustained), to determine the effects of downstream queues on upstream capacity, and to select the best capacity expansion treatment based on the updated queue size and intersection capacity estimation methodologies for signalized intersections in HCM 2010. A spreadsheet-based computational tool was developed to assist in the process of capacity constraint identification and calculation.

A large body of research exists highlighting the effects of queue interaction at closely spaced signalized intersections in an urban road network, especially, the potential upstream capacity cutoff caused by downstream queue spillback. Queue spillback is one of the most common causes of flow restriction at congested intersections [46]. The Traffic Timing Manual [51] has recommended the performance measures of intersection treatments should include queue lengths and the objectives are to minimize the time period during which the queue spillback or spillover exists and to manage queue interaction between intersections during oversaturated conditions. According to the AASHTO Green Book [7], upgrading an existing at-grade intersection to interchange in urbanized area may create queue spillback problem and affect traffic on the interchange off ramp. NCHRP Report 345 exploited the design and operation of single point urban interchange and indicated that queue spillback from the downstream intersection was found to have an adverse effect on the safety of the off-ramp and led to a significant reduction in the efficiency of the off-ramp movements [52].

Several researchers have evaluated downstream queues interfering with capacity, delay and level of service of its upstream intersection. The City of Portland, Oregon, presented a traffic micro-simulation model that simulates the upstream capacity affected by the downstream queue built-in and spillback. The model needs EMME/2 type network data as input, plus the lane configuration of adjoining intersections [53]. A new series of traffic analysis module was integrated with the recent versions of Trafficware's Synchro Studio, which examine how queue can reduce capacity through spillback and a new queue-delay factor was introduced to measure the additional delay incurred by the capacity loss [54]. Elefteriadou conducted a research on the method for the operational analysis of internal overflowing queue blockage of a diamond interchange ramp terminals on at-grade intersections based on the results of simulations to predict different measures [55]. Research at Texas Tech University found that both Synchro and Elefteriadou's methods overestimate delay and queue effects under a certain condition. It introduced an open-source mathematical model based on the HCM 2000 delay model [56]. Ahmed and Abu-Lebdeh developed a macroscopic model for a hypothetical two-signal system to estimate the delay at signalized intersections caused by downstream congestion, using basic traffic flow properties and control parameters at neighboring intersections [57].Virginia Transportation Research Council reviewed a variety of computer programs capable of analyzing capacity at signalized intersections and recommended TRAF-NETSIM for capacity simulation analysis at non-isolated intersections where queuing and spillback are potential problems [58].

In reviewing these models, one can find that most of these analytic approaches are either data-intensive and require network-wide simulation models or computer-intensive and need system-wide mathematical programming models. Although simulation and programming models can measure the interactions of individual vehicles, conducting network-wide analysis of queue evolvement and providing detailed and visual information about queue effects, traffic simulation is always a time and resource consuming and data-intensive endeavor. It may be difficult and expensive to conduct a network or system wide investigation to gather the necessary information for applying these models, especially in the early stage of alternative screenings.

To address these deficiencies, this section presents a process that uses readily available data and standard engineering parameters to evaluate the interaction of downstream queues and upstream capacity. The method can be used to assist traffic engineers in examining the application of capacity expansion treatment at a major urban intersection. Through measuring and comparing the potential capacity loss for different capacity expansion alternatives, the most beneficial and effective option can be identified and whether significant additional resources should be utilized for a traffic simulation or further detailed analysis can also be determined in the detailed measurement level.

4.4.2 Measurement of Queue Spillback

When downstream queues spread back upstream, these prevent vehicles from entering the upstream intersection on green, so the actual traffic carrying capacity of the upstream intersection would be much lower than its normal capacity. The queue interaction between two intersections also creates safety concerns, especially for grade separated structures where hazardous rear-end collisions may occur when the exiting high-speed traffic suddenly comes upon the stopped and queued traffic. Sideswipe crashes may also be observed as existing vehicles make unexpected lane changes in order to avoid the back of the queue.

A simplified set of condition example as indicated in Figure 4.2 is used to demonstrate the queue interaction between two closely spaced intersections (Intersection A and B). The eastbound through approach of Intersection A is carrying 2,000 peak-hour vehicles. The before-treatment through capacity of Intersection A is 1,600 veh/hr and that of its downstream intersection (Intersection B) is 1,200 veh/hr. Queue size would be 400 veh/hr, if the midblock traffic generation and the contribution of left and right turns at Intersection A are negligible.

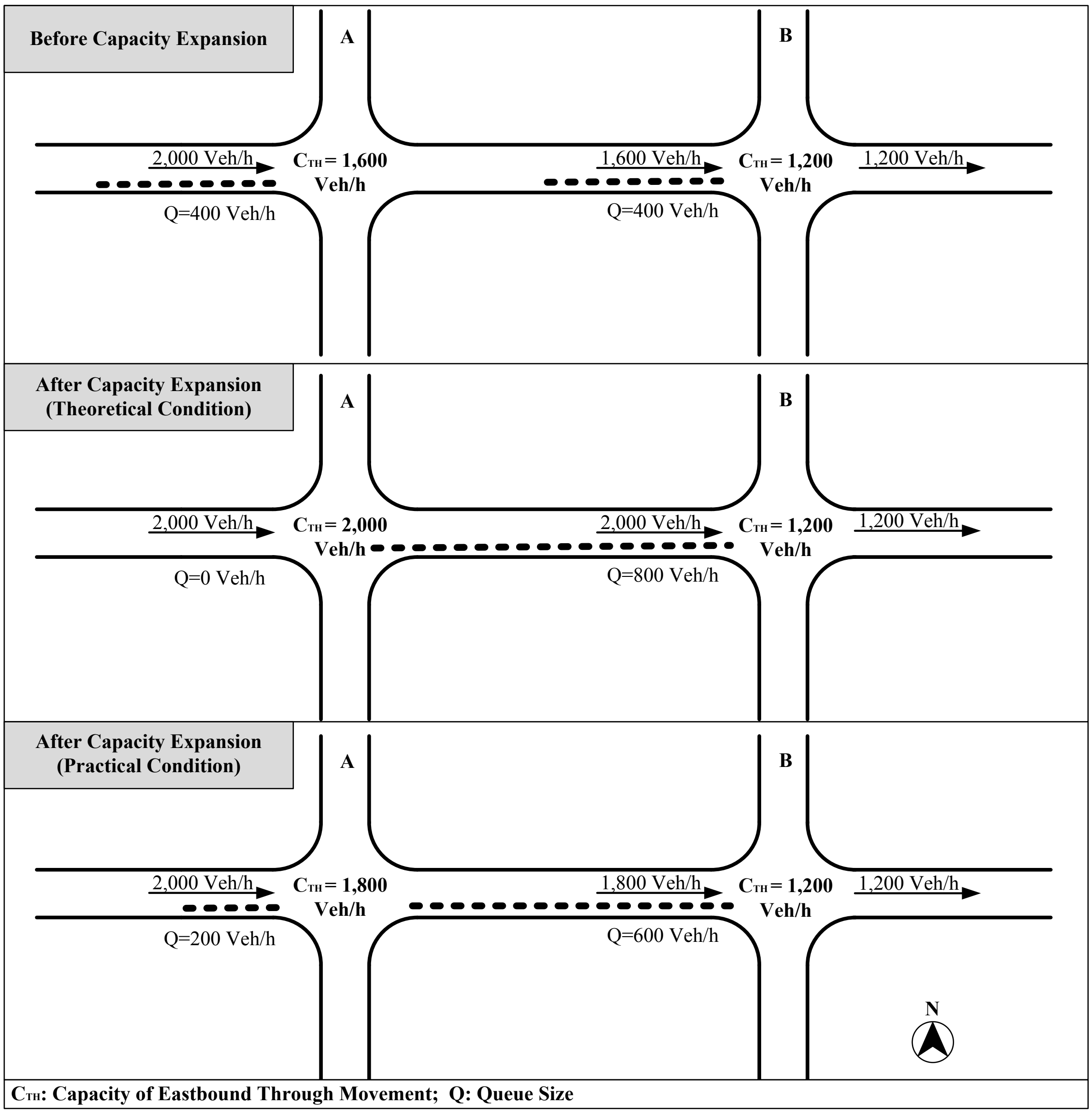


Figure 4.2 Demonstration of Downstream Queue Effects on Intersection Capacity

If one though lane was added to Intersection A and the through capacity theoretically increased from 1,600 to 2,000 vehicles per hour, the back-of-queue on the eastbound through of Intersection A is expected to be eliminated but the queue at Intersection B would increase to 800 veh/hr. However, if the link between two intersections can only store 600 queuing vehicles per hour, the remaining 200 vehicles are unable to enter Intersection A and have to stay on its upstream segment, resulting in the operational eastbound capacity of Intersection A decreasing to 1,800 vehicles per hour.

Downstream queue spillback affects any upstream movement for which the intended destination is being blocked. However, the effects of queue interaction are restricted to the nearest downstream intersections. As shown in the example above, the volume exiting Intersection B towards further downstream (1,200 veh/hr) remains unchanged after deploying the treatment at Intersection A.

The approach presented determines whether queue spillback-related capacity cutoff will occur during the analysis period and to measure how the increased capacity at subject (upstream) intersection may deteriorate downstream traffic conditions. The full set of the analysis method shown in Figure 4.3 consists of two interactive processes: evaluation process and calculation process. The evaluation process is used to identify the performance of proposed treatments for the subject intersection. The calculation process focuses on the analysis of traffic operation and queuing condition at the downstream intersections and estimates the maximum rate of downstream traffic arrivals from the upstream intersection (i.e., the threshold of queue spillback). The threshold value is an essential input for the evaluation process in determining the feasibility and effectiveness of treatments.

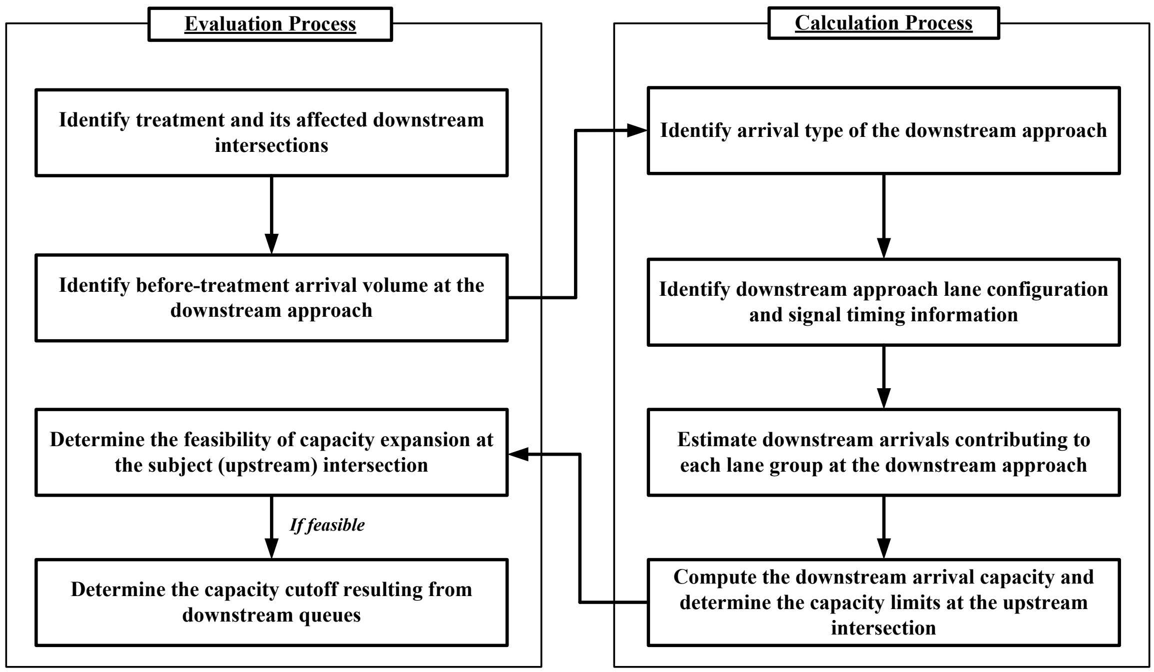


Figure 4.3 Flow Chart of Analysis Method on Downstream Queue Effects

Note that although queue spillback may occur due to oversaturation at unsignalized intersections and access points between major intersections, this dissertation only considers treatments applied on signalized intersection and the queue interaction between the paired signalized intersections. In addition, the approach is developed based on the HCM 2010 back-of-queue size and capacity analysis procedures for signalized intersections.

4.4.3 Calculation Process of Downstream Capacity

The methodology used in the calculation process is based on the queue accumulation and intersection capacity estimation methods introduced in the newly released HCM 2010. The queuing calculation in HCM 2010 is derived from Akcelik's research [59] on the estimation of full stop rate at signalized intersection for uniform arrivals. Akcelik's method was extended by Olszewski [60] for platooned arrival type and the Texas Transportation Institute [61] for coordinated actuated signal system. HCM 2010 further refined the estimation technique of back-of-queue size by eliminating slowing and partially stopped vehicles.

The idea behind the derivation of the methodology is to reverse and integrate the HCM procedures of intersection capacity and queue size estimation. According to HCM 2010, the queue size in any lane of a certain lane group can be estimated by accounting for the queue caused by the signal cycling through its phase sequence and the effect of random and cycle-by-cycle fluctuations in over-capacity demand. Therefore, the back of queue size for a given lane group is computed with Eq. 4.3:

$$
\begin{aligned}
&Q = Q_1 + Q_2 + Q_3 \\
&Q_1 = \frac{s}{3600}\frac{q_r r - q_g d_a}{s - q_g} \\
&Q_2 = \frac{c_A}{3600N} d_2
\end{aligned}
\tag{4.3}
$$

Where

Q = back of queue size (veh/ln)

Q_1 = first term back of queue size (veh/ln)

Q_2 = second term back of queue size (veh/ln)

Q_3 = third term back of queue size (veh/ln)

s = adjusted saturation flow per second per lane in the lane group on downstream approach (veh/s/ln)

q_r =arrival flow rate during the effective red time *(r)*

q_g =arrival flow rate during the effective green time

c_A = average capacity (veh/h)

d_2 = incremental delay (s/veh)

N = number of lanes in lane group (ln)

The first term back of queue (Q_1) represents the queue generated due to signal cycling through its phase queue, the second term back of queue size (Q_2) takes into account of the effect of random, cycle by cycle fluctuations in demand that occasionally exceed capacity and the aggregate demand during the analysis period that exceeds aggregate capacity. The third term back of queue (Q_3) estimation addressed the queue due to an initial queue presented at the start of the analysis period but rarely used in practice. This is not included in this analysis by assuming the initial queue is equal 0.0 veh.

HCM estimates capacity and based on it calculates queue length. This method knows (assumes) the maximal allowable queue length and reverses the calculation to derive the effective capacity of underpass. The parameters used in the method are first defined below:

- Cycle length of downstream intersection, denoted by $\boldsymbol{C_d}$ (sec.)
- Distance between the stop line of the subject intersection and the stop line of the downstream intersection, denoted by $\boldsymbol{D}$ (ft.)
- Maximum back-of-queue size limited by the storage capacity of the road segment linking the subject and downstream intersections, denoted by $\boldsymbol{Q}$ (veh), which can be estimated by $(D+L_v)/L_v$; L_v is average spacing between vehicles in a stopped queue, typically 25 ft. [62].
- Configuration of lane groups at downstream approach. Lane group *i* denotes any one of the lane groups.
- Number of lanes in lane group *i* of downstream approach, $\boldsymbol{N_i}$.
- Proportion of lane group *i* volume in entire approaching volume, $\boldsymbol{P_i}$.
- Effective green time for lane group *i* on downstream approach (sec), $\boldsymbol{g_i}$.
- Saturation flow of lane group *i* (veh/sec), $\boldsymbol{s_i}$.
- Posted speed limit on the road segment linking the subject and downstream intersections, denoted $\boldsymbol{S_{pl}}$. It is used to calculate $\boldsymbol{d_a}$, which is an acceleration-deceleration delay term that distinguishes between a fully and a partially stopped vehicle and can be computed referring to the relevant HCM 2010 equations (TRB 2010):

$$d_a = \frac{1.47(18.04 + 0.423S_{pl})^2}{46.8 + 0.846S_{pl}}\left(\frac{1}{3.5} + \frac{1}{4.0}\right)$$

- Volume generated at midblock access points on the road segments linking the subject and downstream intersections, $\boldsymbol{V_{mid}}$.
- Left turn volume from the subject intersection onto downstream approach, $\boldsymbol{V_{LT}}$.

- Right turn volume from the subject intersection onto downstream approach $\boldsymbol{V_{RT}}$.

Step 1: Define the traffic flow rate from the subject intersection to lane group *i* on its signalized downstream approach, $q_{i.}$ (veh/s/ln)

By solving the inverse function of the arrival rate element in HCM queue size and intersection capacity estimation models, q_i can be calculated by Eq. 4.4 subject to avoidance of queue spillback.

$$\begin{cases} q_i = \dfrac{g_i Q s_i}{C_d((Q-d_a s_i)P - g_i s_i(P-1))} & (Q < s_i(d_a \dfrac{P}{P-1} + g_i)) \\ q_i = \dfrac{g_i(P-1)(C_d Q + 450 g_i s_i)}{C_d^{\,2}(d_a P + g_i(P-1)) + 450 C_d g_i (P-1)} & (Q \geq s_i(d_a \dfrac{P}{P-1} + g_i)) \end{cases} \tag{4.4}$$

Step 2: Define the maximum arrival rate of downstream approach, denoted $\boldsymbol{c_{da}}$ (veh/s/ln).

The downstream arrival rate (q_i) calculated by Eq. 4.4 is only the proportion of total approaching traffic and contributes to the longest queue found in one of the lane groups on the downstream approach. This has to be repeated for each lane group to determine the maximum downstream arrival rate under the constraint of queue storage capacity, intersection configuration and signalization. Once the arrival rate for each lane group on the downstream approach is computed, the maximum arrival rate (c_{da}) that can be accommodated by the downstream approach and queuing space is computed with Eq. 4.5.

$$c_{da} = 3600 \min\left(q_i N_i / P_i\right) \qquad (4.5)$$

The capacity constraint estimated by Eq.4.4 represents the longest queue at the downstream approach and is a conservative estimate. When the queue spillback occurs and blocks some lanes or movements at the upstream intersection, some other lanes or lane groups may still have space to receive traffic. However, in order to minimize the potential of queue spillback and related traffic operation and safety concerns, the longest downstream queue was considered.

Step 3: Estimate the effective underpass capacity $\boldsymbol{c_u}$ (veh/h)

The upstream demand volume, through plus turn volume onto the examined downstream approach and any volume gained or lost at midblock access points, should not exceed the downstream approach capacity. This imposes a constraint on the capacity of the upstream intersection. The effective underpass capacity is estimated as follows:

$$c_u = c_{da} - [V_{mid} + V_{LT} + V_{RT} + V_{TH}(1 - HV\%)] \qquad (4.6)$$

Eq. 4.4 is applicable for an individual lane, the arrival rate and saturation flow for the lane group have to be converted into individual lane inputs. The unequal lane utilization in a lane group is not reflected in the calculation and no initial queue at the start of each analysis period is assumed.

The inequalities in the parentheses of Eq. 4.4 are used to determine the type of queue spillback (cyclic or sustained) by measuring whether the lane group on downstream approach operates under capacity. Based on the definition in Chapter 17 of HCM 2010, if the intersection spacing and effective green time allow the downstream approach operating under capacity, but queue spillback still occurs. This spillback can be classified as cyclic spillback and may result from the long downstream cycle length and/or the poor quality of signal progression between intersections. If there is oversaturation at the downstream intersection, then sustained spillback occurs. The impedance of sustained spillback could not be mitigated until either the upstream demand is reduced or the downstream capacity is increased.

The proportion of all vehicles arriving during green (i.e., Parameter *"P"* in Eq. 4.4) is recommended to be observed in the field because it has a significant impact on the estimation of queue backup and capacity constraint. It can also be estimated by arrivals type and platoon ratio at the downstream approach according to HCM (i.e., $P = R_p\, g/C$, in which *"*R_p*" is* platoon ratio and the default value of *"*R_p*"* can be computed by R_p=*Arrival Type/3*). Downstream arrival type depends on the type of capacity expansion treatments deployed on the upstream intersection. If full or partial grade separation treatment is applied, then downstream traffic arrivals can be assumed to have a random and uniform arrival flow profile. If adding lane or other at-grade capacity improvement treatments are used, then a dispersed and moderately dense platooned arrival type may be more appropriate. Arrival Type 4 ($R_p = 1.33$) is commonly used to establish signal progression for the peak period or travel direction if signals at the paired intersections are properly coordinated. The progression for the off-peak hours or uninterrupted flow was usually characterized as Arrival Type 3 ($R_p = 1.00$). Therefore, if the arrivals are effectively random, the proportion of vehicles arriving on green equals to the green/cycle ratio (i.e., $P=g/C$) and the Eq. 4.4 can be rewritten as below.

$$\begin{cases} q_i = \dfrac{Qs}{(C-d_a-g)s+Q} & (Q < \dfrac{gs(C-d_a-g)}{C-g}) \\ q_i = \dfrac{(C-g)(CQ+450gs)}{C(C^2-C(d_a+g-450)-450g)} & (Q \geq \dfrac{gs(C-d_a-g)}{C-g}) \end{cases} \tag{4.7}$$

The downstream arrival rate calculated by Eq. 4.4 for platooned arrivals) or Eq. 4.7 (for uniform arrivals) is only the proportion of total approaching traffic and contributes to the longest queue found in one of the lane groups on the downstream approach. The maximal downstream arrival rate that can be accommodated by the downstream approach and queuing space can be calculated by using the Eq. 4.6.

The upstream departure volume, plus the traffic gained or lost at midblock access points (if not negligible), should not exceed the downstream arrival capacity in order to avoid queue spillback. The restriction of upstream departure volume imposes a constraint on the traffic carrying capacity of the upstream intersection.

The capacity constraint estimated by Eq. 4.4 and 4.7 derives from the longest queue at the downstream approach and is a conservative estimate. When the queue spillback occurs and blocks some lanes or movements at the upstream intersection, some other lanes or lane groups may still have space to receive arriving traffic. However, in order to minimize the potential of queue spillback and related traffic operation and safety concerns, it could be more reasonable to determine the subject intersection capacity constraint by considering the longest downstream queue, because there will always be a certain amount of weaving and lane changing between the entrance and the exit and the different movements may interfere with each other so that the queue in one lane may spread across the other lanes and eventually block the flow of traffic.

Because of the complexity involved in the formulation of the calculation process and in order to reduce the chances of error if attempting to calculate by hand, an interactive spreadsheet tool by using Microsoft Excel 2007 was developed as an add-in worksheet for the complete planning analysis computerized workbook which is presented in Section 4.6.

4.4.4 Evaluation Process of Downstream Effects

A four-step evaluation procedure is used to examine the performance of upstream capacity expansion treatment and to determine the capacity loss resulting from downstream queues (Figure 4.3).

1. Identify downstream locations affected by the proposed treatment.

During this step, the downstream intersections which experience higher traffic demand after-treatment are identified. This depends on the approach where the treatment is deployed. For example, adding through lanes on one approach only affects its downstream approach, but converting to a four-way interchange may affect all the approaches and their associated downstream intersections.

2. Identify Treatment Downstream Arrival Volume Before Treatment.

As depicted in Figure 4.4, the before-treatment volume of each entry movement towards downstream segment needs to be obtained. It can be measured in the field or forecasted for future years. The traffic entering to and exiting from the driveways and access points between the two intersections may be assumed to be negligible if no midblock volume sources are present or minor. However, if the number of vehicles generated from the driveways, stop-controlled intersections and access points within the downstream segment are available or suspected to be significant, their amount should be included in the estimation of total arrival volume.

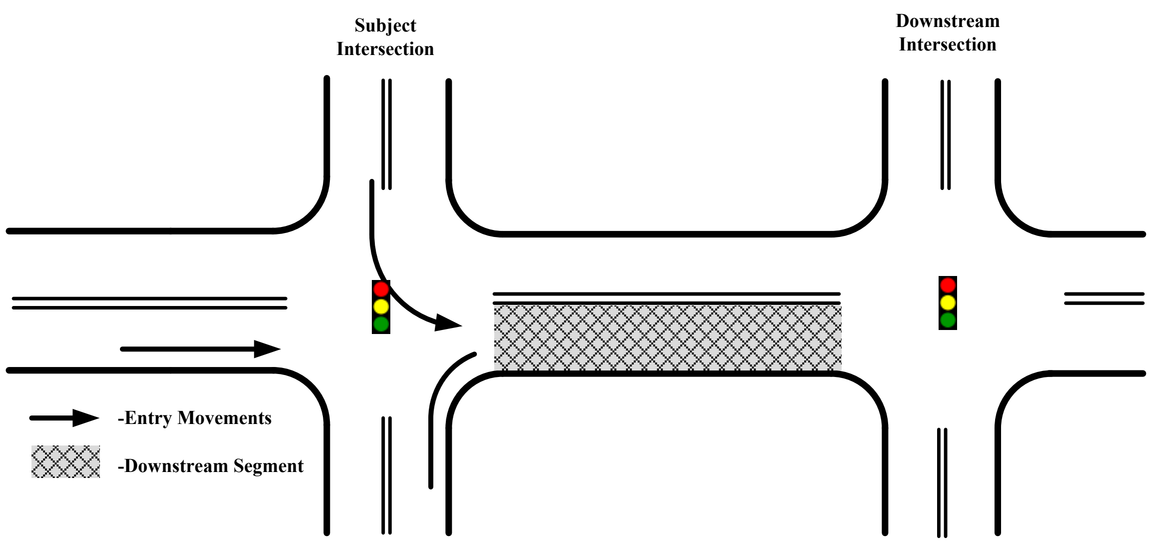


Figure 4.4 Entry Movements and Downstream Segment between Two Signalized Intersections

3. Determine the feasibility of capacity expansion at the subject intersection.

This step is designed to examine whether the existing conditions and the queue storage capacity can accommodate an upstream capacity expansion. The determination of downstream queuing condition in the calculation process must be done prior to conducting this step. If downstream arrival volume under the no-build condition computed in the previous step has already been higher or equal to the downstream arrival capacity, queue spillback from downstream intersection may be already occurring. In this case, an upstream capacity improvement project cannot be justified, because the implementation of a capacity expansion treatment would be counter-productive and have a negative effect on traffic operation and safety at both subject and downstream congestions.

4. Determine the capacity limit

The effective underpass capacity C_u is estimated by Eq. 4.6. The underpass usage is usually lower or equal to the capacity. The process of determining underpass usage is shown in the Eq. 4.8 (all variables have been defined previously), the utilization of underpass lane is the minimal value of design capacity (usually1, 800 veh/h), maximum traffic demand (all the through and light-duty traffic at the approach), and underpass traffic distribution. However, as mentioned before, all eligible through traffic is assumed to use LCUP lane if the traffic signal display is not visible to driver at the lane change distance to the lane leading to the underpass. In this case, traffic volume distributed on underpass lane equals to the total amount of non-heavy through traffic volume.

$$\begin{cases} U_u = \min(C_u, C_{da,} V_u, V_{TH}(1-HV\%)) & \textit{Signal is visible at tunnel entrance} \\ U_u = \min(C_u, C_{da,} V_{TH}(1-HV\%)) & \textit{Signal is invisible at tunnel entrance} \end{cases} \tag{4.8}$$

Underpass usage is an essential input for the further analysis and determination of downstream leaving distance and turning movement organization. If the left turn movement at downstream intersection is not infeasible to operate along with an LCUP then it may be proposed to be restricted (temporary during peak hour or permanent). In this case, underpass effective capacity and usage should be recalculated. The feedback process between level 1 and level 3 is discussed in the following section.

4.4.5 Refine Underpass Usage

The determination of underpass usage is essential in accurately conducting the HCM intersection delay and Highway Safety Manual (HSM) [63] intersection safety study. Because the downstream effects on underpass practical capacity are considered and iterative convergence is involved in volume distribution analysis, the underpass capacity is constrained by the after-treatment signal timing, downstream queuing, and maximum through volume.

In order to make the method more representative and generic, the planning level assessment on downstream queue does not consider the site-specific signal phasing and signal timing plans, and assumes the turning patterns at downstream intersection are unchanged. However, if detailed analysis or simulation in Level 3 justifies the removal of left turning movement or adding of auxiliary left turn lane at downstream intersections, the estimation of underpass capacity subject to downstream queuing can be refined as shown in Figure 4.5.

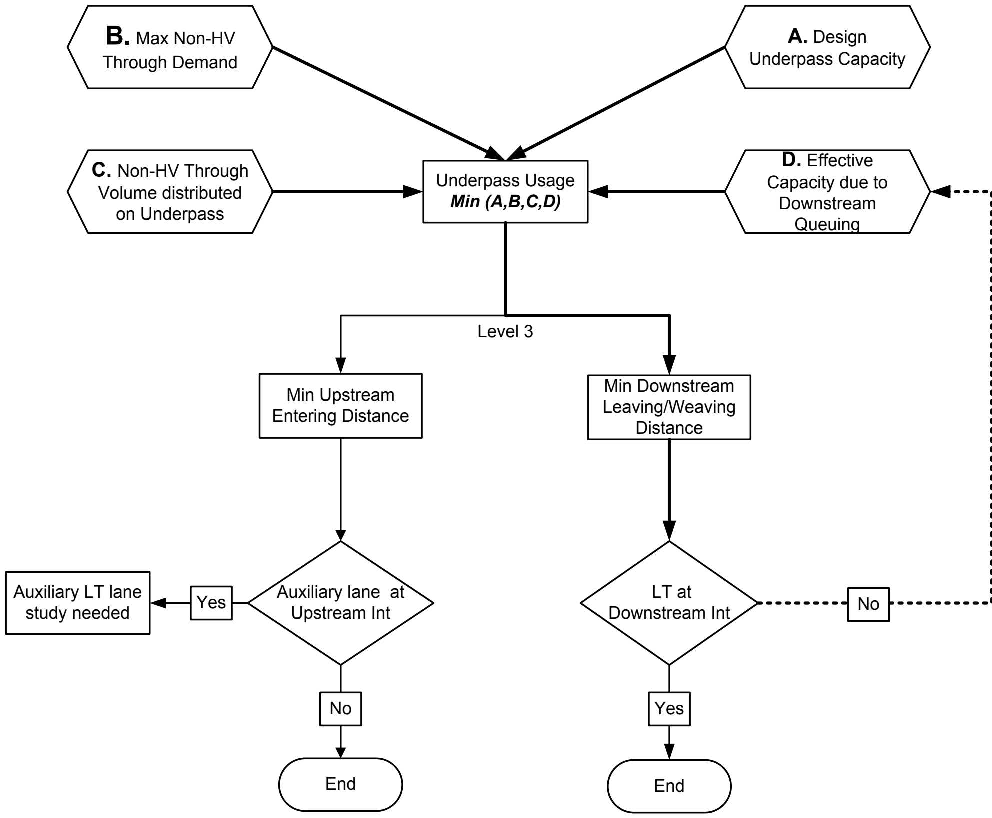


Figure 4.5 Process of Refining Underpass Capacity Analysis

There are four constraints associated with underpass usage:

A) Underpass design capacity is a maximum rate of throughput achieved under ideal condition and what the traffic engineers have designed an underground structure to operate at.

B) Non-heavy vehicle through demand is the maximum traffic demand of underpass lane at peak period. In order to take into account of the effect of fluctuation in peak hour traffic and to accommodate the future growth of traffic demand, a proper PHF and growth rate was applied.

C) Non-heavy through traffic distributed on underpass lane is calculated using equations in section 4.3.4. The estimation of traffic redistribution after LCUP treatment is on basis of the assumption that the approaching driver of light duty though vehicle would tend to use underpass if perceived a red light at the intersection and would not prefer to use the underpass if the green signal or green arrow appears.

D) Effective capacity is actual maximum and sustainable traffic flow that the underpass lane can practically carry given current operating constraints. Effective capacity is often lower than the design capacity owing to realities of downstream queuing interaction, unpredictable driver behaviors and adverse weather conditions. The process of estimating the effective capacity emphasized the impacts of downstream queue spillback on underpass capacity. Under special conditions (such as signal timing, intersection spacing, traffic volume, lane configuration, arrival type and more), the effects of downstream queuing may be neglected. Therefore, a sensitivity analysis by adjusting several factors related to downstream effects (e.g, downstream approach lane configuration, green time allocation, and cycle length) can be conducted by using the computerized tool. This may be helpful in increasing the capacity limit and achieving a system-wide optimization of the LCUP deployment.

As shown in Figure 4.4, the determination of underpass usage is a necessary step in identifying the upstream entering and downstream leaving distance for the detailed analysis of design and implementation characteristics in level 3 by conducting traffic simulation and modeling. The identification of entering and leaving distance would further help to examine the feasibility of auxiliary lane at study intersection and left turn movement at downstream intersection. More details can be found in Chapter 5.

4.5 Estimation of Travel Time Savings

The intersection-wide travel time saving are estimated by referring to the benefits from reduced intersection delay. After-treatment volume and road conditions are used to determine the intersection delay (D_{int}) and its corresponding LOS based on HCM 2010 methods.

$$D_{\text{int}} = d_1 PF + d_2 + d_3$$
$$d_1 = 0.5 \frac{C\left(1 - g/C\right)^2}{1 - g/C \min\left\{X, 1.0\right\}}$$
$$d_2 = 900T\left[\left(X_A - 1\right) + \sqrt{\left(X_A - 1\right)^2 + \frac{8kIX_A}{c_A T}}\right](X_A = v/c_A)$$

Where

D_{int} = intersection control delay (s/veh)

PF = Progression factor

d_1 = uniform delay (s/veh)

d_2 = incremental delay (s/veh)

d_3 = initial queue delay (s/veh)

X_A = average volume to capacity ratio

T = analysis period duration

I = Upstream filter factor

K = Incremental delay factor

Other variables are as previously defined.

Estimation of uniform delay (d_1) is the baseline delay by assuming uniform arrivals, stable flow and no initial queue. Incremental delay (d_2) occurs under non-uniform arrival conditions and temporary cycle failure; random delay and oversaturation are also considered. The initial queue delay (d_3) experienced by vehicles arriving due to unmet demand prior to the analysis period is not described here and is excluded from the delay model (e.g., there is no queue present at the start of a study period).

Note that in order to take account of rerouting traffic delay for left turn prohibition treatment, overall delay (D_{all}) instead of intersection-only delay (D_{int}) is used in the before-after comparison and cost benefit evaluation. The overall delay is computed using a weighted average of intersection delay (D_{int}) of at-intersection volume (V'_{int}) and travel time T_{LR} of rerouting turning traffic (V_{LR}).

$$D_{all} = \frac{D_{\text{int}} V'_{\text{int}} + T_{LR} V_{LR}}{(V'_{\text{int}} + V_{LR})} \tag{4.9}$$

Where

V_{int} = before-treatment intersection entering volume

V_{LR} = rerouted traffic volume, which is the existing LT volume on the approach receiving the LTP treatment

V'_{int} = after-treatment intersection entering volume (the sum of before-treatment entering volume (V_{int}) and re-entering turning traffic, i.e, $V'_{\text{int}} = V_{\text{int}} + V_{LR}$

T_{re} = rerouting travel time

Because the right turn movement usually operates under a shared traffic signal phase with another critical movement and right turn on red is permitted at signalized intersections, right turn traffic at the subject intersection is not supposed to be significantly affected by prohibiting left turn or providing uninterrupted through underpass lanes. At the planning level, if shared through/right turn lane(s) are present, then the right turn volume is counted as through traffic and the shared lane(s) are considered as through lane(s). If there are one or more exclusive right turn lanes, right turn volume is deducted from the approach volume and the exclusive lane(s) are ignored.

In order to make the tool reasonably representative and generic, the operational analysis in this planning method doesn’t consider the site-specific signal phasing and signal timing plans, such as the overlapping phases, but employ a standard signal phasing plan consisting of a protected left turn phase (if applicable) followed by a phase serving the through, right, and pedestrian movements. Intersection signal is assumed to start with a leading protected left turn phase, followed by through and right movements. An intersection’s exact signalization plan is modeled in level 3, with simulation and other measurement tools.

An additional impact of the LCUP treatment on traffic operation is the extensive lane closure requirement during the two to four month period of its construction. It is possible that large benefits of LCUP over the proposed 20 year evaluation horizon will be negated by severe congestion during its construction. This impact is neglected at the planning level but it is assessed with microsimulation and work zone analysis in Level 2 (feasibility and analysis).

4.6 Safety Analysis

The method for intersection safety analysis is extracted from the AASHTO HSM 2010. This manual also provides safety evaluation and prediction for roadway segments, intersections, interchanges, and road networks. Based on 10-year research program funded by NCHRP, TRB, AASHTO and FHWA, the techniques provide assessment of safety impacts.

A catalog of factors for estimating the potential changes in crash frequency and severity due to installing a particular treatment allows for changes in annual crash frequency to be quantitatively evaluated for a variety of geometric and operational treatment types.

The HSM includes a safety management process for project development, predictive methods for rural two lanes road, rural multi-lane highways and urban and suburban arterials. HSM uses crash modification factors extensively as explained below. The safety analysis in this research employed the methods for screening and diagnosis process, focusing on urban arterial and signalized intersections. The HSM predictive models for urban and suburban arterial four legs signalized intersections include three basic elements:

1. Safety Performance Functions (SPFs), which is a statistical "base" models for specified base intersection conditions.

2. Crash Modification Factors (CMFs) are used to adjust crash frequency predicted by the SPF to account for a change in one specific condition such as adding approaching lane and narrow lane width.

3. Calibration Factor (C_r), which is to adjust the basic crash frequency prediction to reflect differences in the jurisdiction or time period between basic condition and local condition.

The HSM predictive models formulation for an urban or suburban arterial intersection is of the general form of simple algebraic equations.

$$N_{pred} = C_r \times (N_{bi} + N_{pedi} + N_{bikei}) \quad (4.10)$$

$$N_{bi} = (N_{bimv} + N_{bisv}) \times \prod CMF_{ib} \quad (4.11)$$

$$N_{pedi} = N_{pedbase} \times \prod CMF_{ip} \quad (4.12)$$

$$N_{bikei} = N_{bi} \times f_{bikei} \quad (4.13)$$

Where

N_{pred} is the predicated average intersection crash frequency in a year

C_r is the calibration factor developed to covert daily accident rate to hourly accident rate

N_{bi} is the predicted average vehicle-only crash frequency in a year (including multiple vehicle collisions N_{bimv} and single vehicle collisions N_{bisv})

CMF_{ib} is a set of CMFs that apply to adjust the vehicle only crash frequency predicted by the SPF under the base conditions

N_{pedi} is the predicted average vehicle-pedestrian collisions in a year

CMF_{ip} is a set of CMFs that apply to adjust the vehicle-pedestrian crash frequency predicted by the SPF under the base conditions

N_{bikei} is the predicted average vehicle-bicycle collisions in a year

f_{bikei} is the bicycle crash adjustment factor

The SPFs of multiple vehicle collisions N_{bimv}, single vehicle collisions N_{bisv} and vehicle-pedestrian collisions $N_{pedbase}$ are presented in Eq. 4.10 through 4.12.

$$N_{bimv} = \exp(a + b \times \ln(AADT_{maj}) + c \times (AADT_{\min})) \quad (4.14)$$

$$N_{bisv} = \exp(a + b \times \ln(AADT_{maj}) + c \times (AADT_{\min})) \quad (4.15)$$

$$N_{pedbase} = \exp(a + b \times \ln(AADT_{maj} + AADT_{\min}) + c \times \ln(\frac{AADT_{\min}}{AADT_{maj}}) + d \times \ln(PedVol) + e \times n_{lanesx}) \quad (4.16)$$

Where

a, b, c, d, e are the model regression coefficients taken from HSM

$AADT_{maj}$ is the Annual Average Daily Traffic of the major street and $AADT_{\min}$ is the Annual Average Daily Traffic of the minor street

$PedVol$ is the total number of daily pedestrian volumes in all the intersection legs

n_{lanesx} is the maximal number of traffic lanes crossed by pedestrian in any crossing maneuver at the intersection.

The regression coefficients for each SPF, CMFs, bicycle crash adjustment factor, and calibration factor used in this study to reflect local conditions and effects of intersection treatments are extracted from HSM and summarized in Table 4.4.

CMFs are significant in adjusting the basic condition and formula after implementing a given countermeasure at a specific site. This study selected the most statistically reliable factors in HSM 2010 with standard errors less than 0.1. The modification factors for various intersection treatments or conditions can also be found online at Crash Modification Factors Clearinghouse [64]. This website hosted and funded by Federal Highway Administration is the external resource attached to HSM 2010. This website provides a database of CMFs along with supporting documentation and a platform for researchers to submit and review updated CMFs.

Table 4.4 SPF Coefficients and CMFs for Urban four-leg Signalized Intersections

SPF coefficients for Urban four-leg Signalized Intersection

Collisions Type	Crash Severity	a	b	c	d	e	f
Multiple Vehicles (N_{bimv})	All Crashes	-10.99	1.07	0.23			
	Fatal and Injury	-13.14	1.18	0.22			
	PDO	-11.02	1.02	0.24			
Single Vehicle (N_{bisv})	All Crashes	-10.21	0.68	0.27			
	Fatal and Injury	-9.25	0.43	0.29			
	PDO	-11.34	0.78	0.25			
Vehicle-Pedestrian ($N_{pedbase}$)	All Crashes	-9.53	0.4	0.26	0.45	0.04	
Vehicle-bicycle (N_{bikei})	All Crashes						0.015

CMFs for Local Intersection Conditions

Applicable SPF	Items	Crash Modification Factors*			
Multiple Vehicles and Single Vehicle	Left Turn Lane	Number of approaches with left turn lane			
		1	2	3	4
		0.9	0.81	0.73	0.66
	Left Turn Phase	Permissive	Protected/Permissive	Protected	
		1	0.99	0.94	
	Lighting	Not lighted	Lighted		
		1	0.9107		
Vehicle-Pedestrian**	No. of Bus Stops	0	1 or 2	3 or more	
		1	2.78	4.15	
	School	No school	School present		
		1	1.35		
	No. of Alcohol Sale Store	0	1-8	9 or more	
		1	1.12	1.56	

CMFs for Intersection Treatments

Treatment Types	CMFs*	Std. Error***
Left turn Prohibition	0.32	0.1
Grade Separation	0.73	0.08

** Applicable to all crashes severities in the area of the intersection*
*** Within 1000 ft of the center of the intersection*
**** More statistically reliable CMFs with Std. Error of 0.1 or less are selected*

The Calibration Factor (Cr) which is to adjust and reflect differences in location or time between the basic condition and the local condition is a user determined parameter [63]. A calibration factor of 1.0 is the default value used in the safety analysis for permanent LTP and LCUP.

The accident prediction model in safety analysis which presents a prediction of annual accidents based on daily volume, may not be applicable to temporary LTP for peak periods only. A calibration factor is developed for addressing this issue by assuming that the proportion of peak hour accidents is linearly related to the ratio of peak hour volume to daily traffic volume (i.e. K-factor) and traffic characteristics of each workday are homogeneous. The factor used to convert the accident rate from annual daily to annually workday's peak periods is defined as

$$C_r = K\eta r \tag{17}$$

Where

K = K-factor

η = the duration of peak period in a workday (typically 4 hours)

r = the ratio of workdays to total days in a year (usually 250/365).

LTP may improve the safety at the intersection, but similar to the substantial trade-off between intersection delay reduction and travel time increase of turning vehicles, the safety enhancement benefit may be offset by increased vehicle miles traveled (VMT) due to rerouting. Additional VMT would potentially impose increasing accident risk. Therefore, the safety analysis after left turn removal has to take into account both intersection crash frequency predicted and rerouting left turn collisions estimated by using VMT and length of rerouting.

An estimation method of accident rate related to rerouting vehicles is developed in this study based on vehicle crash involvement rate by crash severity (Fatal, Injury, and Property Damage Only (PDO)) per million VMT. The accident rate of rerouted traffic for any of the three severity classes (A_{LRi}) is estimated as follows:

$$A_{LRi} = 4aV_{LR}t_{yr}r_i \qquad (4.18)$$

Where

a = geometric mean length of a standard city block

V_{LR} = the rerouting left turn volume

t_{yr} = total prohibition hours in a year (e.g., 365×24 hours if LTP is permanent)

r_i = accident rate per 100 million VMT for each severity class.

The accident rates per 100 million VMT are extracted from annual reports of the National Highway Traffic Safety Administration (NHTSA). The accident rates are slightly different each year and according to the newest report “Traffic Safety Facts 2009 Early Edition” [65], accident frequency (on arterials, highway, and freeway) by severity based on recent decade data is summarized in Table 4.5.

Table 4.5 Accident Frequency by Crash Severity

Year	Fatality Rate per 100 Million VMT	Injury Rate per 100 Million VMT	PDO per 100 Million VMT
1999	1.55	120	164
2000	1.53	116	165
2001	1.51	108	162
2002	1.51	102	161
2003	1.48	100	159
2004	1.44	94	153
2005	1.46	90	152
2006	1.42	85	147
2007	1.36	82	154
2008	1.26	79	153
2009	1.13	74	146

Traffic accident frequency per 100 million VMT has steadily declined in all categories (Fatal, Injury and PDO) in the past 10 years based on the crash data. The safety assessment for rerouting traffic used the 2009 dataset for crash estimation rather than the average rate.

4.7 Preliminary Economic Analysis

Evaluation indicators and units of measurement for assessing traffic operations and safety performance are different so that the side-by-side comparison of the loss and gain in these two aspects cannot be conducted without a single and integrated index of performance evaluation. The cost-benefit analysis (CBA) is designed to provide a monetized assessment by converting benefits from different elements of an intersection treatment into common and monetary unit of measurement so that they can be aggregated across years and road users, and can be comparable across different alternatives and promising project locations. CBA is an aggregated approach assuming a broad view of net benefits over all affected stakeholders and interests and excludes the tradeoffs between stakeholders and performance uncertainties. It may not provide comprehensive assessment to meet decision maker expectations for a proposal. At level 3, the final comprehensive evaluation involving multiple stakeholders and dimensions of performance measurement, this method includes a values-based evaluation approach that captures and disaggregates tangible and intangible attributes of individual stakeholders.

Delay is an increase of travel time and the value of travel time due to delay varies for different user classes. Two user classes were considered: passenger vehicles and heavy vehicles. According to AASHTO's A Manual of User Benefit Analysis for Highways (UBA) [66], the value of travel time for each vehicle type is estimated by multiplying the prevailing percentage, average vehicle occupancy and the prevailing wage rates or total compensation. The overall time used in delay reduction benefits analysis is calculated by weighting the individual time means for two vehicle types by the traffic volume in each class. Four-hour long peak periods in a workday (two AM and two PM) are commonly adopted in engineering practice, but this can vary as required. In this cost-benefit analysis, a peak period expansion factor of 2.0 is used to extrapolate a single peak hour travel time savings benefits to daily peak period travel time savings. In other words, our method doubles the travel time savings or losses from the AM and PM peak hour analyses and sums them up to represent the outcome for a full work day.

The primary measurement of traffic operation quality for signalized intersection is delay in seconds/vehicle, which can be interpreted as an increase of travel time. In this research, we considered two user classes: passenger vehicles and heavy vehicles. Passenger vehicles are the vehicle types used for carrying passengers including cars, SUVs, mini vans and pickups. Heavy vehicles are the vehicle types that are defined in the classes 4 – 13 of the FHWA-13 vehicle classification categories, including public bus, single unit truck, semi trailer truck, and multiple-trailer combination trucks.

According to Table 4.6 which summarizes the guidelines for assigning values of time presented in UBA [66], the value of travel time is estimated by multiplying a specific percentage for various types of transportation modes, average vehicle occupancy and the prevailing wage rates or total compensation. The time value used in delay reduction benefits analysis is calculated by weighting the individual time value means for two vehicle classes by the traffic volume in each class. The UBA summarizes the accident costs by crash severity provided by NHTSA and suggests net user costs of accidents with deduction of insurance reimbursement should be used in calculating accident costs.

Table 4.6 Travel Time Value and Accident Cost

Travel Time Costs (2011 $)					
Vehicle Types	**Recommended Value of Time***	**Wage Rate***	**Total Compensation***	**Occupancy Rate****	**Value of Time Per Hour**
Passenger Vehicles	50% of the wage rate	$24.24	$28.64	1.71	$20.73
Truck and Heavy Vehicles	100% of total compensation	$21.99	$26.42	1.12	$29.59

Accident Costs (2011 $) *			
Accident Types	**Average Perceived User Cost**	**Average Insurance Reimbursement**	**Net Perceived User Cost**
Fatal	$4,901,958	$38,529	$4,863,429
Injury	$180,369	$38,529	$141,840
PDO	$5,094	$4,832	$261

**Values in User and Non-User Benefit Analysis for Highways were in year 2000 dollars. They have been converted to 2011 dollars*
***Values were estimated based on 2009 National Household Travel Survey and extracted from Transportation Energy Data Book, Edition 29*

In order to consider the inflation associated with the dollar value of the costs and benefits, both travel time costs and accident costs have been converted to 2012 dollars using Consumer Price Index (CPI) Inflation Calculator available on U.S. Bureau of Labor Statistic website [67].

HSM predictive models only produce crash frequency estimations for fatal and injury. In order to separately apply the accident costs to each severity class, the distribution rates of 99.22% for injury and 0.78% for fatality are used. These rates are estimated based on 1,306 urban, four-leg, signalized intersections accident type and accident severity samples as summarized in Table 4.7.

Table 4.7 Summary of Intersection Accident by Types [68]

Accident Type*	Fatal	Injury	Total
Single vehicle	12	527	539
Multiple vehicles	85	11,830	11,915
Total	97	12,357	12,454
Percentage	0.78%	99.22%	100.00%

* Sum of accidents at 1306 study intersections in 3-year period

Travel time benefits and accident reduction estimated by using valuation factors are the annual direct benefits for tbe proposed intersection treatment. The most apparent project costs include sunk investments (i.e. planning, design and construction cost), annual operation and maintenance cost and other annual miscellaneous costs (e.g. traffic signs, road furniture and road painting, etc.) Both costs and benefits associated with the intersection treatment are adjusted for the time value of money and then analyzed to determine the number of years to payoff and the 20-year B/C ratio under a given interest rate. (An annual discount rate of 3% recommended in UBA for the cost-benefit analysis if the inflation is removed).

4.8 Planning Assessment Tool

4.8.1 Introduction

Because of the complexity involved in the evaluation process and calculation, an interactive spreadsheet model was developed to facilitate the planning level evaluation of LTP and LCUP (Figure 4.6). Given certain input data for signalized intersection and proposed treatments, the model automatically calculates the potential effects on intersection traffic and safety conditions and estimates the payback period and a 20-year benefit/cost ratio. The tool was coded in Visual Basic for Applications (VBA) in a Microsoft Excel spreadsheet and arranged into eight worksheets containing Introduction, Inputs (general inputs and special additional inputs for different treatments), Parameters, Intersection Conditions, Operational Analysis (respectively for LTP and LCUP) Safety Analysis, Results and Evaluation. The user is taken through this series of worksheets where traffic and geographic information about an intersection and its surrounding area is input.

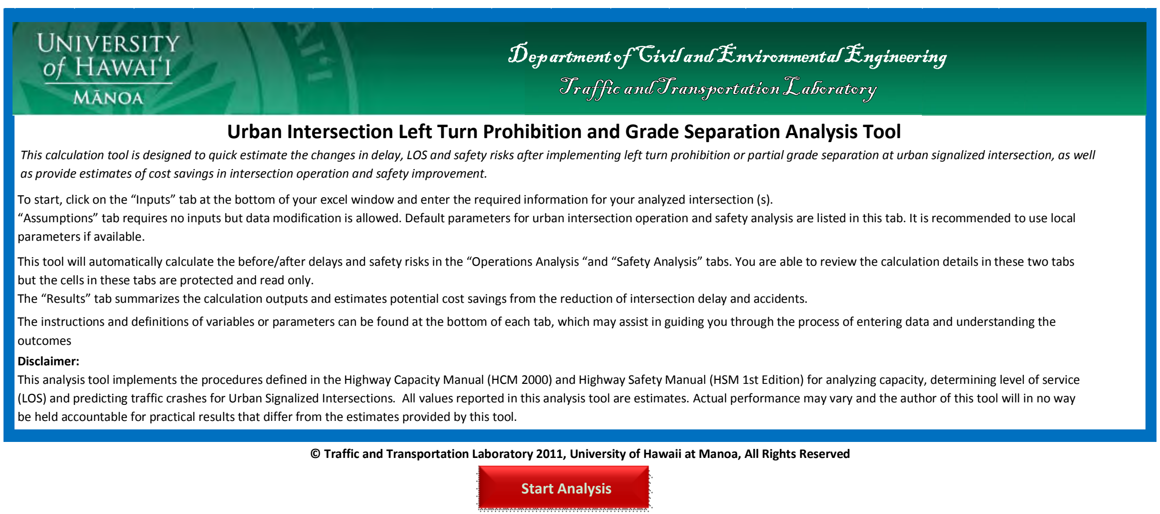


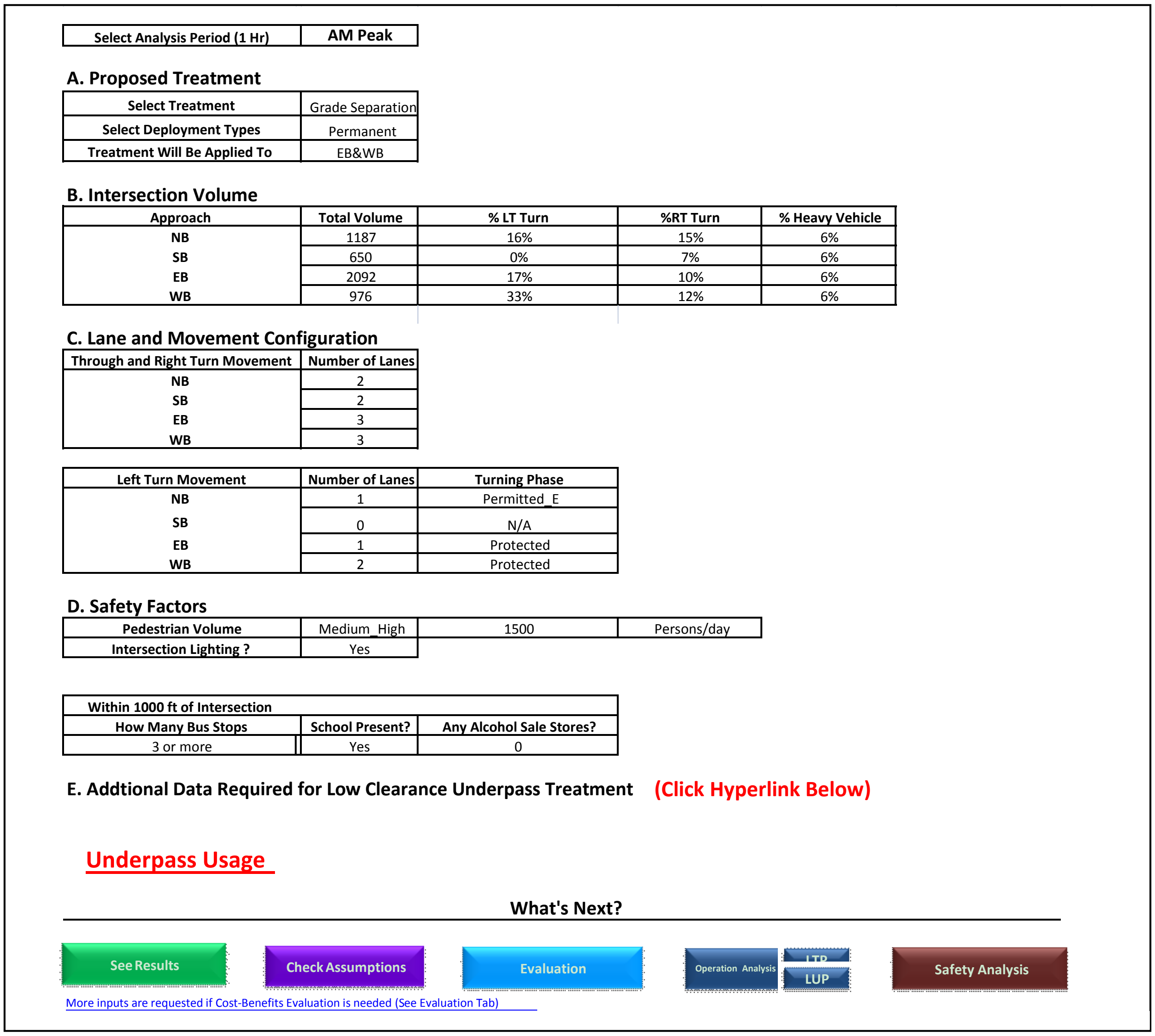
Figure 4.6 Interface of Planning Level Analysis Workbook

Explanatory comments are integrated with the spreadsheet cells to facilitate navigation through the process and to assist in entering data and understanding the outcomes. The cell containing a specific instruction, reference source or definition of variable has a red right triangle sign on the top right and the guide information can be found in a pop-out comment box when the cell is clicked.

4.8.2 Inputs Worksheet

The spreadsheet model is designed so that the user is generally required to select or enter data only in the green boxes. The blue boxes turn green once data are inputted. As shown in Figure 4.7, the "Inputs" worksheet requires the user to specify the analysis period, select the proposed treatment, and enter the intersection information including approach volume, proportion of left turn and heavy vehicles, lane configuration and existing type of left turn phase (permitted with exclusive lane or shared lane, protected, and no left turn). Intersection safety factors consisting of pedestrian volume level, intersection lighting, and the number of bus stops, schools and alcohol sale stores within 1000 ft. of the intersection are also required to be specified.

More user inputs and selections including analyzed periods, annual interest rate, and project costs are requested if cost benefit analysis is to be conducted in the "Evaluation" worksheet. Once user finishes the input of data, s/he is given the choice to directly check the analysis results, or examine assumptions, or review the summary of intersection conditions, or conduct the cost benefit analysis.



Select Analysis Period (1 Hr)	AM Peak

A. Proposed Treatment

Select Treatment	Grade Separation
Select Deployment Types	Permanent
Treatment Will Be Applied To	EB&WB

B. Intersection Volume

Approach	Total Volume	% LT Turn	%RT Turn	% Heavy Vehicle
NB	1187	16%	15%	6%
SB	650	0%	7%	6%
EB	2092	17%	10%	6%
WB	976	33%	12%	6%

C. Lane and Movement Configuration

Through and Right Turn Movement	Number of Lanes
NB	2
SB	2
EB	3
WB	3

Left Turn Movement	Number of Lanes	Turning Phase
NB	1	Permitted_E
SB	0	N/A
EB	1	Protected
WB	2	Protected

D. Safety Factors

Pedestrian Volume	Medium_High	1500	Persons/day
Intersection Lighting ?	Yes		

Within 1000 ft of Intersection		
How Many Bus Stops	School Present?	Any Alcohol Sale Stores?
3 or more	Yes	0

E. Addtional Data Required for Low Clearance Underpass Treatment (Click Hyperlink Below)

Figure 4.7 Data Input Interface of Spreadsheet Model

The inputs spreadsheet provides a hyperlink to another worksheet for additional data. If LTP treatment is selected, rerouting options and rerouting speeds for the "no left turn" approaches need to be entered at the "LTP" spreadsheet (Figure 4.8). If LCUP treatment is selected, the "LCUP" worksheet of underpass capacity and downstream effect analysis is evoked. It requires additional inputs including intersection spacing, downstream approach lane configuration, intersection cycle length and green time of downstream approach (Figure 4.9).

Left Turn Rerouting

Left Turn Reroute	Need Detour?	Select Rerouting Options			Select Rerouting Speed
NB	NO	No_Rerouting	N/A	N/A	N/A
SB	NO	No_Rerouting	N/A	N/A	N/A
EB	YES	Estimated	City block size (mile^2)	0.0024	10
WB	YES	Designated	Distance (mile)	0.3000	15

Figure 4.8 LTP ReroutingWorksheet

Optimization Trigger	1	ON

Inputs

A. Low Clearance Underpass Design Criteria

Deployment Approaches	EB&WB	
Design Capacity	2000	veh/hr/ln
Underpass %Slope	5%	
Underpass Vertical Clearance	8	ft
Length of Solid White Line	50	ft

B. Downstream Intersection Condition

Road Segment Posted Speed Limit		25	mph
Terrian		Level	
Signal Progression between Intersections		3	(Arrival Type)
Distance to Upstream Int (D)	EB	900	ft
	WB	450	ft
Estimated Cycle Length (C)		120	sec
Int. U Signal Visible at Underpass Entrance		Yes	

C. Downstream Lane Configuration and Signal Timing

				EB	
Select Lane Group (LG)	TH	RT	LT	NA	-
No. of Lanes	3	1	1		-
Saturation flow	0.48	0.45	0.42		veh/s/ln
% LG Vol in Total Approaching Vol (Pi)	0.80	0.1	0.10		-
Effective Green (g)	25	25	12		sec

				WB	
Select Lane Group (LG)	TH	RT	NA	NA	-
No. of Lanes	3	1			-
Saturation flow	0.48	0.45			veh/s/ln
% LG Vol in Total Approaching Vol (Pi)	0.90	0.1			-
Effective Green (g)	25	25			sec

Outputs

Underpass Effective Capacity	EB	1503	veh/h
	WB	1038	veh/h
Underpass Usage	EB	1213	veh/h
	WB	426	veh/h
Saturation Status	EB	Under Capacity	
	WB	Under Capacity	

Figure 4.9 LCUP Downstream Analysis Worksheet

In the "LTP" and "LCUP" spreadsheets, the user is guided through the cells where traffic rerouting (LTP) and downstream intersection information (LCUP) is collected and the new information automatically recalculates the results. As shown in

Figure 4.8 and 4.9, the “LTP” spreadsheet contains rerouting option and rerouting speed which require users’ inputs.

The “LCUP” spreadsheet is a one-page worksheet containing three sections: Inputs, Outputs and Summary. The user is required to select the lane group and enter data including the downstream intersection geographic and signal timing information in the green boxes of the input section. The summary section includes the intermediate outputs during the calculation process, such as the acceleration/deceleration delay, the types of queue spillback and the order of spillback occurrence. These values provide a handy review and assist in understanding the final output. The section specifies the lane group which would most likely generate the longest queue and be the first one to create queue spillback and lane blockage at the upstream intersection. The value of downstream arrival capacity presented in the summary section of the worksheet is crucial to determine the potential loss in capacity during the analysis period and to justify the feasibility of a capacity expansion treatment.

The “LCUP” workbook presented the outputs of underpass effective capacity and usage. The saturation flow rates of underpass lane for both directions are shown using the evaluation scales: “under capacity” if the rate is lower than or equal to 0.95, “near capacity” if the rate is higher than 0.95 but lower than 1, and “at capacity” if the rate is 1.0. The color of the cell will turn to yellow at “near capacity” status and red at road capacity. The underpass usage is always lower or equal to capacity. No oversaturation of underpass lane is considered because underpass capacity is restricted by the downstream queue spillback and storage space. If the underpass is operating at or near its full capacity, motorists will avoid using the underpass lane weaving onto the underpass lane would be difficult due to queue spillback.

Because the adverse downstream effects are related to the queuing space, intersection spacing, signal timing and green time allocation at the downstream approach, the negative impacts and underpass capacity limit can be raised if some of the adjustable factors can be modified or improved. This workbook enables sensitivity analysis by varying the inputs of downstream approach green-cycle rate, lane configuration, and cycle length for a specific project. Intersection spacing and other settings information can also be adjusted, but in reality those modifications may not be feasible or affordable.

The automatic computing process in the planning analysis workbook involves iterative calculations and a process of converging to discover the correct calculation sequence. The optimization trigger (see Figure 4.9) in the "LCUP" worksheet needs to be turned on in order to obtain balanced and optimal traffic redistribution estimation. If Microsoft Excel displays the error value "#DIV/0!" as the result of the calculation in the analysis workbook, then the optimization and iteration process was stopped due to changes made on key parameters and values. The optimization trigger should reset to 0 (OFF), then turn it back 1 (ON) to resume the process and correct the error.

In addition, the circular reference which is a series of references where the last object references the first should be allowed and enabled in Excel to result in a closed loop calculation. As shown in Figure 4.10, the iterative calculation is enabled. The default maximum number of iterations (100) and maximum changes (precision = 0.001) are sufficient in this analysis.

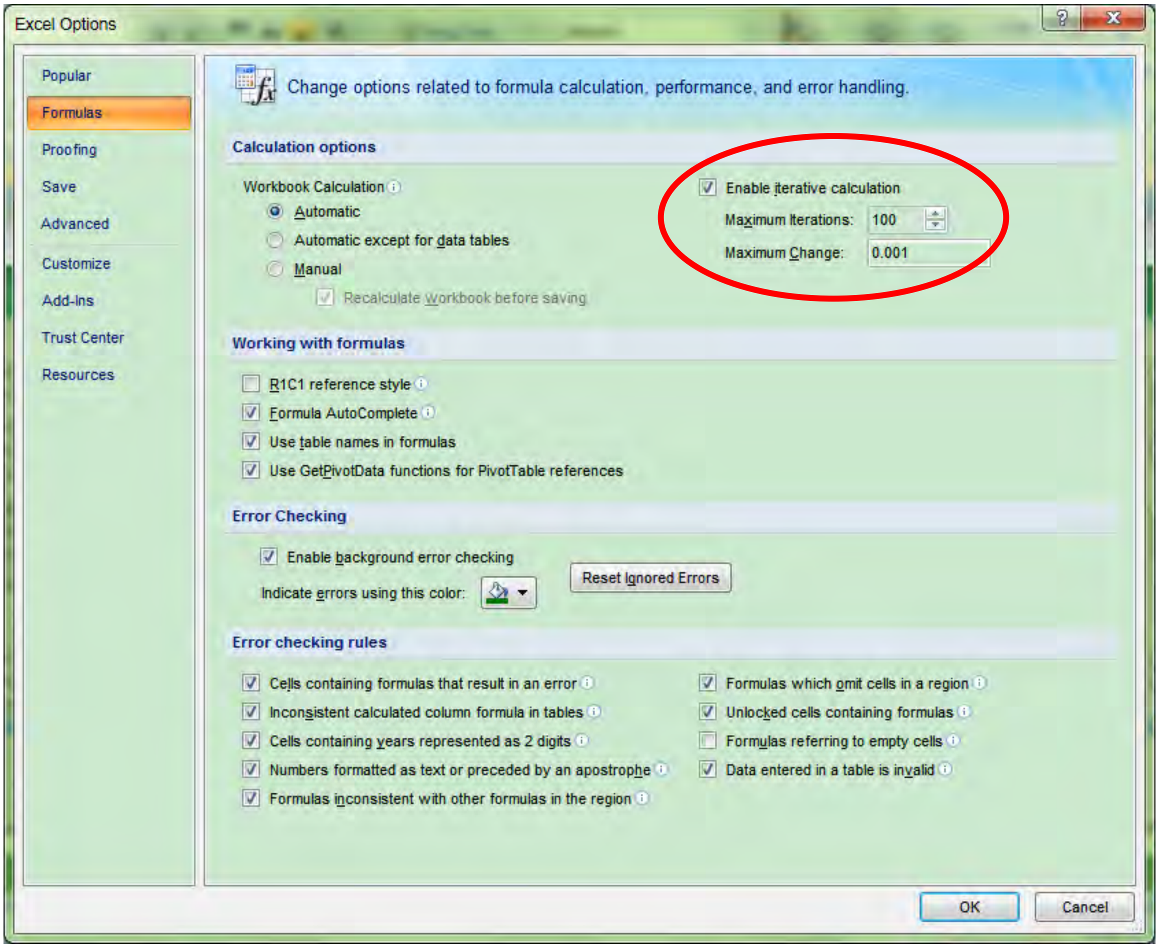
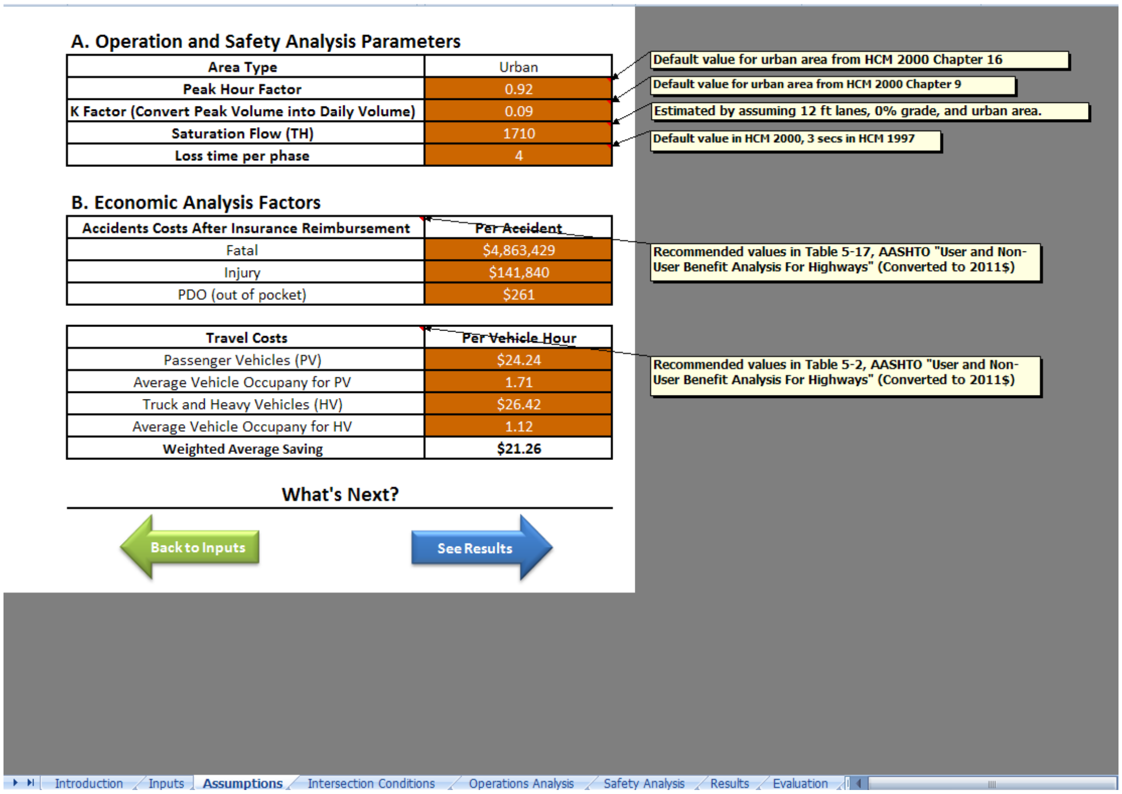


Figure 4.10 Enable Iterative Calculation

4.8.3 Parameters Worksheet

The model based on the quick planning process requires limited field data and relies instead on default values for parameters in the required traffic, safety and economic appraisals. In the process of calculation and evaluation, some typically accepted assumptions and factors are necessary. These are given in the "Parameters" worksheet (Figure 4.11). Figure highlights the pop-up comment boxes which includes the resources and references of the default parameters.



A. Operation and Safety Analysis Parameters

Area Type	Urban
Peak Hour Factor	0.92
K Factor (Convert Peak Volume into Daily Volume)	0.09
Saturation Flow (TH)	1710
Loss time per phase	4

Default value for urban area from HCM 2000 Chapter 16
Default value for urban area from HCM 2000 Chapter 9
Estimated by assuming 12 ft lanes, 0% grade, and urban area.
Default value in HCM 2000, 3 secs in HCM 1997

B. Economic Analysis Factors

Accidents Costs After Insurance Reimbursement	Per Accident
Fatal	$4,863,429
Injury	$141,840
PDO (out of pocket)	$261

Recommended values in Table 5-17, AASHTO "User and Non-User Benefit Analysis For Highways" (Converted to 2011$)

Travel Costs	Per Vehicle Hour
Passenger Vehicles (PV)	$24.24
Average Vehicle Occupany for PV	1.71
Truck and Heavy Vehicles (HV)	$26.42
Average Vehicle Occupany for HV	1.12
Weighted Average Saving	$21.26

Recommended values in Table 5-2, AASHTO "User and Non-User Benefit Analysis For Highways" (Converted to 2011$)

What's Next?

Back to Inputs
See Results

Introduction / Inputs / Assumptions / Intersection Conditions / Operations Analysis / Safety Analysis / Results / Evaluation

Figure 4.11 Assumption Parameters Used in the Spreadsheet Model

After entering the required data in the input worksheet, the user may proceed to the parameter worksheet to review these parameters in the brown boxes and to adjust them for specific projects or locations, if high quality and local parameters are available. The default parameters are also required to be updated if newer or more reliable references became available. These assumptions are relaxed in subsequent levels if detailed analysis is warranted by the planning level results.

4.8.4 Automatic Calculation Spreadsheets

Automatic calculation spreadsheets consist of four worksheets which are Intersection Condition, Operations Analysis (specialized for LTP and LCUP), and Safety

Analysis. The user can proceed to these spreadsheets for reviewing the intermediate outputs and summary of changes in intersection volume redistribution, signal timing, delay, and crash rates. No inputs are required in these spreadsheets. Because the values in these sheets are generated by the automatic calculation process and coded with Visual Basic for Applications (VBA), any changes or modifications in a spreadsheet cell are not subject to "undo/redo" and may lead to difficulty in tracking the accuracy of results. Therefore, the cells are locked and editing is disabled.

The spreadsheet "Intersection Condition" is shown below (Figure 4.12). It summarizes and calculates the before and after signal phases, loss time, adjusted volume after applying PHF factors, lane configuration, saturation rate for through and turning lane and for permitted or protected signal according to HCM 2010. The information and data prepared in this spreadsheet are essential inputs and reference for the computation of operational delay and accident frequency.

A. Intersection Condition - Before

Phases	3
Total Loss time	12
Saturation Flow (TH) + %HV Adjusted	1709
Saturation Flow (Protected LT)	1624
Has Unprotected Left Turn On	NB&SB

Left Turn Movement	Saturation Rate
NB	1274
SB	0
EB	1624
WB	1624

Approach	Adj. Volume
NB	1290
SB	707
EB	2274
WB	1061

		Permitted Left Turn	
Left Turn Movement	Through Car Equivalents	Saturation Flow(S_LT)	Saturation Flow (E_LT)
NB	3.1	1067	1274
SB	6.6	1709	1709
EB	4.5	883	1067
WB	11.9	247	370

B.Intersection Condition - After

Phase	3
Loss time	12

Left Turn Movement	After	Saturation Rate
NB	Permitted_E	1274
SB	N/A	0
EB	Protected	1624
WB	Protected	1624

Approach	Total Volume	% LT Turn	Adj. Volume
NB	1187	16%	1290
SB	650	0%	707
EB	1169	17%	1270
WB	628	33%	683

		Permitted Left Turn	
Left Turn Movement	Through Car Equivalents	Saturation Flow(S_LT)	Saturation Flow (E_LT)
NB	3.1	1067	1274
SB	6.6	1709	1709
EB	3.1	1039	1255
WB	5.6	453	678

What's Next?

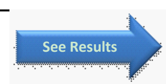


Figure 4.12 Intersection Condition Worksheet in the Analysis Workbook

Automatic calculation of operational analysis is performed for LCUP and LTP. The respective sheets calculate the intersection delay and LOS, as indicated in Figures 4.13 and 4.14.

A. Intersection Operation - Before

Approach	Movement	Volume	Number of Lanes	V/s	MAX (V/s)	Green time	Pedestrian WALK +FDW	Adj. Green Time	V/C	D1	D2	Delay	Approach	Intersection
NB	TH+R	994	2	0.29	0.29	49	27	49	0.92	74.34	14.11	88.45	84.69	78.25 E
	LT	193	1	0.15		49		49	0.48	62.13	3.21	65.34		
SB	TH+R	650	2	0.19	0.00	49		49	0.60	65.10	2.50	67.60	67.60	
	LT	0	0	N/A		49		49	N/A	0.00	0.00	0.00		
EB	TH+R	1732	3	0.34	0.34	56	18	56	0.92	73.69	9.04	82.72	86.52	
	LT	360	1	0.22		37		37	0.92	75.15	29.62	104.77		
WB	TH+R	652	3	0.13	0.22	56		56	0.35	55.90	0.51	56.41	59.79	
	LT	324	2	0.10		37		37	0.42	64.97	1.63	66.59		
			Optimal Cycle	154			Adj. Optimal Cycle	154						
Cycle Length	154													

B. Intersection Operation - After
(Intersection Only)

Approach	Movement	Volume	Number of Lanes	V/s	MAX (V/s)	Green time	Green for Pedestrian	Adj. Green Time	V/C	D1	D2	Delay	Approach	Intersection
NB	TH+R	1354	2	0.40	0.40	39	27	39	0.89	39.81	7.90	47.72	45.28	40.74 D
	LT	193	1	0.16		39		39	0.27	27.29	0.89	28.18		
SB	TH+R	974	2	0.28	0.00	39		39	0.64	33.62	2.04	35.67	35.67	
	LT	0	0	N/A		39		39	N/A	0.00	0.00	0.00		
EB	TH+R	2092	3	0.41	0.41	40	18	40	0.89	39.63	5.35	44.97	44.97	
	LT	0	0	N/A		40		40	N/A	0.00	0.00	0.00		
WB	TH+R	976	3	0.19	0.00	40		40	0.41	28.97	0.54	29.51	29.51	
	LT	0	0	N/A		40		40	N/A	0.00	0.00	0.00		
			Optimal Cycle	87		Adj. Optimal Cycle	87							
Cycle Length	87													

C. Rerouting Movements

Approach	Rerouting Volume	Rerouting Distance	Rerouting Delay	Travel Time Saving (+)
NB	0	0.00	0	0
SB	0	0.00	0	0
EB	360	0.20	71	34
WB	324	0.30	72	-5

What's Next?

Back to Inputs   See Results

Figure 4.13 Layout of Operations Analysis for LTP

A. Intersection Operation - Before

Approach	Movement	Volume	Number of Lanes	V/s	MAX (V/s)	Green time	Pedestrian WALK +FDW	Adj. Green Time	V/C	D1	D2	Delay	Approach	Intersection
NB	TH+R	994	2	0.29	0.29	49	27	49	0.92	74.34	14.11	88.45	84.69	78.25 E
	LT	193	1	0.15		49		49	0.48	62.13	3.21	65.34		
SB	TH+R	650	2	0.19	0.00	49		49	0.60	65.10	2.50	67.60	67.60	
	LT	0	0	N/A		49		49	N/A	0.00	0.00	0.00		
EB	TH+R	1732	3	0.34	0.34	56	18	56	0.92	73.69	9.04	82.72	86.52	
	LT	360	1	0.22		37		37	0.92	75.15	29.62	104.77		
WB	TH+R	652	3	0.13	0.22	56		56	0.35	55.90	0.51	56.41	59.79	
	LT	324	2	0.10		37		37	0.42	64.97	1.63	66.59		
			Optimal Cycle	154			Adj. Optimal Cycle	154						
Cycle Length	154													

B. Intersection Operation - After
(Intersection Only)

Approach	Movement	Volume	Number of Lanes	V/s	MAX (V/s)	Green time	Green for Pedestrian	Adj. Green Time	V/C	D1	D2	Delay	Approach	Intersection
NB	TH+R	994	2	0.29	0.29	25	27	35	0.77	39.70	4.34	44.04	42.29	42.92 D
	LT	193	1	0.15		25		35	0.31	31.95	1.32	33.28		
SB	TH+R	650	2	0.19	0.00	25		35	0.50	34.77	1.38	36.15	36.15	
	LT	0	0	N/A		25		35	N/A	0.00	0.00	0.00		
EB	TH+R	519	2	0.15	0.15	13	18	18	0.77	42.92	8.05	50.97	51.69	
	LT	360	1	0.22		19		26	0.77	41.44	11.28	52.72		
WB	TH+R	226	2	0.07	0.22	13		18	0.33	38.98	1.32	40.31	38.26	
	LT	324	2	0.10		19		26	0.34	35.83	1.00	36.83		
			Optimal Cycle	69		Adj. Optimal Cycle	91							
Cycle Length	91													

What's Next?

Back to Inputs   See Results

Figure 4.14 Layout of Operations Analysis for LCUP

The safety analysis spreadsheet (Figure 4.15) starts with an estimation of the 24-hour intersection volume before and after project by applying the K-factor and computing crash modification factors for the specific project including type of treatment, intersection location, pedestrian density, area type and neighboring communities and establishments.

A. Before

Major 24 Hrs Volume	34089
Minor 24 Hrs Volume	20411

Ped Max Lane Crossing	5
Approach with left turn lane	3

Items	Crash Modification Factors
Left Turn Lane	0.73
Left Turn Phase	0.88
Lighting	0.91
Bus Stop	4.15
School	1.35
Alcohol Sale Store	1.00

Basic Conditions	Multiple Vehicles Collisions	Single-Vehicle Crashes	Ped	Bike
Fatal and Injury	4.02	0.15	0.16	0.11
PDO	7.68	0.49	0.00	0.00
Total	***11.70***	***0.65***	***0.16***	***0.11***

Adjusted Conditions	Vehicle Collisions	Ped	Bike
Fatal and Injury	2.45	0.92	0.11
PDO	4.80	0.00	0.00
Total	***7.25***	***0.92***	***0.11***

Total Accidents In A Year	8.28

B. After

Major 24 Hrs Volume	20411
Minor 24 Hrs Volume	19711

Ped Max Lane Crossing	5
Approach with left turn lane	3

Items	Crash Modification Factors
Left Turn Lane	0.73
Left Turn Signal	0.88
Lighting	0.91
Bus Stop	4.15
School	1.35
Alcohol Sale Store	1.00
Grade Separation	0.73

Accidents per 100 Millions VMT	
Fatal and Injury	56.14
PDO	139

Increasing VMT Due To Rerouting Left Turn		
Peak Hr VMT (Mile)	Daily VMT (Mile)	Year VMT (in 100 Million)
0.00	0.00	0.00

Basic Conditions	Multiple Vehicles Collisions	Single-Vehicle Crashes	Ped	Bike
Fatal and Injury	2.18	0.12	0.16	0.06
PDO	4.52	0.33	0.00	0.00
Total	***6.71***	***0.45***	***0.16***	***0.06***

Adjusted Conditions	Vehicle Collisions	Ped	Bike	VMT of Left Turn Vehicle
Fatal and Injury	0.99	0.67	0.05	0.00
PDO	2.08	0.00	0.00	0.00
Total	**3.07**	**0.67**	**0.05**	**0.00**

Total Accidents In A Year	3.79

What's Next?

Back to Inputs

See Results

Figure 4.15 Safety Analysis Worksheet

The safety analysis sheet estimates and compares the total yearly crashes and crash severity by type of accident (vehicle collisions, pedestrian and bicycle) before and after treatment. Because spreadsheet users may need to modify the CMFs when updated CMFs become available, the cells of CMFs in this spreadsheet have been enabled for editing.

4.8.5 Results and Evaluation Worksheets

The “Results” worksheet requires no inputs. It presents the summary of outputs and provides the user with the choice to conduct analysis for another peak hour or conduct a cost-benefit analysis (Figure 4.16). There are three sections in the results worksheet. Section A summarizes intersection operational improvement including delay reduction and LOS enhancement. The after treatment operational condition has two columns, one on intersection only and another on both intersection and rerouted traffic. The values in the two columns should be identical for LCUP because there is no traffic detour. Section B summarizes the predicted crash frequencies for each severity class. Similar to Section A, the after treatment safety condition considers both intersection wide and rerouted traffic. Section C monetizes the changes in operation and safety due to deployment of treatments by using the Economic Analysis Factors provided in the Parameters worksheet. The “Results” worksheet only presents calculation outputs of the current analysis period (shown in the yellow box at top left) and doesn’t store previous outputs. The outputs may be copied and saved as a separate file or sheet for multiple evaluation periods.

AM Peak

A. Intersection Operation

Measures of Operation	Before	After: Intersection Only	After: Int. & Affected Traffic	Overall Difference
Delay	78.25	42.92	42.92	35.33
LOS	E	D	D	Better

B. Intersection Safety

Severity	Before	After: Intersection Only	After: Int. & Affected Traffic	Overall Difference
Fatal and Injury	3.48	1.70	1.70	1.77
PDO	4.80	2.08	2.08	2.72

C. Benefit Monetization

Annual AM Peak Travel Time Savings	Annual Accident Savings
$266,069	$317,258

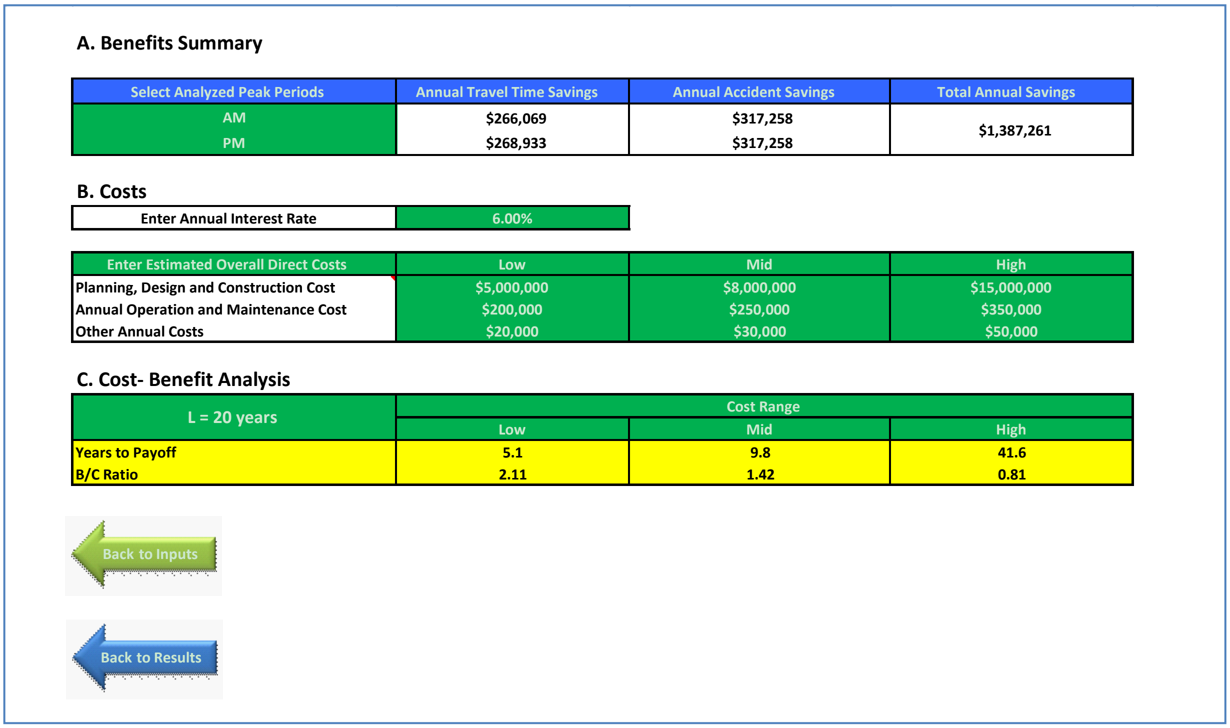
AM Peak analysis is done. Will you analyze PM Peak ?

Yes — Analyze Another Period

No, All Done — Cost-Benefits Evaluation

Figure 4.16 Worksheet Result Summary and Economic Analysis Interface

Although the Results spreadsheet is not featured with storage memory and database, the monetized savings/losses for the AM and PM peak periods analyzed at a time, can be saved in the "Evaluation" worksheet (Figure 4.17) for a complete cost-benefit analysis. The CBA evaluation process requires the user to select periods and provide additional inputs such as the annual interest rate and project costs (e.g, planning, design and construction cost, annual operation and maintenance cost and other annual costs sheet) in three levels of cost range: low, mid, and high. The background of non-blank input cells are filled with green color consistent with all the input areas through this workbook. Based on the inputted project costs and interest rate, economic analysis factors and calculated benefits and costs in traffic operation and safety, an expected payoff period and the benefit/cost ratio over 20 years are provided.



A. Benefits Summary

Select Analyzed Peak Periods	Annual Travel Time Savings	Annual Accident Savings	Total Annual Savings
AM	$266,069	$317,258	$1,387,261
PM	$268,933	$317,258	

B. Costs

Enter Annual Interest Rate	6.00%

Enter Estimated Overall Direct Costs	Low	Mid	High
Planning, Design and Construction Cost	$5,000,000	$8,000,000	$15,000,000
Annual Operation and Maintenance Cost	$200,000	$250,000	$350,000
Other Annual Costs	$20,000	$30,000	$50,000

C. Cost- Benefit Analysis

L = 20 years	Cost Range		
	Low	Mid	High
Years to Payoff	5.1	9.8	41.6
B/C Ratio	2.11	1.42	0.81

Figure 4.17 Worksheet of Cost-Benefits Analysis Interface

Note that Figure 4.16 and 4.17 appear to be generic rather than for a specific treatment. The numbers shown are for illustration. All the worksheets in this analysis workbook have comments and control buttons assisting users to navigate and review the calculations and evaluation at the planning level analysis for LTP and LCUP treatments.

4.9 Chapter Summary

This chapter introduced methodologies and computerized tools designed to provide a comprehensive and practical planning process to evaluate two intersection treatments, LTP and LCUP for urban complex and congested signalized intersection. The planning level analysis is an important element of the entire treatment analysis and evaluation method. It focuses on measuring the basic and most critical potential benefits from reductions of delay and safety risk including a preliminary cost benefit analysis over a 20 year planning horizon. The assessment considers the direct effects on intersection delay using HCM 2010, accident frequency using HSM 2010, and includes a cost-benefit evaluation using UBA.

A spreadsheet model was developed and discussed in this chapter. It facilitates the quick-estimation planning analysis. A computerized procedure is able to assist analysts in quickly evaluating treatments and comparing costs and benefits. Through the entire analysis, the analyst is able to determine the most promising treatments or locations in advance of undertaking feasibility study, detailed measurement of secondary and indirect impacts, further road network analysis and simulation and conflict evaluation.

CHAPTER 5

FEASIBILITY AND ANALYSIS

5.1 Introduction

LTP and LCUP analysis is conducted in three levels using four modules. This chapter presents the second level followed by a comprehensive evaluation level in Chapter 6. This level has two modules: Feasibility Analysis and Performance Analysis. Once the proposed treatment is selected at the planning level assessment, the feasibility analysis module in the second level is conducted to examine the construction impacts and local limitations including the applicable legal requirements and roadway conditions. A detailed performance analysis and simulation of secondary effects on road network, considering community and environmental and energy criteria is also conducted at this level.

Feasibility analysis includes impacts and local restrictions associated with an intersection treatment at the stage of project planning, design and construction periods. The potential effects of the treatment during the implementation and operation periods are considered issues of performance and are handled at the third level. Feasibility analysis is one of the most important steps of developing an intersection improvement project prior to conducting cumbersome measurement and simulation of intersection performance. It is the connecting and transitional step between planning assessment and detailed performance analysis. A checklist is developed for these treatments to understand and conduct the feasibility analysis procedures.

The performance analysis module covers the options and dimensions of performance measures followed by a description of available measurement models or tools which have been used to measure intersection improvement activities and effectiveness. A simple performance measurement framework is outlined, which not only includes performance criteria but also introduces the existing methods, the process of data collection, and the prioritization of criteria.

This chapter starts with a definition of project objective, stakeholders and influence area followed by the discussion of the feasibility and performance analysis. It is necessary to define the purpose of the proposed project, the stakeholders being affected during or after the implementation of the project, and the influence area of the project. Definition of project objectives, stakeholder desires and influence area are prerequisites to understanding which criteria should be considered in the feasibility analysis and which performance indicators need to be quantified in the performance analysis. Project objectives usually describe what the project will accomplish or the user benefits the project will achieve. The development of a transportation project, especially the intersection-wide project is usually beginning with identification of the primary objectives. Stakeholders can be organizations or individuals with a specific interest which may be articulated or not in the development of a project. A transportation project may be developed to address the concerns from one or more stakeholders and the objectives may coincide with the interests of some stakeholders. Stakeholder interests may also become additional objectives. Care should be taken in defining project objectives, listing stakeholders that are likely to affect or be affected by the project and distinguishing stakeholder interests from expected project benefits. Influence area consists of the intersection's functional area and the affected adjacent intersections and road segments. The stakeholders within this area who are expected to be directly influenced by the intersection traffic and would benefit from better traffic conditions are defined as the intersection's users.

5.2 Project Objectives

The primary objectives are mitigation actions to lessen observed or predicted problems in the transportation system. As shown in Figure 5.1, the development of an intersection improvement project consists of five steps, in which the project objectives are identified according to existing problems and their causes. They are used to develop alternatives for improvement. Traffic engineer seeks to understand and identify the causal factors of excessive delay or frequent collisions within the functional boundaries of the intersection. The information gathered by an automatic traffic monitoring system, site visits, field counts and accident reports are reviewed to develop the problem statement.

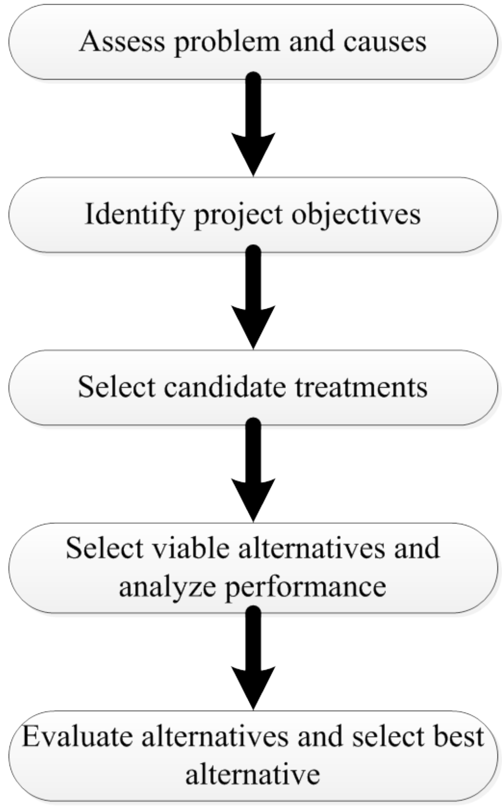


Figure 5.1 Development of an Intersection Improvement Project

Most of the primary objectives of an intersection improvement project are related to the improvement of safety, mobility or both. Table 5.1 summarizes an example set of main objectives of signalized intersection treatments extracted from ITE's "A Toolbox for Alleviating Traffic Congestion" [69], FHWA's "Objectives and Strategies for Improving Safety at Signalized Intersections" [70] and "Signalized Intersection Information Guide" [6].

Table 5.1 Example Set of Main Objectives of Signalized Intersection Treatments

Treatments	Purpose	Mobility	Safety
Signal Coordination or Optimization	Maximize bandwidth efficiency and reduce frequency and severity of intersection conflicts	●	○
New Traffic Signs and Pavement Markings	Improve driver awareness of intersections and signal control	○	●
Add Left Turn Lanes	Improve turning movement capacity and may provide protected turning phases	●	○
Intersection Channelization	Reduce frequency and severity of intersection conflicts through geometric improvements	○	●
Left Turn Prohibition	Reduce frequency and severity of intersection conflicts through traffic control and operational improvements	●	○
Unconventional Intersection Designs	Reduce the amount of vehicle travel time at the intersection and left turning crashes at intersections	○	●
Roundabout	Improve safety, operations and aesthetics of an intersection	○	●
Grade Separation	Provide a significant benefit to the operations of through movements given that conflicts with opposing and adjacent traffic are eliminated	●	○

● Primary Objective ○ Secondary Objective

5.3 Project Stakeholders

Generally stakeholders are defined as persons or groups of people who have a vested interest in the success or failure of a project and the environment in which it operates [71]. Stakeholders of transportation projects are people, communities and businesses who are either involved in transportation decision-making or will be potentially impacted by the proposed project. Stakeholders usually have information, experience, or insight that is helpful in developing a transportation plan and may be in a position to either support or oppose the project based on their perceptions or specific interests.

Primary stakeholders are those who are directly affected by a project. Secondary stakeholders are those who are indirectly affected or are non-beneficiaries of a project [71]. Decision-making stakeholders are final or key decision makers who can approve and implement the project. Non-decision-making stakeholders influence decision-making indirectly and their concerns may be reflected in the priorities of their representatives [72]. This research uses the role of stakeholders in decision-making process to classify stakeholders into decision-making stakeholders and non-decision-making stakeholders.

There are many stakeholders that can be involved in an urban signalized intersection project. It is important to highlight and summarize the interests of all stakeholders and clearly define their expectations on this project, in order to achieve the beneficial performance of the selected treatment most effectively and to mitigate negative performance most acceptably. The summary of the key concerns and issues of each stakeholder should be circulated to ensure a clear understanding of the constraining factors of a project and to manage the interaction between the various stakeholders. Table 5.2 provides an example set of cataloging stakeholder interests and expectations of an intersection project identified by FHWA that provides a broad basis for identification of stakeholders and their interests [6].

Table 5.2 Sample Set of Stakeholder Main Interests and Expectations

Stakeholder	Primary Interest	Expectations
Motorist	Delay, stops and safety	Coordinated signal system, limited stop-and-go conditions
Pedestrian	Delay and safety	Fewer conflicts, reduced crossing distance, direct connections, adequate facilities
Bicyclist	Stops and safety	Provision of bike lane, minimized conflicts with motor vehicles, extended clearance interval
State Traffic Engineer	Corridor capacity	Maximize throughput of mainline
City Planner	Fit in long range plan	Obtain necessary right-of-way and funding to construct improvements sufficient through a 20-year horizon to accommodate all modes
City Traffic Engineer	Safety and city grid operations	Minimize severity and frequency of crashes
Neighborhood Group	Access and safety	Provide bike pedestrian connections linking residential area with shopping district
Business Owner	Access	Maintain full-access turn movements at driveways
Planning Commissioner	Compliance with local standards and policies	Ensure intersection meets operations standards and intent of policy for safety, accessibility, and usability for pedestrian, bicyclist, and transit.

The costs and benefits of intersection treatments to the transportation system and adjacent communities are generated by the supply of infrastructure by government and its usage by people. Transportation activities give rise to a variety of costs, which can be internal, such as fuel consumption and travel time or external, such as vehicle emission, noise and accidents. Not all of the costs are of concern to everyone or all externalized. For example, government develops policies to control vehicle emissions; Road users are not typically concerned with the emissions of their vehicles, but the manufacturers must produce vehicles compliant with emission regulations. The emission compliance cost is built into the vehicle purchase price.

Substantial variations and concerns of effects exist in different groups. This research identified the typical stakeholders for signalized intersection improvement projects and aggregated them into three groups based on their common interest: users, neighbors and owners.

1. **Intersection Users.** They are road users, such as drivers, pedestrian and bicyclists. The group may be further categorized in *Motorists* and *Non-motorist,* because their characteristics and needs are different.
2. **Intersection Neighbors.** They are residents, business and property owners at or near the subject intersection. The access and circulation needs for adjacent properties and business owners and air quality and noise impacts to adjacent properties and businesses are important to them.
3. **Intersection Owners.** They are the owners and managers of the facility. They are usually the developers of intersection projects and the main decision makers. This group includes the senior engineers and administrator. They can be local (e.g., city department of transportation or public works),

state (e.g., State DOT, State Department of Health), federal (e.g., FHWA, EPA) or private agencies (e.g., consultants, contractor and in same case, private financiers). It is also important to include other governmental officials in addition to local jurisdiction and transportation officials, if they are playing a role in project development and decision-making process.

5.4 Influence Area

The stakeholder group varies in size, location and sensitivity to a project's potential effects. The geographical area wherein a group is directly influenced by an intersection improvement project is also different. Therefore, the influence area of an intersection project to intersection users and neighbors needs to be defined.

5.4.1 Influence Area for Intersection Users

An intersection area is defined by both its functional and physical areas. The functional area of an intersection consists of decision distances, maneuvering distances and storage lengths. As defined by AASHTO, the functional area extends both upstream and downstream [73]. The functional and physical areas of a signalized intersection are shown in Figure 5.2 [74].

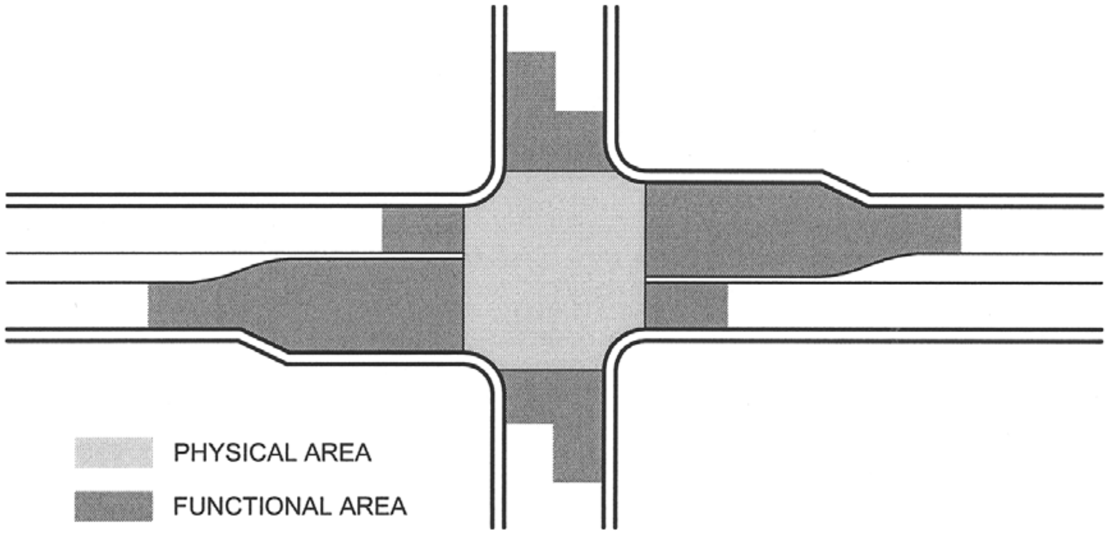


Figure 5.2 Physical and Functional Areas of an Intersection [74]

Driving maneuvers within the intersection's functional areas are directly affected by the intersection condition. Hence the functional areas are adopted to delineate the influence area of the intersection to its users.

The lengths of the intersection functional area vary according to the speed limit, right turn conflict area and storage queues. A location-specific analysis would be appropriate for each intersection's functional area. For a general nationwide analysis, it will be more convenient to use an average value that can be applied to most intersections. Based on the findings in Stover's research [75], the desirable upstream functional area (distance) for speed limits of 35 mph is 370 ft. and the desirable downstream functional area for this speed limit is 350 ft. For approaches with 20 mph or 25 mph speed limits, 300 ft. upstream functional areas and 205 ft. downstream functional areas are suggested.

5.4.2 Influence Area for Intersection Neighbors

The definition of a project influence area for intersection neighbors can be complex because it is rarely restricted to the project footprint or some set distance from the intersection's physical area. The area of influence to intersection neighbors varies in size and is dependent on the characteristics of intersection treatments and project locations.

In this study, the influence area to intersection neighbors is defined on the basis of MUTCD definition of intersection spacing for coordinated signal operation [50].Traffic signal coordination can be achieved at short signal spacing, at 0.25 mile as its optimum signal spacing. As shown in Figure 5.3, Intersection influence area for neighbors is the surrounding area of an intersection within a circle of 0.25 mile centered at the intersection.

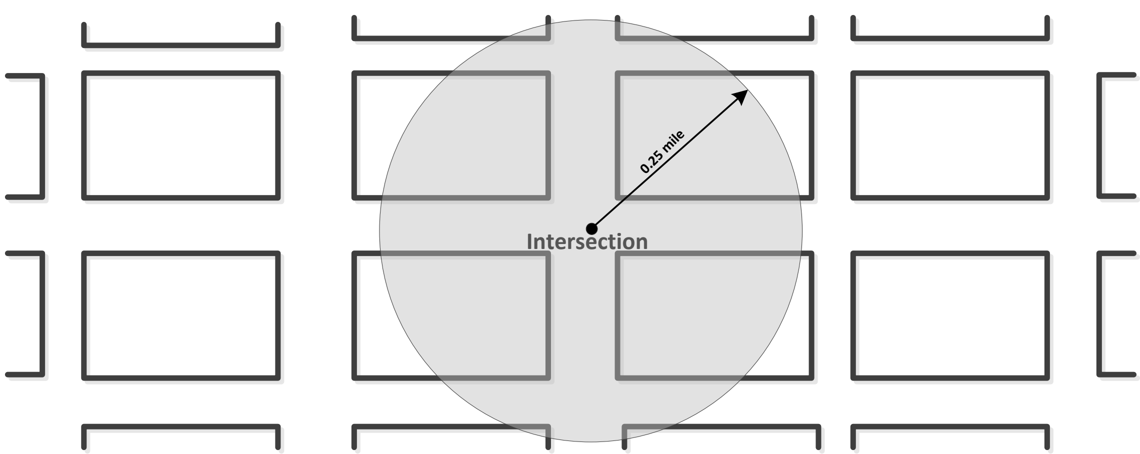


Figure 5.3 Intersection Influence Area for Neighbors

This is a static method and only good for treatments requiring no traffic rerouting. The service area may be extended to other adjacent intersections and road segments depending on traffic rerouting routes. If the rerouting routes are designed, the overall influence area for intersection neighbors are the sum of areas at subjective and affected intersections. If the rerouting routes are selected randomly based on drivers' preferences, the influence area will be a circle area with a radius of 0.5 miles.

5.5 Feasibility Analysis

New intersections or rural intersections typically afford greater flexibility for selection, design and deployment of treatments than do existing ones. Existing intersections especially on urban arterials are often constrained by utility placement, developments surrounding the intersection, and issues related to construction and to maintenance of traffic flow. A feasibility study is more than just a set of checklists. If it is done properly, it provides important guidance for all subsequent detailed analysis. The purpose of the feasibility study is designed to identify all barriers to implementation. In turn, this assures a minimal waste of resources before the costly and labor-intensive process of implementation.

This feasibility analysis is established based on detailed local information including implementation plan, construction scheduling and deployment constraints from the site. The goals of the feasibility study are to ensure that the recommended treatment is feasible and applicable for a specific location and gathers all site-specific information needed in performance analysis, evaluation and decision-making.

The feasibility analysis is structured to facilitate the assessment of the viability of the treatment in different locations by providing a feasibility checklist. The checklist developed in this research is believed to be appropriate and typical for the application of LTP and LCUP at urban signalized intersections. However, it is not intended to be used as a substitute for state or local design standards for these two treatments if applicable.

The checklist is shown in Table 5.3. Traffic analysts who are considering implementing treatment feasibility analysis can use it to select analysis subjects and criteria, to help on developing the study scope, and to review the results of a complete feasibility study. The checklist includes the items and issues that are suggested to consider for applying LTP and LCUP. Not all items in the checklist are necessarily applicable to all LTP and LCUP projects.

Although the checklist is developed based on the discussion of feasibility for LTP and LCUP, it is not restricted to be only used for these two treatments. It is a generic reference for conducting feasibility analysis for transportation project. The proposed project may be considered as infeasible if the project cost exceeds project budget, the maximum or expected project benefits are completely offset by the negative construction impacts, or the implementation is unable to accommodate site-specific restrictions. The discussion of each item in the checklist is detailed in the following sections.

Table 5.3 Feasibility Analysis Checklist

Feasibility Analysis Checklist	Included	Not Applicable	Notes
General Project Information			
1. Define proposed treatment			
2. Identify project benefits from Level 1 analysis (in dollar value)			
3. Determine outline implementation and design plan			
Economic Feasibility			
1. Define project cost range			
2. Funds availability			
3. Evaluate the risk factors for cost over project budget			
4. Evaluate the risk factors attributed to construction delay			
5. If applicable, assess local ability to pay or willingness to pay			
6. Prepare financial management plan or measures to avoid cost overruns and delay			
Construction Feasibility			
1. Indicate construction duration, phases and sites			
2. Identify construction site trip generation			
3. Identify construction equipment used in each phase			
4. Identify influence areas and affected traffic facilities during construction			
5. Assess and mitigate construction period traffic and safety study			
6. Deduct costs of construction impacts from total benefits			
7. Assess and mitigate noise, air quality and other impact assessments			
8. Other countermeasures to address significant impacts			
Local and Legal Feasibility			
1. Justify availability of alternative routes for rerouting traffic			
2. Identify accessibility impacts after treatment			
3. Evaluate the potential of driver confusion and traffic violation			
4. Study transportation facility relocation or removal			
5. Assess traffic equity for non-motorists and persons with disabilities			
6. Measures to accommodate local and legal requirements			

5.5.1 Defining Outline Design and Deployment Plans

The outline plan for applying an intersection treatment includes construction methods and timeline, project budget and cost estimation. The preliminary design of a LTP or LCUP treatment should address the following topics:

- Alternative routes of turning vehicles (LTP)
- Rerouting options (LTP)
- Size of underpass including %Slope and Vertical clearance (LCUP)
- Design Capacity (LCUP)
- Underpass entrance distance to intersection signal (LCUP)
- Length of double solid line prohibiting lane change (LTP and LCUP)
- After-treatment adjustment of lane configuration (LTP and LCUP)
- Deployment approaches (LTP and LCUP)
- Posted speed limit on arterial and alternative routes (LTP and LCUP)
- Intersection terrain (LTP and LCUP)
- Basic controller settings, phase sequence and operation (LTP and LCUP)

A reliable design and implementation plan requires basic traffic operational and safety information obtained from the planning level analysis. The planning level spreadsheet tool can also be used to examine various deployment plans by adjusting the implementation approach, signal phasing and other parameters.

5.5.2 Economic Feasibility

The project cost ranges and economic cash flow for 20-year horizon have been estimated in the preliminary CBA at the planning level assessment, in order to identify the overall costs and benefits in the project construction, maintenance and operation in both the short and long-term. The preliminary CBA considered benefits and project costs, the time value of money, and uncertainties (represented by cost ranges). Although the CBA study demonstrates the net benefit of project in the context of direct and indirect benefits and costs, it doesn't reflect the constraints of project budget. Therefore the economic feasibility discussed in this level is actually budgetary feasibility.

A determination of economic feasibility requires an identification of financial availability associated with an intersection improvement project. The treatments discussed in this research range from low-cost measures of movement restriction (i.e., LTP) to high-cost measures of intersection reconstruction (i.e., LCUP). The total costs of LTP would be much lower than that of LCUP, but LTP usually requires significant public involvement and cooperation from communities, in activities to promote and achieve the goals and objectives of the project and to address intersection congestion or safety conditions. A significant part of total cost for LCUP comes from varied expenditures in construction, operations and administration of underpass. Table 5.4 presents a summary of LTP and LCUP project costs extracted from recent research papers or project reports. All the dollar values shown in this table have been converted into 2011 values by using the construction CPI inflation calculator [67]. It is important to note that LTP and LCUP project costs were difficult to find in the literature and some of them are dated which makes the cost estimates questionable due to advances in construction methods and project designs.

Clearly, grade separation is high cost mitigation. LCUP is a special type of grade separation because of its relatively compact size and lower clearance. Costs of LTP treatment are usually low but may vary depending on the need for channelization modifications at the subject or at the nearby affected intersections. Turn restrictions can be implemented with low-cost signing, but enforcement of the regulation and public information and education campaigns regarding the new regulation will increase the costs [82].

The project costs summarized in Table 5.4 can be used (if local data is unavailable) to determine the cost-effectiveness of a proposed treatment. The costs of goods, steel, asphalt and fuel cannot always be controlled and fluctuate over time. A transportation project involving massive construction, long project timeline and labor-intensive operation work could be potentially over budget due to significant increases in material costs, delays or unforeseen conditions at the jobsite, which cause the proposed treatment project at risk of falling behind schedule or going over budget. In addition, the construction usually does not occur until five or more years after the assessment was done. Therefore, the economic feasibility analysis is necessary to assure the current project scope fits within the project budget and future improvements in this area.

Table 5.4 Intersection Treatment Project Costs

Intersection Treatments	Project Description	Location	Estimated Project Costs*	Resource and Year	Project Type
Turning Movement Restriction	Posted with "No Left Turn" signing during peak AM and PM	Freemont Junior High School Driveway/1001 North Power Road, City of Mesa, AZ	Two signs at a cost of $211	Transportation Advisory Board Report, City of Mesa, AZ , 2009 [76]	Signs
	Turn Restrictions at Multi-Lane Highways with J turn modifications	Undefined	$5,280 to $52,800	Office of Safety, Federal Highway Administration, 2009 [77]	Signs and medians
	Allow left turns during low traffic flow situations and prevent left turns during peak traffic period	Left turn from Dolliver Street to Pomeroy Avenue, City of Pismo Beach, CA	Roughly $15,770 for two signs	Pismo Beach Council Agenda Report, 2008 [78]	Changeable peak/off-peak signs
	Remove the existing left turn bays at the main intersection, Adjust lane geometry (restriping) and storage bay lengths at the nearby minor intersections and install no left turn signs	SW 72 Street/SW 107 Avenue, Miami-Dade County, FL	Range of $136,700 to $210,300	Miami-Dade County Government , 2008 [79]	Restriping and signage
	Remove the existing left turn bays at the main intersection, remove left turn signals and install no left turn signs, Adjust signal timing/phasing and progression offsets at the affected signals	NW 27 Avenue/NW 20 Street/N River Drive, Miami-Dade County, FL	Range of $1,062,160 to $1,240,930	Miami-Dade County Government , 2008 [79]	Intersecting re-construction
	Two-way street left turn restrictions (signage)	Undefined	$492/intersection	Central Federal Lands Highway Division, 2003 [80]	Signs
Grade Separation	8 feet low clearance Underpass design	Urban Arterial Intersections in Honolulu, Hawaii	$5,742,080	University of Hawaii at Manoa, 2004 [12]	Underpass
	A highway underpass	Diagonal Highway in Boulder, CO, USA	$2.4 million	City of Boulder, CO, USA, Planning and Public Works, 2003 [12]	Underpass
	Roadway overpass over the railroad	7th Street-8th Street, in Rosenberg in Fort Bend County	$5,460,085	Texas Department of Transportation, 2007 [81]	Overpass
	Two-lane underpass intersection combines Griggs Road from the east, Mykawa Road from the south, Griggs Road from the west, and Long Drive from the southeast	Griggs Road, Long Drive, and Mykawa Road are four-lane roadways that intersect in south Houston in Harris County	$25,116,392	Texas Department of Transportation, 2007 [81]	2-lane underpass
	Four-lane underpass under the railroad would connect with depressed ramps from US 90A, which will join with Eldridge Road under the westbound US 90A mainlines, while the US 90A mainlines continue at grade	Eldridge Road is currently a four-lane median divided roadway located in Sugar Land in Fort Bend County.	$22,932,358	Texas Department of Transportation, 2007 [81]	4-lane underpass

* Costs are based on 2011 dollars.

Identical intersection treatments built in different locales can have much different construction costs. Regional or local factors such as fuel usage, labor rate, accessibility to construction materials, transportation and logistics, and weather are related to costs. Local economy background and construction demand could also affect construction costs. There are general cost adjustment factors for estimating of regional construction costs or adjusting prices over various states.

5.5.3 Construction Impacts

The construction of an intersection improvement project may have substantial and significant impacts on the existing flow of vehicular and pedestrian traffic, community accessibility and neighborhood quality of life. Constructability issues including maintenance of traffic and minimization of social impacts for an intersection treatment should be considered as well. Construction duration or project phases should also be identified, because there are instances where a potential impact may be of short duration or insignificant during certain period. For example, the impacts on air quality may only need to be assessed during excavation and filling stages of construction.

The construction impacts are typically associated with LCUP treatment. Installation of LTP signs and signal timing adjustment can be done within a few days to a few months depending upon the extent of public information and education provided [29]. The potential impacts to traffic and communities during the installation period of LTP are usually in a short term and can be neglected.

Construction of LCUP treatment must carefully measure the quantity and duration of impacts on traffic and environment, because it is possible that large benefits of an LCUP treatment over the proposed 20 year evaluation horizon will be negated by severe impacts during its construction. Accurate and detailed inventories of infrastructure in the area are necessary. In some instances, the relocation of underground utilities may be sufficiently extensive and costly to render an LCUP proposal infeasible. The identification of construction impacts can also help on providing correction or mitigation measures to reduce the amount of community disruption resulting from the construction.

The direct construction impacts are extracted from a Florida Department of Transportation report and summarized below [83].

1. Air quality impacts related to open burning and dust control;
2. Noise and vibration impacts related to construction activities;
3. Water quality impacts related to erosion control, sedimentation, and turbidity reduction;
4. Traffic maintenance and detour routing;
5. Maintenance of access to businesses and residences;
6. Safety considerations;
7. Public involvement and community interaction to ease disruptive effects;
8. Disposal of construction material;
9. Stock piling of construction material and fill; and

10. Use of borrow areas and any mitigation measures proposed to reduce dredge and fill-related impacts.

The impacts summarized in the list are typically generic and may not all applicable to all LCUP projects. The most substantial and sensitive disruptive effects during LCUP construction are discussed below.

(1) Work Zone Delay and Safety

Underpass installation at urban intersection would cause delay and safety concerns at the intersection and other adjacent locations throughout the construction period. FHWA shows that work zones represent 10% of congestion problems [84]. These impacts would be attributable primarily to lane closure and accessibility blockage at the work zone. The temporary closure of several lanes, the traffic disruptions during underground utility relocation, the construction and installation of cut and cover tunnels, and the traffic signs and pavement markings modification will cause extensive traffic diversions. Because of traffic diversions combined with generated traffic by the work zone itself, traffic will likely be congested near the project site. In addition, the potential closure of pedestrian and non-motorist access on some road segments during some phases of construction would also occur, which may block accessibility to business and residences, primarily in urban core and along pedestrian routes with moderate to high background pedestrian traffic.

Work zone analysis is the process of understanding the safety and mobility impacts of a road construction, maintenance, and rehabilitation project. More specifically, the purpose of assessing work zone impacts is [85]:

- Understand the work zone safety and mobility implications of alternative project options and design strategies.
- Identify those projects that are likely to have greater work zone impacts so that resources can be allocated more effectively to projects.
- Identify strategies to manage the expected work zone impacts of a project and develop an effective transportation management plan.
- Estimate costs and allocate appropriate resources for the implementation of the work zone transportation management strategies.
- Understand, coordinate, and manage multiple projects and construction schedules to minimize overall impacts.
- Monitor and manage work zone impacts during construction, maintenance, and utility work, and adjust the transportation management strategies if needed.
- Provide information for conducting performance assessment.
- Use work zone performance assessment information to improve and update work zone policies, procedures, and practices.

Some updated guides and advanced tools are available to effectively help on construction work zone operational and safety analysis. QuickZone is a computer-based traffic analysis tool [86]. It was designed specifically for work zone related analysis and able to compare the traffic impacts for work zone mitigation strategies and estimates the costs, traffic delays, and potential backups associated with these impacts. Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS) is another software tool supporting the integrated analysis of project alternatives for different pavement design, construction logistics, and traffic operations options at a work zone [87]. It is specially designed to develop construction paving schedules that minimize traffic delay, extend the service life of pavement, and reduce agency costs [87]. DYNASMART-P developed by University of Florida is an advanced work zone traffic analysis tool suitable for macro transportation project with long term duration, large influence areas and multiple construction sites [88]. It is a dynamic traffic assignment analysis tool that can be used to support development of traffic management strategies for regional work zone management.

FHWA recommended using the Highway Safety Manual in work zone safety analysis. Analytical process and CMFs for predicting the impact of project construction on road safety have also been developed through cooperative research initiated by FHWA [89]. In this research, HSM has been used in planning level analysis for crash prediction. It also provides information and a method to assess work zone safety.

If applicable, additional impacts on other transportation facility nearby the work zone should also be considered, such as parking supply caused by occupying curb side lanes or removing of parking spaces, especially for a project site near retail businesses and residential areas. For multiple phase projects, potential construction impacts on traffic condition should be developed for each phase.

There are several countermeasures to mitigate construction impacts on traffic and safety, such as construction taking place earlier or later than AM and PM traffic peak hours, temporary changes in signal phasing/timing, modification of lane configuration, changes in traffic and curbside parking regulations, deployment of traffic enforcement agents, etc.

For a work zone creating significant impacts on pedestrian, bicyclists or resident accessibility, access may need to be maintained to certain locations through temporary walkways, or temporary signage may be required directing non-motorists to other access points. If construction requires the closure of facilities, a temporary facility may be constructed alongside the site and pedestrian fencing as well appropriate signage should be provided to maintain pedestrian safety.

(2) Construction Air Quality and Noise

According to CEQR technical manual [90], an assessment of air quality and noise for construction activities is likely not warranted if the project's construction activities are characterized as short term (less than 2 years), not located near sensitive receptors, do not involve construction of multiple buildings, and only a limited number of diesel equipment are operated in a single location at peak construction.

The construction noise of LCUP depends on the work schedule, location and construction technologies. Noise in a construction site is usually generated by pile driving, blasting, demolition, truck and crane. The analysis of noise is generally conducted only for a certain sensitive period, such as early morning or at night and sensitive locations such as residential buildings, hospitals and schools. State DOTs have various policy and standard on determining whether it is necessary to conduct a quantitative noise analysis. For example, the construction noise impacts analysis may not need to be conducted in New York City, unless the proposed project operated construction equipments within 1,500 feet of a receptor for a period of time exceeding two years [90].

Noise analysis modeling have been developed by a variety of US federal, Canadian and German agencies. CadnaA (Computer Aided Noise Abatement) is analysis software developed by Canadian companies for calculation, presentation, assessment and prediction of environmental noise [91]. SoundPlan model specializes in computer simulations of noise and air pollution situations [92].FHWA Roadway Construction Noise Model released in 2006 is the only available noise analysis tool emphasizing construction noise for transportation facilities. This model is an evaluation tool that can be used for the prediction of construction noise during project development and construction phases. It can predict noise emissions from construction equipment and determine a construction work plan's compliance with noise criteria [93]. It is able to estimate three key metrics of interest: L_{max}, L_{eq}, and L_{10} at receptor locations for a construction operation by using the typical noise levels from representative construction equipment based on an EPA report [94] and incorporates the noise criteria applied to Central Artery/ Project in Boston, Massachusetts [94].

If noise impact is substantial, a noise reduction plan should be developed and implemented to minimize intrusive noise affecting qualified receptors. The plan includes prohibition of loud activities at night, noise barriers, use of low noise emission equipment, relocation of noisy equipment, and shield sensitive receptors or noisy equipment. More construction noise mitigation measures for transportation or highway projects can be found in "Highway Traffic and Construction Noise - Problem and Response" [95] and "Construction Noise Handbook" [94]. These manuals provide additional information about noise abatement procedures.

In addition, traffic diversion due to road closure at a construction site may cause increase of traffic volume on local and neighborhood streets, which not only results in potential traffic congestion and accidents, but also affects air quality and noise level. Noise control measures may be developed to address increasing traffic noise in affected residential or business communities. Unfortunately, no analytical tools or models are recently available to assess street-level and/or intersection-wide traffic noise conditions.

Other construction impacts such as water resources and wetlands, visual impacts and borrow/disposal of materials are not specifically discussed in this section, because generally they may not be considered as significant effects for underground an LCUP project at urban area. However, the analyst of construction feasibility should note that these disruptive effects may become sensitive and significant for a specific project or in a certain community near the project.

In virtue of these existing analytic tools and guidelines of construction impacts, the process of assessing construction impacts is summarized below:

1. Estimate the construction employee and construction related vehicle trips.
2. Collect background traffic information during construction periods.
3. Determine the required lane closure and traffic restrictions.
4. Define the potential impacts and influence area.
5. Estimate traffic delay, safety, noise, and air quality using applicable tools and guides, especially for the overlapping period of construction and peak traffic period.
6. Develop mitigation measures if severe impacts are expected.
7. Estimate the costs associated with the adverse impacts (e.g., delay and safety risks) during construction.

5.5.4 Local and Legal Restrictions

Local restrictions (e.g., availability of ROW and social and environmental constraints), and legal restrictions (e.g., accessibility and traffic equity) are site-specific constraints. The availability of ROW and the costs of inquiring additional ROW for an improvement on an existing urban intersection are usually the major local limitation. Some effective treatments may have to be eliminated because the layout of treatment design requires acquisition of significant amounts of ROW. As mentioned in Chapter 1, the treatments LTP and LCUP discussed in this study have the advantage that they require no additional ROW. However, LTP requires movement restriction and traffic rerouting and LCUP is associated with intersection partial reconstruction and modification. They are also necessary to be studied for feasibility in term of site-specific constraints. These constraints are listed and discussed below.

1. Availability of Alternative Routes

The signalized intersection that is likely to be candidate for either partial or full turning restriction should be evaluated on a case-by-case basis with consideration of the road network effects. When turning movements are closed without providing any rerouting guidance or available rerouting roads, there is a high potential that the problem will be transferred to another location, especially in a compact road network. If there are no designated alternative routes, the surrounding road network density and capacity within a reasonable rerouting distance (usually less than 0.5 mile) should be carefully studied to assure the rerouted traffic does not generate congestion and safety concerns. Transportation agencies may encounter complaints and even lawsuits if the unavailability of suitable alternatives results in drivers continuing to make illegal and dangerous maneuvers or trespassing on private property or restricted streets. Similar concerns may arise during the lane closures for the construction of an LCUP.

2. Accessibility of Business and Residential Areas

High-value business locations and residential buildings are typically situated along major urban arterials, especially for the types of business which cater to pass-by traffic. Investors and merchants understand that high traffic volume means greater opportunity and higher property values. LTP may restrict the accessibility to some establishments due to the rerouting traffic. Although the planning analysis looked at a worse case scenario from a traffic operation's perspective, e.g., all left turn traffic makes a loop of three right turns, in reality, the traffic may divert and avoid the intersection altogether.

LCUP may also decrease or restrict the business exposure and resident access because a large amount of traffic goes underground with no opportunities to glance at surface offerings. Local sensitivity and fears of losing commercial and residential property values and business sale may resist the implementation of treatments involving accessibility restrictions, particularly if the access already exists.

3. Enforcement and Obedience to Traffic Regulations

Motorists may violate active turn prohibition signs and make illegal left turns, especially during light traffic condition, particularly if the left turn lane is left open (e.g., with a simple crosshatch striping), or if the LTP is temporary and not enforeced with a physical barrier. Oversize vehicles may attempt to use the LCUP due to failure to obey or to understand height clearance regulations. Serious safety concerns and disruption of road traffic flow are associated with these violations. Excessive disobedience of turning prohibition or height clearance regulations may occur if the traffic signs is not properly designed or operated or the education on the motorists and road users is insufficient.

Periodic enforcement may be needed to ensure that drivers obey restrictions, and the deployment of ITS sensors and warnings for overheight vehicle is necessary.
If local conditions are likely to cause high disobedience and violation rate, countermeasures should be deployed and budgeted for or the proposed treatment may become infeasible.

4. Consideration of Traffic Equity

It is important to be aware of traffic equity issue if the intersection treatment may change intersection layout, relocate or remove facilities (such as transit stations and parking), or restrict existing accessibility. Under Americans with Disabilities Act (ADA) of 1990, all people, including those with disabilities, have the right to equal access to transportation [96]. Intersection treatment that has the potential to remove facilities used by people with disabilities constitutes discrimination under the ADA. Existing safe and usable facilities for persons with disabilities should not be removed or restricted to be accessed.

In addition, pedestrian facilities should be provided at all intersections in urban and suburban areas [6]. Pedestrian facilities should serve all pedestrian including pedestrian with mobility or visual impairments. If new or altered facilities will be established together with the intersection improvement project, it is required that those facilities for the use of state and local government entities be designed and constructed to be readily accessible to and usable by individuals with disabilities [96]. LTP and LCUP may have limited effects on exiting pedestrian crossing or facilities for the disabled. However, if tolled LCUP is proposed, equity concerns may arise.

5.6 Performance Analysis

The purpose of this section is to present performance indicators used to evaluate intersection treatment and some of the common techniques used to quantify these measures. Alternatives that were identified and justified in the planning and feasibility assessment proceed to the detailed performance measurement and impact analysis. The results are used in the alternative evaluation and selection level which is the subject of Chapter 6.

In the performance analysis, adjacent road networks and other environmental and energy impacts are analyzed along with the subject intersection, not only mobility and safety considerations, but also environmental, energy, noise, and socio-economic impacts are addressed.

Identifying and quantifying performance indicators for multiple attribute evaluation are the primary purpose of the detailed analysis. The section begins by presenting an overview of the criteria that affect signalized intersection performance, including both transportation system and other user characteristics. It then presents dimensions of performance and targets for outputs. Finally, the section presents a discussion of techniques to analyze performance indicators.

5.6.1 Selection of Performance Attributes and Measure of Effectiveness

Identification of the attributes of performance and selection of appropriate MOEs originate from many sources, including project goals and objectives, available data, legal and localized requirements, and interests of stakeholders and other constituencies.

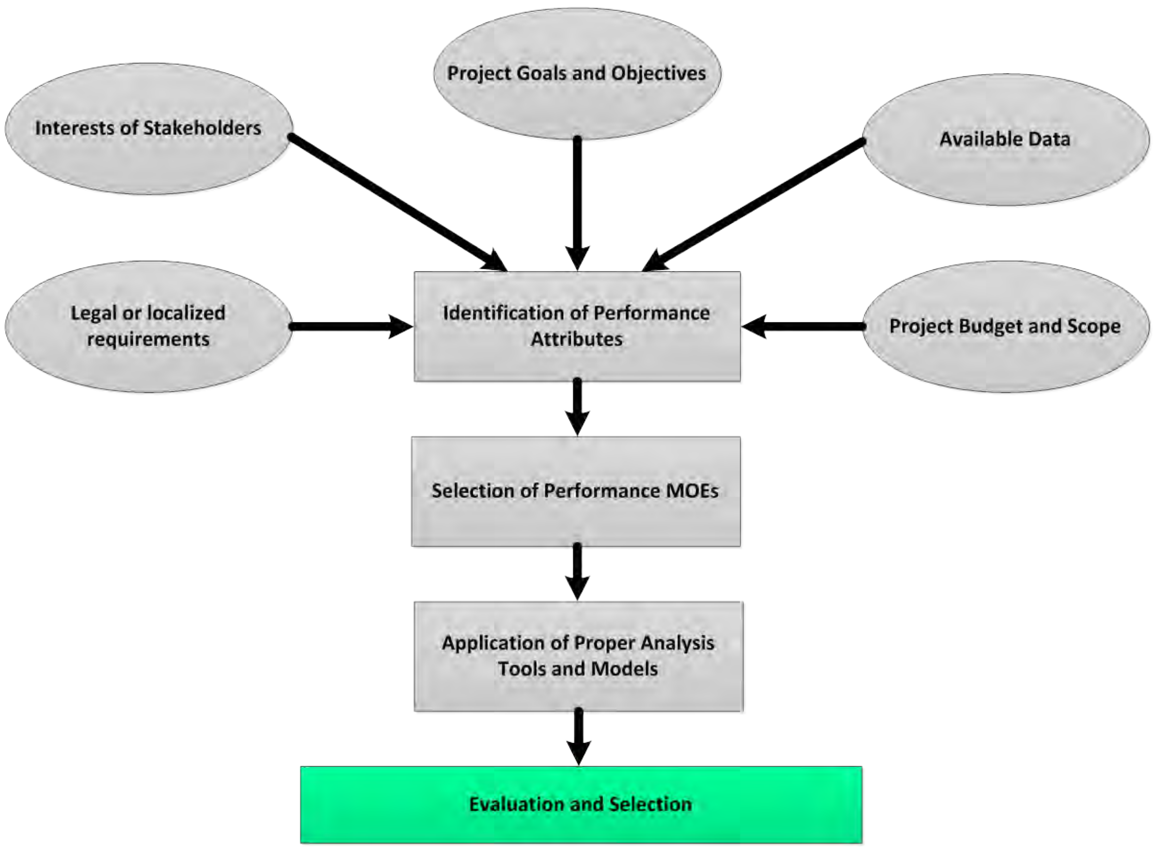


Figure 5.4 Identification of Performance Attributes

Sample performance attributes and criteria are listed in Table 5.5, which can be modified for site-specific conditions and requirements. The table provides a data-driven and comprehensive plan to identify the potential criteria and priorities in detailed performance analysis of proposed treatment. The criteria are used to select and validate MOEs. MOEs present an indicator for assessing the effectiveness of treatments in each performance dimension, such as capacity improvement and safety enhancement.

Table 5.5 Example Set of Performance Attributes and Criteria

Performance Attributes	Criteria
Operation	A. Reduce average delay at subject intersection
	B. Acceptable LOS at subject Intersection
	C. Acceptable operation of minor movement or affected movements at subject intersection
	D. Reduce system average delay
	E. Acceptable LOS at adjacent intersections and access
Safety	A. Reduce total crash frequency at subject intersection
	B. Reduce estimated crash rate
	C. Reduce accidents involving pedestrian and bicyclists
	D. No relocation of safety issues
	E. Management of construction safety
Energy	A. Reduce amount of consumed fuel or energy
	B. Reduce stops, especially for heavy vehicles
	C. Promote the switch to public transportation
Environment	A. Reduce emissions
	B. No increase to existing noise levels
	C. No or controllable effects on natural or historical resource
	D. No or acceptable visual impacts
Accessibility	A. Improved travel time to destination
	B. No blockage of access or alternative route is provided for pedestrian and the disabled
	C. No significantly negative impacts on business and land values

Guidelines for identifying proper MOEs were developed by Schofer and are widely adopted by governments, State DOTs and other traffic agencies[97]. The seven rules discussed below extracted from his study can serve as a framework for defining MOEs in an intersection improvement project.

1. Understandable

The selected MOE should be able to define the problem so that it is understandable to the decision makers and the general public. Not every MOE need to be understandable by the public. Some of the signalized intersection congestion indicators, such as progression rate, is an important factor in traffic delay estimation but do not necessarily need to be understood by the public. However, the public should be able to understand the problem in layman terms.

2. Measurable

Each MOE should be possible to be measured by using standard traffic engineering practices or existing methods. Select MOEs that are measurable based on fundamental data availability, project budget and usable technical or human resources. For example, there are no available methods or models to evaluate the traffic noise level at local or minor streets within residential communities. The sound level at those areas has to be measured in the field and manually by using noise dosimeters or other noise measurement instruments.

3. Labor-intensiveness

The MOEs should not be excessively labor-intensive and its sources requirements should be acceptable. If multiple MOEs can be proper to use for one performance attribute, the MOEs that most satisfy project requirements and are easier to be obtained should be selected. For example, evaluation of changes in system-wide delay using origin-destination distributions would reliably reflect different congestion levels in a road network. However, it may be difficult and cost prohibitive to conduct this system-wide analysis, given that the scope of an intersection improvement project is limited. Although some state-of-the-art programming tools and complicated mathematical algorithms may be available for estimating those MOEs, the required field data inputs or available budget may be unable to support the measurement. Therefore, the MOEs should also be defined based on the project scope and resource availability.

4. Reliability

The MOEs should be reliable to reflect the changes in intersection performance after treatment. The results should be consistent and predictable. In another word, the MOEs selected and the associated methods should be robustly sensitive to the changes the treatment is intended to trigger. For example, the method evaluating operational improvement after LTP or LCUP should be sensitive to the changes in volume redistribution and in travel time estimation.

5. Congestion-based

The MOEs proposed for performance measurement of signalized intersection treatment should also be congestion-based, which means the MOEs are the indicators to reflect intersection conditions during peak and congested periods in order to represent the effectiveness of treatment under such conditions. Some MOEs such as emissions and fuel consumption are not inherently congestion-based, but they are derived from congestion-based MOEs and are indirect reflections of intersection conditions.

6. Sensitive

The MOEs should be not only sensitive to the changes triggered by the treatment but also generally sensitive to other factors so that their values vary among alternatives. The appropriate MOEs should be sensitive to some basic engineering parameters and intersection conditions such as traffic volume, signal timing and geometric changes. For example, the queue size and number of stops defined in HCM are considered as good congestion indicators, but may not be sensitive to changes in geometrics.

7. Can be validated using field measurements

Last but not least important, the MOEs selected should be able to be measured in the field manually or using equipment in order to validate the estimated calculation using a traffic model. The purpose of validation is to be able to testify the reliability of MOEs and to adjust and calibrate model parameters for a specific location or different alternatives. Once the model can accurately present and reflect real-world conditions, the analyst can assume that the quantification of MOEs using the model will be accurate as well.

Suggested MOEs for various performance attributes are introduced in Table 5.6. This research doesn't specify MOEs for any performance attribute listed in table, because this selection is dependent on the specifications of an intersection improvement project, such as data availability, project budget and other criteria as discussed above. In addition, the evaluation method in Chapter 6 is an independent process regardless of the selected MOEs. Analyst can select one or more from the table or use other MOEs based on site-specific conditions.

Table 5.6 Suggested MOEs for Performance Attributes

Performance Attributes	MOEs	Description
Operation	Average vehicle delay	Average vehicle delay for all entering vehicles (typically used to define LOS)
	Number of vehicles stopped	Number or proportion of entering vehicles that are required to stop
	95% queue length	Length of the queues on all approaches at the 95% confidence level
	V/c ratio	Degree of Saturation
Safety	Crash rate and severity	The number and severity of crashes (historical or predicted) involving cars, trucks, animals, bicycles, and pedestrian at intersection
	Crash rate per 100 million VMT	Average fatal, injury and PDO crash frequency every 100 million vehicle miles traveled
	Number of alcohol or drug related accidents	Number of fatalities, injuries and PDO in crashes involving DUI motorist
	Safety behavior measure	Observed seat belt use for passenger vehicles, %using helmet, number of speeding citations issued
Energy	Fuel usage	Fuel used (gallons) of all entering and leaving vehicles within the intersection network
	Modal trips	Number of transit and walk/bike trips in study area
	Mode choice	Usage of high energy efficiency or alternative energy vehicles
	Duration of truck engine idling	If %truck in traffic flow in high, extra energy consumption of heavy vehicles during the congested or waiting period due to engine idling
Environment	Vehicle emissions	Change in emissions by pollutant and by vehicle type
	Greenhouse gas emissions	Change in emissions of greenhouse gases by vehicle type
	Release of harmful chemicals	Amount of hazardous chemicals and wastes to the road user, residential area and the entire environment
	Noise level	Noise level generated by traffic
Accessibility	Average travel time	Average travel times by mode to specific locations in influence area
	Land value	Changes of property or land value after project
	Business profits	Impacts to business patronage and profits in the influence area

5.6.2 Study Area of Performance Analysis

The study area of performance analysis is discussed in this section, especially for LTP and LCUP. Note that although the study area may partially overlap with the influence area introduced earlier, they should not be confused. The influence area is used to define an area wherein a stakeholder group is influenced by an intersection improvement project. The study area is an area wherein the traffic and other performance need to be analyzed.

The study area of performance analysis is restricted to the intersection functional area, only if the study intersection can be assumed to be isolated from other major intersections, access roads or on/off ramps. According to MUTCD [50], signalized intersection is relatively isolated with a minimum of one mile intersection spacing, and interconnected with a 0.25 miles or less intersection spacing. LTP is not an ideal treatment for isolated intersection due to absence of rerouting network and LCUP may be a better candidate.

For a non-isolated condition, the extent of the study area's coverage is primarily based on the proximity of the subject intersection to other intersections. If the queue from adjacent signalized intersections may spill back into the study intersection or part of traffic are diverting from the study intersection to other streets, then the subject intersection may have interactive influence with one or more nearby intersections. The analysis of the proposed treatment to improve conditions at the study intersection should consider the operation of several intersections in the study area.

Although LTP is classified as intersection-wide and approach treatment [29], the rerouting traffic may produce regional impacts. LCUP would generate significant impacts on downstream intersections on the subject arterial. If left turn at the LCUP downstream approach has to be prohibited to accommodate high speed and high volume leaving vehicles from the underpass, the influence area would be extended to surrounding road network due to rerouting demand. Therefore, the study area of LTP and LCUP analysis are defined below:

1. If the rerouting roads are designated and known, the study area of LTP is the functional area of the subject intersection and the entire areas of rerouting roads and intersections.
2. If the rerouting roads are unknown, driver may reroute a couple of blocks around the LTP approach. The study area of LTP includes intersection functional area and feasible rerouting roads within two blocks on each direction at the intersection. Figure 5.5 represents the study area for all four approaches.

Figure 5.5 Study Area of LTP (each direction of traffic flow)

3. The study area of LCUP consists of the functional area of study intersection and all its immediate adjacent intersections (less than 1 mile intersection spacing) at downstream approach of the underpass and the connecting road segments.

4. As shown in the Figure 5.6 (study area are shaded grey and figure is not scaled), if LTP at any one or more downstream approaches of underpass is removed, the study area of LCUP at that approach (es) should be extended to the given rerouting roads using the 2 blocks rule.

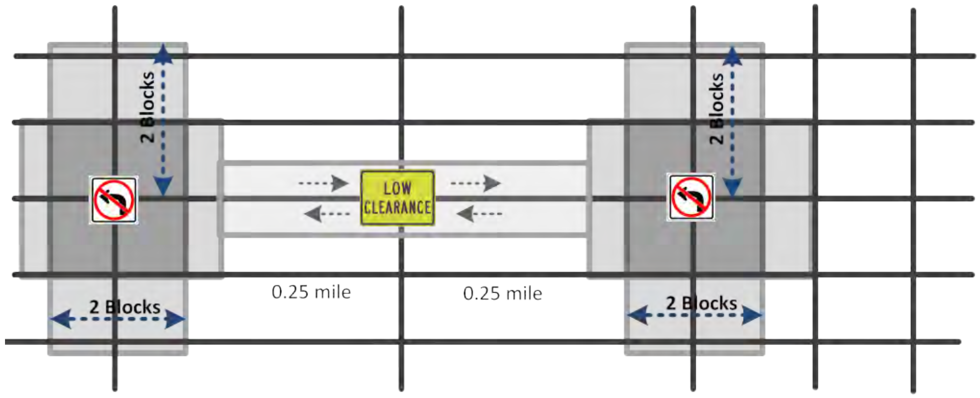


Figure 5.6 Study area of LCUP with downstream LTP

The study area is applicable to traffic-related performance analysis, except for safety whose study area is within 1000 ft of the subject intersection as given in HSM.

5.6.3 Analysis Tools and Models

The selection of analysis and measurement tools and models depends on the particular application. Each tool has specific advantages and disadvantages, limitations, and capabilities that must be considered during selection.

A popular methodology for determining whether an intersection improvement meets the operational requirements at the study intersection and surrounding road system is traffic simulation. Microscopic models (such as VISSIM and AIMSUN) consider the characteristics of each individual vehicle, and its interactions with other vehicles in the traffic stream. Macroscopic models (such as TRANSYT and NETFLO) are characterized by continuum fluid representations of traffic flow in terms of aggregate measures such as flow rate, speed, and traffic density [98]. Both microscopic and macroscopic models are currently available and applicable for simulating urban intersection and arterial traffic system environments. Microscopic simulation models can simulate traffic operations in detail and consider car-following behaviors. In addition to detailed output of MOEs in traffic operation, some of simulation models are integrated with energy consumption and vehicle emissions simulator, which enable the measurement of environmental and energy MOEs. Although minor differences in features and application limitations exist in simulation models, detailed traffic operation information about control delay, number of stops and queue size at the subject intersection and influence area are typically included. Table 5.7 summarizes current experience and applicability of simulation model in the traffic operations analysis of intersections.

Microscopic simulation tools are particularly effective for analyzing the interactive effects between intersections within a road network. In addition, simulation can provide a visual description of traffic operations for audiences. The simulation output may be desired to identify the queue size and congestion period and can account for surrounding impacts and affected travel patterns associated with the proposed intersection treatment.

Table 5.7 Simulation Model Roles in Traffic Operations Analysis

Study Area	Performance Analysis Challenge	Simulation	Current Status
Intersection Wide	Underpass usage and lane utilization	Can Do	Driver-visual perception of congestion and green light ignored.
	Lane choice with or without tolling	Can Do	Common use.
	Underpass offset distance for a lateral lane	Can Assist	Need to re-run simulation for with/without lane scenario.
	Intersection LOS and control delay	Can Do	Common use.
	Intersection safety	Can Assist	FHWA developed SSAM model to use simulation conflict points summary to estimate crash rate. But it is not applicable to assess the safety of roadway designs that have yet to be built or flow-control strategies that have yet to be applied. HSM provides prediction model for non-built road and calibration factor for management strategies.
	Congestion period safety (peak)	Can't Do	HSM or existing safety models are unable to address the distribution of crashes under the volume and speeds during the congested periods.
	Oversaturated conditions that HCM method cannot model	Can Do	Common use.
Network Wide	Distance for upstream entry/merge	Can Assist	Lane change model is not very realistic (lane change as early as possible or merge as much as requested). New utility models are being developed.
	Impacts of downstream queuing	Can Do	Common use.
	Distance for downstream leaving/weaving	Can Assist	Concerns of unrealistic lane change modeling.
	Determine left turn treatment at downstream approach	Can Assist	Need to re-run simulation for with/without left turn scenario.
	Signal progression between intersections	Can Do	Simulation was used to evaluate actuated signal timing analysis before HCM 2010 method, common use.
	Volume distribution if sign/green time counter is provided	Can't Do	Cannot assess drive perception of underpass availability and remaining green time.
	Strategies for heavy /non-through traffic assignment	Can Assist	Can assist in determine/verify the distance for heavy vehicle /turning traffic leaving the lane linking to underpass.
	Determine decision point for the underpass and consider the effects of road access points	Can Assist	May be able to estimate the decision distance and effects by running several simulation scenarios.
Area Wide	Effects of diverted traffic on adjacent intersections If downstream approach left turn is prohibited.	Can Assist	Can do for operation with extra data of other intersections, not for safety. But the distribution of detour turning vehicles and routes is site specified and hard to define.
	Affect the O-D distribution (latent demand, route switch, temporal switch)	Can't Do	Need to employ Dynamic Traffic Assignment (DTA) model instead.
	Multiple underpasses or bypass underpass design	Can Do	Can do multiple scenario analysis by giving the start and end point of bypass underpass to maximize usage of bypass traffic and mitigation of downtown congestion, common use.
Evaluation	Measure/quantify indicators	Can Do	Many indicators can be outputted by simulation, such as emissions and energy consumption.
	Construction impacts on traffic	Can Do	Delay due to construction may be significant and offset benefits. Simulation can be used to determine the impacts, common use.
	Determine temporary left turn restriction period/tolling fee scale	Can Assist	Simulation may help on testing the benefit change by setting many scenarios using various volume and travel time to generate a curve for determination.

● Can Do ◐ Can Assist ○ Can't Do

The design characteristics and consideration for LCUP are relatively complex, especially if downstream LTP is added. The simulation design of LCUP is shown in Figure 5.7.

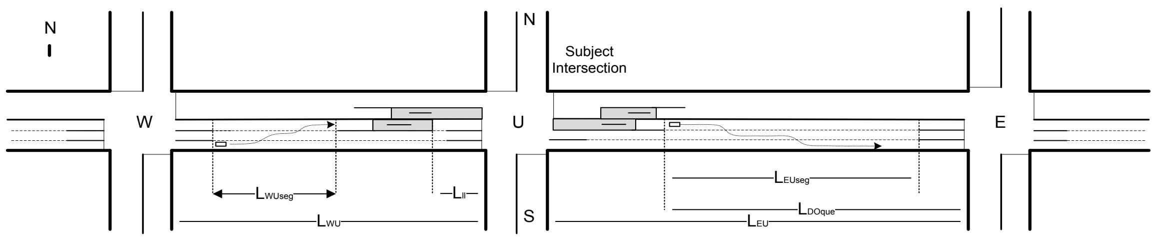


Figure 5.7 Simulation Design of LCUP in Intersection Network

Legend:

L_{WU}: Intersection Distance between Int W and Int U.

L_{WUseg}: Road segment between Int W and the entrance of underpass where vehicles are allowed to make lane change to merge into underpass .

L_{II}: Underpass offset distance where an auxiliary lane may be deployed.

L_{EU}: Intersection distance between Int E and Int U.

L_{EUseg}: Road segment between the exit of underpass and Int E where vehicles are allowed to make lane change to leave underpass lane.

L_{DOque}: Max downstream queuing storage space

Figure 5.7 shows an LCUP simulation design at Intersection U. For eastbound (westbound) underpass deployment, Intersection W (E) is the upstream intersection and Intersection E (W) is located downstream. For LCUP project, analysts should estimate the following distances by using simulation models, which are critical in determining the operational performance of an LCUP:

1. The merging distance (L_{WUseg}) provided at upstream to ensure safe and smooth lane change distance for vehicle merging into and overheight vehicle leaving the lane leading to underpass.
2. Potential underpass offset distance (L_{II}) provided sufficient space for deploying a left turn bay. It is optional and can be considered only if the upstream intersection spacing is long enough to accommodate upstream merging distance, underpass structure and a left turn bay
3. Downstream leaving (downstream approach without left turn) or weaving distance (downstream approach with left turn) (L_{EUseg}) is the road segment between the exit of underpass and downstream intersection. The left turn movements at downstream approach may have to be prohibited if the downstream intersection spacing is not long enough to provide sufficient weaving section.

Quantification of safety performance MOEs for ongoing and anticipated projects is supported by HSM. The HSM method includes CMFs for a few intersection treatments. In addition a calibration process is also available in HSM to further refine and calibrate the prediction model by using local crash modification factors and historical crash records.

Finally, a full performance analysis also needs to consider socioeconomic indicators, such as energy, environment and accessibility. The applicable analysis tools to measure the performance of intersection treatments in energy, environment and accessibility are summarized in Table 5.8.

The assessment of social and economic performance for an urban intersection treatment is inherently complicated and has received little attention. Although some site-specific studies have assessed the social and economic impacts of intersection improvement projects, these studies are relatively rare. As shown in Table 5.8, the assessment tools for these performance indicators are relatively few and limited. For example, there is no available noise model to understand how the noise level increase due to rerouting traffic on local streets will affect a community. Some of the indicators can only be measured on the basis of surveys or interviews (such as land value and intersection-wide accessibility), which is unable to support the development of a quantitative methodology and may produce considerable inaccuracy because of the insufficiency of samples, ineffectiveness of community engagement, and variation of local conditions.

Table 5.8 Summary of Analysis Tools for Socioeconomic Indicators

Performance Indicators	Units	Quantification	Assessment Tools
Street Noise Level	dB	◐	SIDRA Trip, IMAGINE, the Noise Emission Model for European Road Traffic, Statistical Models for traffic noises at signalized intersection available in literature (Jordan, Hong Kong, Thailand, China…)
Accessibility	% or 1	○	Network-wide method available but may not applicable to project-level and intersection wide analysis.
Land Value	$ or %	○	Localized empirical models are available, mostly for transit projects. Comprehensive evaluation model is also available but is data-intensive. Historical data or real estate tax revenue are needed to build that model. Some research concluded no significant impacts on land value at fully-developed and congested urban area.
Business Loss	$ or %	◐	NCHRP 420 analytical tools
Latent Demand	$ or 1	◐	FHWA SMITE, Tranus, Meplan
Fuel Consumption	gallon or $	●	Microscopic simulation, EPA statistical regression model
Emissions	lbs or mile	●	Microscopic simulation, MOVES

● Commonly accepted method available ◐ Methods available ○ No existing method

5.7 Chapter Summary

The second level of LTP and LCUP is feasibility analysis and performance analysis. Feasibility analysis section is the process of preparing outline design and deployment plans, and the methods of conducting economic, construction, legal feasibility analysis. A checklist is provided as part of the analysis process to enumerate the necessary considerations for measuring the impacts of a proposed treatment. The feasibility analysis tests the applicability of LTP and LCUP given a set of economic, construction, local or legal regulations and constraints. Performance analysis is the technique used in operational, safety and other socio-economic impacts assessments. The attributes of performance analysis for LTP and LCUP treatments are defined along with performance indicators or MOEs. A complete and accurate performance analysis is essential to ensure a reliable and comprehensive evaluation and decision-making process.

CHAPTER 6

EVALUATION UNDER HYBRID UNCERTAINTY AND FUZZINESS

6.1 Introduction

This chapter discusses the approach for evaluation and selection of intersection treatments. The evaluation and decision-making process is the third and last level of the entire method proposed in this research. Although the process developed and described in this chapter is an essential component of the comprehensive analysis and evaluation method for LTP and LCUP, its application may not be restricted to the proposed two treatments LTP and LCUP. The process is discussed both specifically for LTP and LCUP and generically for various intersection treatments. Any treatments whose preliminary potential of feasibility have been investigated and performance in operation, safety and other aspects have been analyzed can be evaluated with this procedure to measure the tradeoffs among multiple attributes under uncertainty and risk.

The commonly used CBA method for intersection treatments evaluation is unable to be comprehensive and detailed, because:

- it introduces critical value assumptions of non-monetary variables (e.g., travel time, safety and noise) [99],
- it ignores stakeholder preference variation on attributes and alternatives [99],

- it disregards information about the probabilistic distribution and uncertainty ranges of evaluation criteria [100], and
- it aggregates certain and uncertain costs and benefits on a common scale [100].

It should be noted that in circumstances here:

- either certain and reliable performance indicators or MOEs can be obtained,
- no uncertain effects and/or multiple stakeholders are involved in the intersection improvement project (for example, isolated intersection), or
- geometric and traffic conditions are consistent with the assumptions underlying the warrant used to verify the alternative's viability,

Then the CBA may be sufficient, and the advanced evaluation process considering fuzziness and uncertainty may not be necessary.

Most urban intersection treatments are associated with substantial uncertainties in advantages, drawbacks, impacts and costs. The implementation in an urbanized area can raise public controversy and may affect multiple stakeholders with different preferences. The evaluation module MAFU is developed to address this issue. MAFU is a **M**ulti-**A**ttribute evaluation process under hybrid **F**uzziness and **U**ncertainty, which features:

- Fuzzy mathematics (FAHP) to capture the stakeholder preferences
- Utility function theory (MAUT) to combine performance measures and describe risk sensitivity

- Probabilistic Monte Carlo simulation (MCS) to model output uncertainties and generate the tradeoff space.

The MAFU is designed to be:

- A general urban intersection treatment evaluation method for selecting the optimal alternatives under the conditions of system and evaluation complexities.
- An integration of stakeholder trade-offs, the technical capabilities of alternatives, and variable uncertainty without any built-in prescriptive guidance.
- A new insight for transportation decision-making through the visualization complex preference tradeoffs, and criteria uncertainty.
- An open-ended approach, which is capable of integrating additional evaluation criteria and performance attributes as needed.

6.2 Evaluation Procedure

The structure matrix of the MAFU evaluation method can be visualized by modifying Sinha and Fwa's a three-dimensional matrix structure for comprehensive highway asset management [101]. The three dimensions represent project objectives, stakeholders and performance attributes as shown in Figure 6.1.

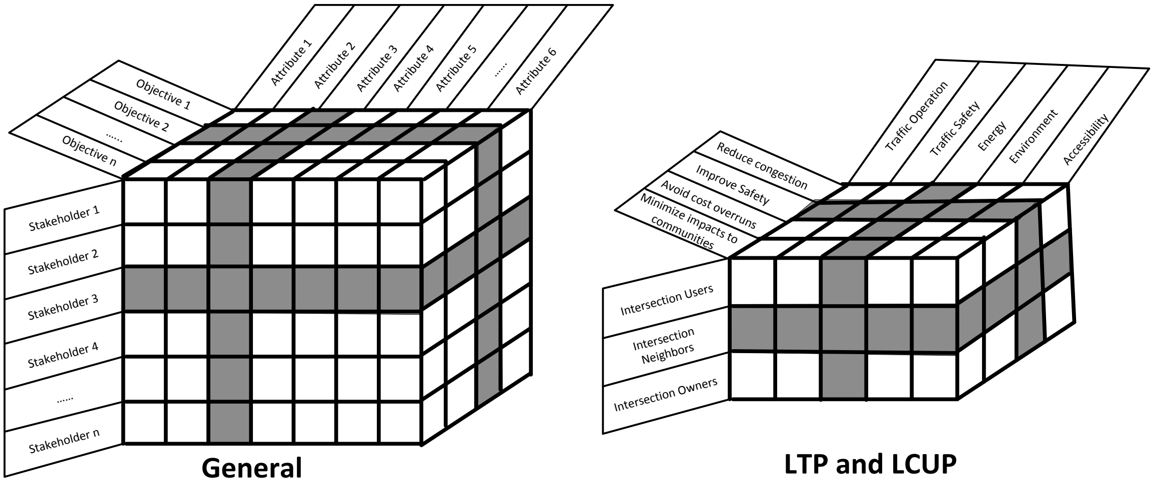


Figure 6.1 A Structure Matrix of the MAFU Evaluation Method

An intersection improvement project evaluation involves three dimensions including stakeholders, project objectives and performance attributes. The interest range of stakeholders is widespread and each stakeholder group plays a unique role in defining their priorities of interests and expectations. For instance, as defined in LTP and LCUP evaluation structure, the intersection neighbor may be concerned about maintaining access to their business or home, the intersection user may prefer a treatment that improves the intersection mobility and safety. The intersection owner, such as traffic agencies, may be interested in the options which can maximize throughput on the mainline facility and minimize the risk of budget overruns. The overall effectiveness of a proposed treatment depends on the balance of tradeoffs among the concerns of these constituents.

Project objectives may or may not match the interests of one or more stakeholder. The objectives may also include maximization of the operational, safety conditions and socio-economic benefits of intersection facility and minimization of agency and user cost, energy use, and adverse environmental impacts. The objectives of an intersection improvement are usually determined to address current or anticipated problems, such as high traffic accident frequency, excessive traffic congestion, or a high rate of traffic accidents.

To facilitate the project objectives and highlight the interests of all stakeholders, the achievement of objectives and fulfillment of stakeholder perceptions can be assessed using MOEs in different performance attributes. The performance attributes reflect the potential scope, degree and significance of impacts associated with a treatment. Therefore, stakeholders and their interests and project objectives need to be considered in the process of defining and measuring performance attributes and their indicators or MOEs, in order to provide effectiveness of evaluation and reliability of selection.

The MAFU process is able to assess the magnitudes of intersection treatment performance and to integrate conflicting interests and tradeoffs among stakeholders for assisting decision makers in selecting the best treatments. MAFU is a detailed and disaggregated evaluation model requiring the development of utility functions and measurement of performance uncertainties. It should be used only when it is necessary. The key criteria in determining the need for the MAFU approach are:

- Considerable uncertainty regarding the estimation of performance indicators.
- Multiple stakeholders with conflicting interests in their expectations for a proposed project.

- Changes in the underlying assumptions can result in a significant variation in the ranking of alternatives.

The flowchart of MAFU procedure is shown in Figure 6.2. This process assumes that the problems at an intersection have been identified and potential treatments have also been examined in preliminary screening, feasibility and performance analysis.

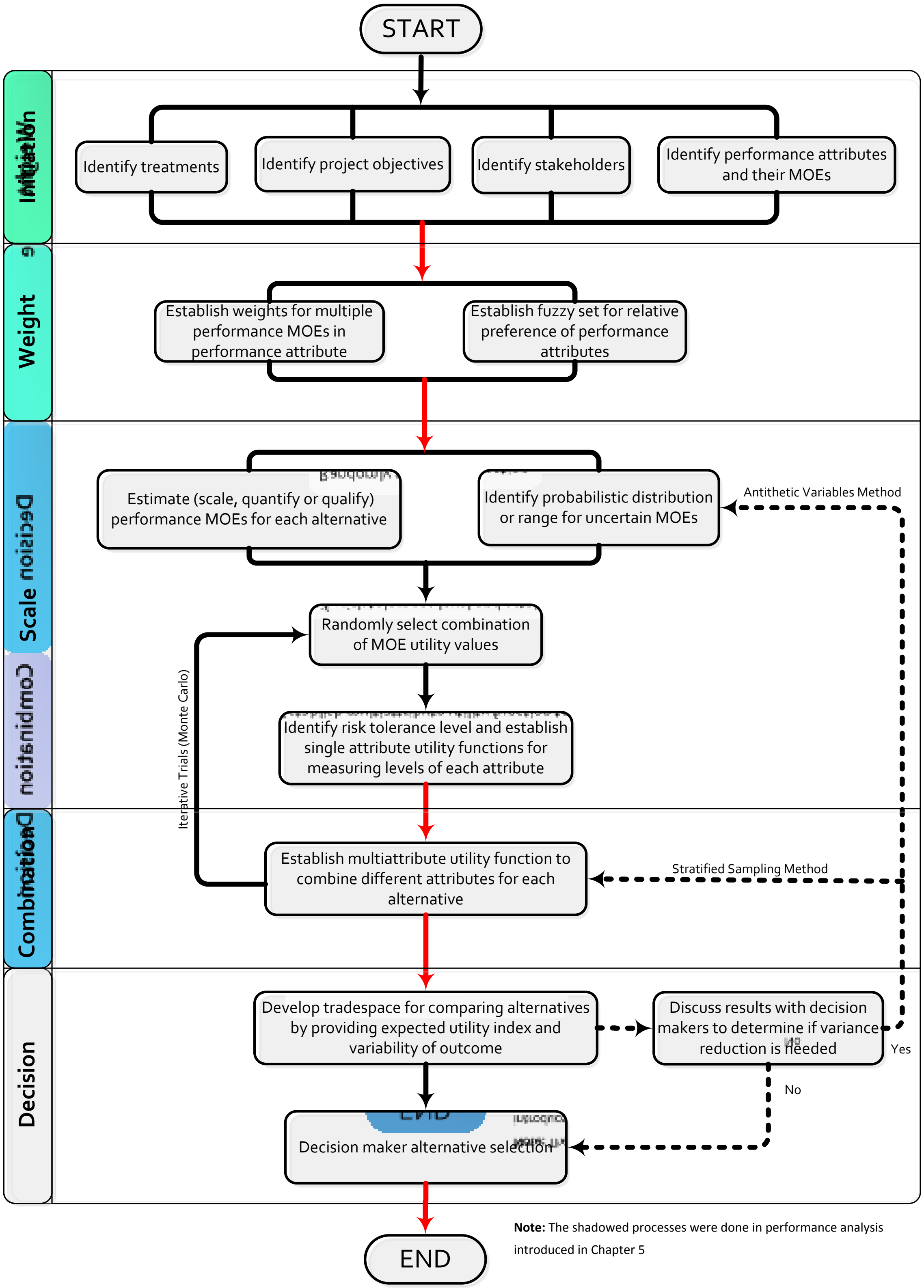


Figure 6.2 Flowchart of MAFU Process

The MAFU process has five stages: initiation, weight, scale, combination and decision. During the initiation stage, information about feasible treatments, project objectives, stakeholders and performance attributes identified in Chapter 5 are collected. The candidate treatments should be able to produce substantial benefits to some extent and have been examined for feasibility. Project objectives can be manifold, multicriteria and multiattribute. The objectives of successful transportation project typically emphasize increasing capacity, reducing congestion, providing safe and efficient operations, developing sustainable transportation modes, mitigating traffic impacts to the environment and surrounding communities, coordinating with adjacent land use development, and supporting the future growth in population and economics. A stakeholder is not necessarily a decision maker who has direct influence over making improvements to the facility. Their interests may be conflicting to and not completely reflected in the definition of project objectives, but their interests and comments should be integrated and considered in the decision-making process. Performance indicators or MOEs were selected for each performance attribute including operation, safety, accessibility, environment and more. The identification of the different types of performance attributes and corresponding MOEs are critically dependent on the understanding of project objectives, affected area and stakeholder perceptions.

The weight stage is designed to assign weighing scores to the performance MOEs in a performance attribute and between various performance attributes. In some of the performance attributes, multiple performance MOEs may be identified. For example, traffic delay and number of stops can be both used as indicators of traffic operation performance. If multiple MOEs are defined in one performance attribute, the Delphi technique [102] may be used to establish relative weights for them. This weighting strategy for performance MOEs does not specifically consider public involvement and comments, but relies on the opinions from a panel of experts, because the selection of single or more MOEs in a performance attribute is usually solely related to the characteristics of the attributes and the site-specific conditions (such as the MOEs of environmental attribute may include air pollutants, greenhouse gas and noise). In addition, the estimation of MOEs may involve some engineering terminologies, guidelines or warrants that are unfamiliar to the public. Therefore, Delphi technique may be used to weigh multiple MOEs within a performance attribute. The Fuzzy Analytic Hierarchy Process (FAHP) is used to weigh the relative preference between performance attributes [103]. This weighting process considers both objective and subjective factors and reflects the different or conflicting interests of each stakeholder group. The Fuzzy method is introduced as a synthetic extension of the classic AHP method to address the vagueness and uncertainty in assigning relative weights.

The scale stage describes a process to summarize the estimates of MOEs in each performance attribute which have been done in the performance analysis module. A utility function is established to present stakeholder preferences of each proposed treatment for each attribute (values of utility functions are subject to normalization) as well as risk parameters to describe the risk tolerance level of each stakeholder (e.g., risk prone, risk neutral, or risk averse).While some MOEs may be readily quantifiable and certain, there is uncertainty associated with some MOEs, because the analysis tools of MOEs may have inherent variation or use unrealistic assumptions. In this stage, the probabilistic distribution or variation ranges are identified for the MOEs with a substantial uncertainty in their measurements.

The combination stage is a mathematical amalgamation of certainty, uncertainty and risk. Additive utility theory was employed to establish system-wide multi-attribute utility functions on the basis of single attribute utility functions developed for various performance MOEs. The system-wide utility functions were utilized to establish a non-dimensional value. The functions also contain a risk parameter to vary the utility curves which allow for the exploration of sensitivity of the shapes of the utility functions.

The last stage, Decision, is designed to be a decision-making process for treatment selection including a tradeoff analysis and treatment selection and programming. Since the utility theory is not directly applicable to situations involving uncertainty, the utility values with uncertainty distribution or ranges are randomly selected and combined to develop a tradespace for tradeoff analysis by using Monte Carlo simulation. A tradeoff analysis was established by consulting the tradespace which provides the expected utility index, variability and Pareto optimum among candidate treatments. The tradespace can be presented for each treatment or stakeholder. The process of tradespace development may involve a revision of risk and preference parameters in order to reflect the emphasis of this project on certain performance attributes and interest groups. Because the utility values for each alternative are given in terms of expected value and variance, the basis of goal programming is to maximize the expected value but minimize the associated variance. Several decision-making methods, such as min-max distance metrics proposed by Stever in 1989 [104] are utilized to measure the attainment level of proposed treatments to select the best alternative which reaches the global optimum.

The following sections elaborate on the general foundation of MAFU stages and its application to LTP and LCUP.

6.3 Initiation Stage of MAFU Evaluation

In an evaluation framework involving multiple criteria and stakeholders, the critical steps are to assess how decision makers attach a relative level of impotence to each criterion, how conflicting interests among various stakeholders can be accounted for in the evaluation process, and how to scale and convert the performance indicators or MOEs from their original dimensions to a uniform and commensurable unit accruing all the performance attributes.

The initiation stage is designed to identify what the project objectives are, who are the affected interest groups, and how to assess the performance of treatments. Understanding the project objectives helps structure the decision-making process in a clear, rational and well-defined manner. Definition of stakeholders helps carry out a comprehensive and defensible project decision with investigation of tradeoffs between stakeholders preferences. Performance analysis is essential to fully exploit the potential of treatments in addressing traffic and/or other problems.

The tasks of the initiation stage have been presented in Chapter 5. As shown in Figure 6.1, the stakeholder groups and performance attributes defined for LTP and LCUP can be directly used in the MAFU process. The proposed MAFU process itself doesn't dictate the classification of stakeholders and selection of performance attributes. Different identifications of stakeholders and performance attributes can also be used while employing the MAFU process for other projects or activities.

The definition of stakeholders for LTP, LCUP and other intersection treatments uses both decision-making and non-decision-making stakeholders. Several evaluation methods do not consider non-decision-making stakeholders by assuming that the concerns of non-decision-making stakeholders are represented by decision-making stakeholders [105]. This assumption may be valid if the transportation project involves a variety of decision makers who can represent diverse community interests. Non decision-making stakeholders are included in this research for evaluating intersection treatments because intersection improvement projects are usually localized and conducted by a local agency as a single decision maker. In this case, a single decision-maker is unable to represent, consider and balance all the organizations or individuals who will be ultimately affected (positively or negatively) by the intersection treatment.

6.4 Weight Stage of MAFU

Weights are explicitly considered in multi-attribute decision-making environments where multiple conflicting and interacting performance attributes associated with a treatment need to be evaluated in making decisions. It is unusual to have all the main attributes we consider reach a maximum or expected values at the same time. For example, LTP and LCUP which improve intersection mobility and safety may restrict the accessibility to business or decrease the business exposure. Because a unique optimal solution for such problem is absent, it is necessary to use weights to reflect decision maker perceptions. The weights are often used in project and portfolio management. For example, portfolio managers assign a percentage weighting to every stock to predict average (i.e., risk weighted) long-term performance in the portfolio model and then individual portfolios are modified to match up against this weighting mix [106]. In transportation project management, weights are used in determining the significance of performance attributes, priorities of project options and other decision issues.

In addition, multi-attribute evaluation involving multiple stakeholders complicate the decision-making process. For an intersection improvement project, usually the city transportation agency will looks for a cost-efficient measure mitigation that fits in a limited budget, while road users prefer an improvement measure which can better the traffic conditions at intersections without restricting movements, extending travel distance and raising operation cost. Interest groups try to maximize their shares of the traffic system benefits, and minimize the negative impacts from the project. To validate the tradeoff process among multiple and incommensurable goals, relative weights between the system goals must be established to scale the incommensurable variables under individual goals into dimensionless utility values. Therefore, the relative weights that are elicited from the decision makers and are captured in the multi-attribute utility function allow the analyst some flexibility in adjusting the importance of one or more attributes and the priority of one or more stakeholder groups to examine the robustness and sensitivity of the alternative selection method.

There are many commonly used methods in establishing weights, such as [107]:

- Equal weighting, a simple and easy approach to aggregate multiple values by assigning the same weights to all evaluation criteria.
- Point allocation (cardinal) or ranking (ordinal) which involves a simple number allocation of ordering of criteria to reflect the importance perceived by the decision makers.
- Regression-based observer-derived weighting, a data-intensive but scientific weighting method through statistical regression of previous projects and their overall impacts.
- Delphi Method [102] is a group decision-making tool. It is an iterative process used to collect and distill the judgments of experts using a series of questionnaires interspersed with feedback.
- Gambling method assigns a weight for one criterion or goal at a time via survey respondents to compare their preference for a guaranteed outcome against unguaranteed outcomes.

- Analytic Hierarchy Process (AHP) developed by Saaty in 1977 [108] can consider both objective and subjective factors in assigning weights to multiple goals based on three principles of decomposition, comparative judgments, and synthesis of priorities.

6.4.1 Generic Foundation: Delphi Weights of Multiple Performance MOEs

Assignments (explicit or implicit) of weights to performance MOEs for each attribute is a key step and should be approached carefully, because weights can make a large difference in selecting alternative projects. The Delphi method is suggested to weigh performance MOEs in a performance attribute for intersection improvement project. Note that the weighting process is only applicable for the performance attributes including multiple MOEs. The multiple MOEs selected for one performance attribute should be independent of each other (i.e., no or weak internal correlation between MOEs) and MOEs are not interrelated. The reasons why this method is appropriate for weighting MOEs are provided below:

Delphi is an expert consensus method and experts in intersection improvement projects are those who are responsible for identifying, selecting and estimating the performance MOEs. This process requires adequate participant commitment and is part of an engineering study containing terminology and complicated calculation, so internal or external experts familiar with the project and site conditions including traffic planners, designers, engineers and managers are the best survey respondents for assigning weights to MOEs.

Usually several experts in different departments (e.g., planning, design, construction and management) cooperate in the development of transportation projects. Delphi method is based on group judgments which can aggregate the perspectives of these professionals and reflect consensus and a holistic final assessment. Delphi method can be conducted anonymously in writing or online requiring no face-to-face meetings, which is inexpensive, relatively free of social pressure, personality influence, and individual dominance, and helps keep attention directly on the issue. In addition, a consensus emerges in most cases after two iteration cycles [102].

Application of Delphi Technique begins with the development of a set of open-ended questions on weighting the multiple MOEs. These questions are then distributed to various experts and the responses to these questions are summarized as a feedback report followed by a concise summary of previous survey results and a second set of survey. The iteration cycle of answering the survey and reviewing previous individual responses continues until the areas of agreement have been clarified and there is no change in scores. Finally the relative weights can be produced by averaging the final scores. Cardinal weighting scale is more appropriate in giving scores in MOEs, because there are usually less than two to three MOEs in one performance attribute and cardinal scale gives better meaning to the relative importance of the MOEs. The process is further demonstrated in Figure 6.3.

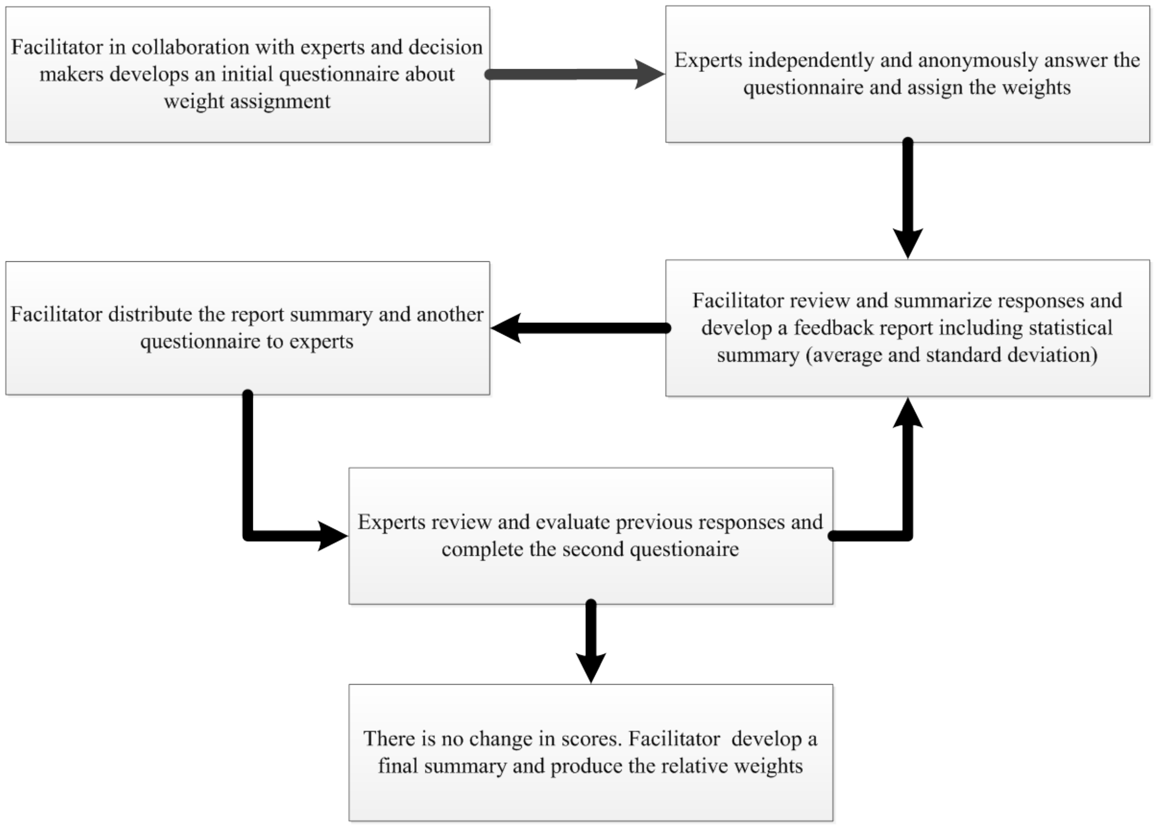


Figure 6.3 Flowchart of Delphi Technique

6.4.2 Generic Foundation: FAHP Weights of Multiple Performance Attributes

The Fuzzy Analytical Hierarchy Process (FAHP) technique was utilized to establish the consensus weights among stakeholders concerning the performance attributes in an intersection improvement project.

AHP is one of the best ways for deciding among the complex criteria structure in different levels [109]. It is the only multicriteria evaluation method with which the error in judging the relative importance of factors by means of relative measurement can be detected and corrected with new observation, reflection, and discussion [110]. Traditional AHP process involves pair wise comparison matrix construction which allows the survey respondent (stakeholders) to consider objective and subjective factors in assessing the relative importance of each performance attribute in a project. Estimation of the value of eigenvector yields the relative weights and a process of checking the consistency is used to assess the degree of randomness in judgments. Briefly, the step-by-step procedure in using AHP is as follows [110]:

1. Define decision criteria in the form of a hierarchy of objectives. The hierarchy is structured in different levels: from the top (i.e. the goal) through intermediate levels (criteria and sub-criteria on which subsequent levels depend) to the lowest level (i.e. the alternatives).

2. Weight the criteria, sub-criteria and alternatives as a function of their importance for the corresponding element of the higher level. For this purpose, AHP uses simple pair-wise comparisons to determine weights and ratings so that the analyst can concentrate on just two factors at a time.

3. After a judgment matrix has been developed, a priority vector to weigh the elements of the matrix is calculated. This is the normalized eigenvector of the matrix.

The decision generated by using AHP can involve multiple criteria or objectives. The criteria considered in the decision-making process are dimensionless and can be mixed tangibles and intangible, In addition, the structured technique is able to consider the relative importance or priority of the criteria representing preferences and priorities of multiple participants. The general consensus is that AHP is both technically valid and practically useful in organizing and analyzing complex decisions. However, the method is criticized for its unbalanced scale of judgment and insufficiency to precisely address the inherent uncertainty and vagueness in constructing the pair-wise comparison matrix.

Fuzzy set theory [111], which was introduced as a synthetic extension of the classic AHP method to address this weakness, utilizes fuzzy numbers for pair-wise comparisons. When dealing with the comparison of performance attributes, respondents (stakeholders in this research) may have different, uncertain or imprecise scales over these attributes by using vague and values to describe relative importance. The fuzzy set theory is used to account for the quantification of vagueness in human perceptions and thoughts, and the variation in stakeholder preferences.

The basic characteristic of fuzzy set theory is to define the boundaries of an element belonging to a given set vaguely instead of crisply as in the classic set theory. In classic set theory, the membership of elements in relation to a set is assessed in binary terms according to a crisp condition (i.e, in the classic notion, mapping all elements to either 1 “belongs” or 0 “does not belong” to the set). By contrast, fuzzy set theory allows for the gradual assessment of the membership of elements in relation to a set (i.e. partially belongs to the set valued in the real unit interval [0, 1]) and the transition between the membership and non-membership.

Membership function is the way to describe the potential vagueness. The difference in weight assignment among various interest groups and the fuzziness of preference is propagated to the AHP process in the form of a membership function through the operations of fuzzy arithmetic.

The membership function *μ(x)* quantifies the grade of membership of the elements *x* to the fundamental set *X* as shown in Figure 6.4 below, in which an element mapping to the value 0 means "not included in the given set" and 1 describes a fully included member. Values between 0 and 1 characterize the fuzzy members.

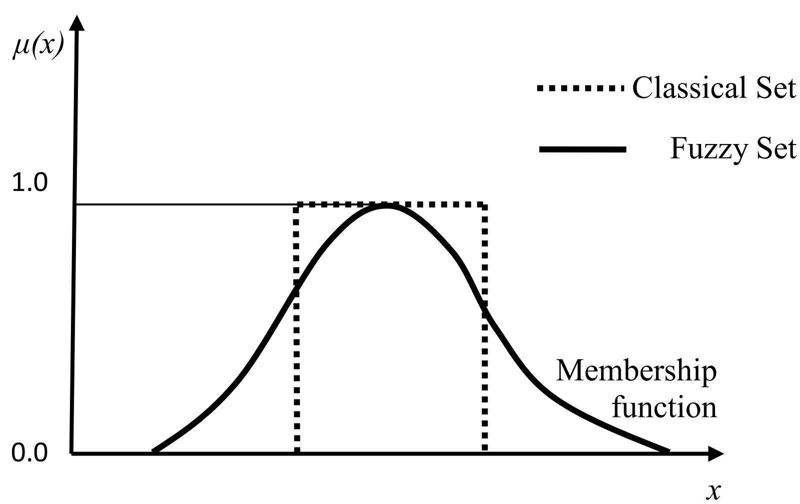


Figure 6.4 Grade of Membership of the Elements x to the Fundamental Set X

Although any fuzzy number shape is possible and a proper fuzzy number function is suggested for use, when sufficient information is available to justify the shapes, simpler triangular and trapezoidal fuzzy numbers or TFN are used in practice [112].

Three questions proposed by Kaufmann and Gupta [113] should be carefully addressed in order to construct an appropriate TFN: "What is the smallest value given to the uncertain number? What is the highest? Further, if we were authorized to give one and only one value, what value should we give?" An example of TFN is shown in Figure 6.5. The membership function $\mu(x)$ of a TFN can be written as follows, where *l* represents the smallest value, *m* means the most probable value and *u* is the largest value.

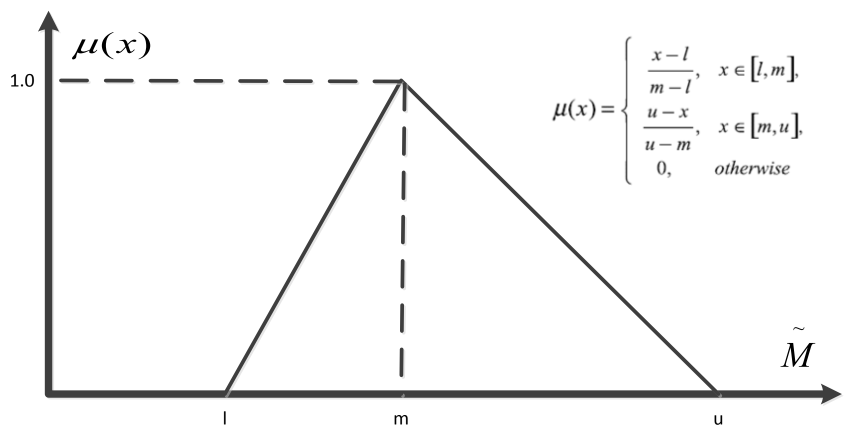


Figure 6.5 Demonstration of Triangular Fuzzy Number

The arithmetic operations of two fuzzy numbers can be performed level by level and there are various operations on triangular fuzzy numbers. Three important operations used in the MAFU process are illustrated below and more details about algebraic operations with fuzzy numbers can be found in Zimmermann's book "Fuzzy Set Theory and Its Applications" [114]. Assuming that two positive triangular fuzzy number TFN_1

(l_1, m_1, u_1) and TFN_2 (l_2, m_2, u_2) are defined, the arithmetic operations of two fuzzy numbers can be written as below:

$$TFN_1 \pm TFN_2 = [l_1 \pm l_2, m_1 \pm m_2, u_1 \pm u_2]$$

$$TFN_1 * TFN_2 = [l_1 * l_2, m_1 * m_2, u_1 * u_2]$$

$$TFN_1^{-1} = [1/l_1, 1/m_1, 1/u_1]$$

For weighting performance attributes of LTP and LCUP, FAHP process is utilized to analyze uncertainty and discrepancy arising due to stakeholder preferences on performance attributes. The uncertainty and discrepancy in stakeholder perceptions are a non-probabilistic form and defined as vagueness which is not on the basis of a well grounded and quantitative probability. The triangular fuzzy number is used in establishing FAHP membership functions for LTP and LCUP, because TFN is the most typical type used in project evaluation [112] and is often convenient to work, because of their computational simplicity and useful in promoting representation and information processing in a fuzzy environment [115] [116].

FAHP method is used to obtain the relative weights for performance attributes. Let $X = \{x_1, x_2, \ldots.., x_n\}$ be an object set, and $U = \{u_1, u_2, \ldots., u_m\}$ be a goal set. According to a method by Chang's [117] [118] extent analysis on FAHP, each criterion is taken and extent analysis for each criterion, g_i is performed on, respectively. Therefore, *m extent* analysis values for each criterion can be obtained by using the following notation [119]:

$$M_{g_i}^1, M_{g_i}^2, M_{g_i}^3 \ldots\ldots M_{g_i}^m$$

Where g_i is the goal set ($i = 1, 2, 3, \ldots\ldots, n$) and all the $M_{g_i}^{j}$ ($j = 1, 2, 3, \ldots\ldots, m$) are fuzzy numbers. Once the extent analysis values are determined, the steps of Chang's extent analysis of FAHP can be given as follows:

Step 1: The value of fuzzy synthetic extent value (S_i) with respect to the *i th* object is defined as:

$$S_i = \sum_{j=1}^{m} M_{g_i}^{j} \otimes \left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j}\right]^{-1} \tag{6.1}$$

The two parts of equation above can be obtained by performing the fuzzy addition operation of *m* extent analysis values for a particular matrix and $M_{g_i}^{j}$ ($j = 1, 2, 3, \ldots\ldots, m$).

$$\sum_{j=1}^{m} M_{g_i}^{j} = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j\right) \tag{6.2}$$

$$\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j} = \left(\sum_{i=1}^{n} l_i, \sum_{i=1}^{n} m_i, \sum_{i=1}^{n} u_i\right) \tag{6.3}$$

In addition, the inverse of the vector $\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j}$ can be computed:

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j}\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} l_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} u_i}\right) \tag{6.4}$$

Step 2: Since $\tilde{M}_1 = [l_1, m_1, u_1]$ and $\tilde{M}_2 = [l_2, m_2, u_2]$ are two TFNs and the degree of possibility of $\tilde{M}_2 \geq \tilde{M}_1$ is defined as Eq. 6.5

$$V(\tilde{M}_2 \geq \tilde{M}_1) = \sup_{y \geq x}[\min(\mu_{\tilde{M}_1}(x), \mu_{\tilde{M}_2}(y)] \tag{6.5}$$

and x and y are the values on the axis of membership function of each criterion. This expression can be equivalently written as in Eq. 6.6.

$$V(\tilde{M}_2 \geq \tilde{M}_1) = hgt(\tilde{M}_1 \cap \tilde{M}_2) = \mu_{\tilde{M}_2}(d)$$

$$= \begin{cases} 1, & if \quad m_2 \geq m_1 \\ 0, & if \quad l_1 \geq u_2 \\ \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} & otherwise \end{cases} \tag{6.6}$$

As illustrated in Figure 6.6 [120], where *d* is the ordinate of the highest intersection point D between μ_{M1} and μ_{M} . To compare M_1 and M_2, we need both the values of $V(\tilde{M}_2 \geq \tilde{M}_1)$ and $V(\tilde{M}_2 \leq \tilde{M}_1)$.

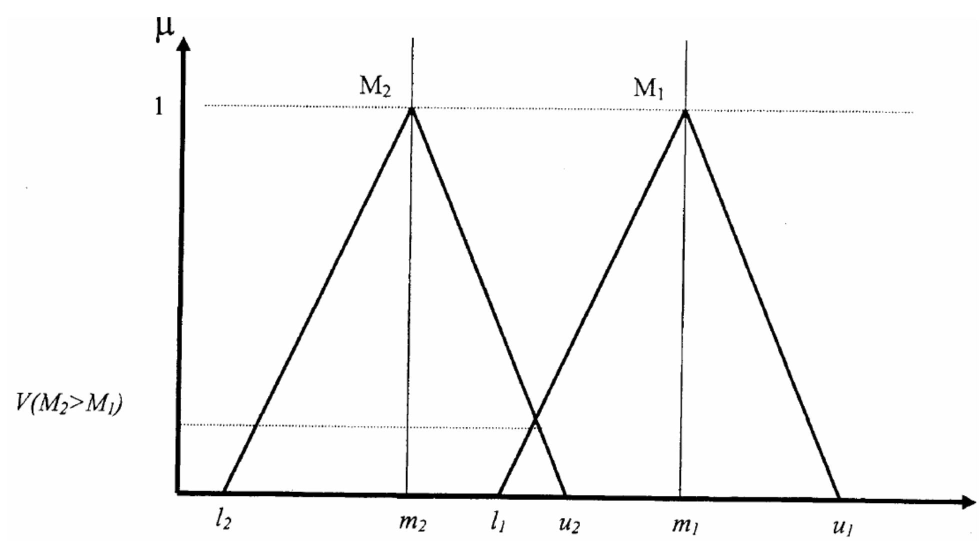


Figure 6.6 Ordinate of the Highest Intersection Point between μ_{m1} and μ_m

Step 3: The degree possibility for a convex fuzzy number to be greater than k convex TFNs M_i *(i = 1, 2, 3, 4, 5, ..., k)* can be defined by

$$
\begin{aligned}
&V(M \geq M_1, M_2, \ldots\ldots M_k) \\
&= V[M \geq M_1 \text{ and } M \geq M_2, \text{and} \ldots\ldots \text{and } M \geq M_k) \\
&= \min V(M \geq M_k),\ i = 1,2,3,\ldots\ldots,k
\end{aligned} \tag{6.7}
$$

Assume that $d(A_i) = \min V(S_i \geq S_k)$ for *k = 1, 2, 3, 4, 5, ..., n*; k≠i. Then the weight vector is given by Eq. 6.8:

$$
W^{'} = (d^{'}(A_1), d^{'}(A_2), \ldots\ldots, d^{'}(A_n))^T \tag{6.8}
$$

Where A_i *(i = 1, 2, 3, 4, 5, 6, …., n)* are n elements.

Step 4: Via normalization, the normalized weight vectors are given in Eq. 6.9, where W is a non-fuzzy number.

$$
W = (d(A_1), d(A_2), \ldots\ldots, d(A_n))^T \tag{6.9}
$$

Usually, a questionnaire or interview is necessary to determine the importance levels of the evaluation attributes among different interests groups. There is high possibility of discrepancy in stakeholder choice and assigning the importance level. The survey respondents or representatives of stakeholder groups only select the related linguistic variable. Table 6.1 is an example set of linguistic statements for fuzzy pair-wise comparison developed in other studies [121] [122] [123]. In the calculation of FAHP, these variables are converted into scales including triangular fuzzy numbers and generalized for further analysis.

Table 6.1 Example Sets of Scale (TFNs) for Fuzzy Pair-Wise Comparison

Linguistic Statement	**Scale Value**		
The relative importance of the two sub-elements	***TFNs [121]***	***TFNs [122]***	***TFNs [123]***
Absolute/Extreme	[7/2, 4, 9/2]	[0.9, 0.95, 1]	[0.7, 0.9, 1.0]
Very Strong	[5/2, 3, 7/2]	[0.8, 0.85, 0.9]	[0.5,0.7, 0.9]
Fairly Strong	[3/2, 2, 5/2]	[0.7, 0.75 , 0.8]	[0.3, 0.5, 0.7]
Weak/Slight	[2/3, 1, 3/2]	[0.6, 0.65, 0.7]	[0.1, 0.3, 0.5]
Equal	[1, 1, 1]	[0.5, 0.5, 0.5]	N.A

6.4.3 Weight Stage for LTP and LCUP

For weighing the MOEs in one performance attribute of LTP and LCUP, the experts involved in the Delphi weighting process would especially consider the following aspects while assigning a number of points among the MOEs.

- **Reliability and accuracy in MOEs quantification.**

  The MOEs associated with immature method tools, immeasurable factors or controversial assumptions may be given lower score. For example, the CMFs associated with high standard errors in HSM accident prediction model.

- **Relative importance in reflecting the effects associated with the projects.**

The MOEs who can best measure the project performance and evaluate the achievement of project objectives are usually higher scored.

- **Site-specific conditions, such as local regulations and legal requirements.**

Some MOEs must be included and examined in order to meet specific local or national standards (e.g, emission standards and air pollution index) or to consider specific requirements of affected organizations, individuals. For example, noise level should be measured if there are schools, hospitals or other sound-sensitive locations nearby the project site. These MOEs reflecting site-specific conditions or requirements should be assigned a higher score.

There are five (5) performance attributes defined for LTP and LCUP: Operation, Safety, Energy, Environment and Accessibility. Complex structures representing performance attributes are organized in hierarchical cluster to facilitate pair-wise comparisons and to estimate their relative weights, pair-wise comparisons between any two performance attributes *i* and *j* can be represented using the fuzzified reciprocal 5×5 judgment matrix $\tilde{A}$ containing all the comparisons between two attributes *i* and *j* for all *i, j* in the $\{1,2,\ldots,5\}$

$$\tilde{A} = \begin{bmatrix} (1,1,1) & \tilde{a}_{12} & \cdots & \tilde{a}_{15} \\ \tilde{a}_{21} & (1,1,1) & \cdots & \tilde{a}_{25} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{51} & \tilde{a}_{52} & \cdots & (1,1,1) \end{bmatrix}$$

Where the elements $a_{ij} = [l_{ij}, m_{ij}, u_{ij}]$ are TFNs with l_{ij} the lower and u_{ij} the upper limits and m_{ij} is the point where the membership function $\mu(x) = 1$. The elements on the diagonal have a value of unity because of comparison to itself. In addition, the elements of the matrix (for performance attributes *i* and *j*) are typically reciprocal with respect to the main diagonal.

$$\tilde{a}_{ij} = \tilde{a}_{ji}^{-1}$$

Each entry $\tilde{a}_{ij}$ is the quantified stakeholder judgments of relative importance by translating their uncertain or imprecise linguistic statements into scaled TFN value. The TFN ratios for pair wise comparisons matrix used in this research (Table 6.2) is developed on the basis of the 1to 9 scale defined by Saaty [124].

Table 6.2 Linguistic Statement and Corresponding Triangular Fuzzy Numbers

Linguistic Statement	Explanation	TFN	Inverse TFN
Attribute i is Equally Important as Attribute j	Two attributes are considered equally to the stakeholder	[1, 1, 1]	[1, 1, 1]
Attribute i is Slightly More Important as Attribute j	Stakeholder slightly favors one attribute over another	[1, 2, 3]	[1/3, 1/2, 1/1]
Attribute i is Moderately More Important as Attribute j	Stakeholder favors one attribute over another	[3, 4, 5]	[1/5, 1/4, 1/3]
Attribute I is Strongly More Important as Attribute j	One attribute is favored strongly over another, its dominance	[5, 6, 7]	[1/7, 1/6, 1/5]
Attribute i is Extremely Moore Important as Attribute j	One attribute is extremely and affirmatively important to stakeholder over another	[7, 8, 9]	[1/9, 1/8, 1/7]

The importance levels of the performance attributes among different stakeholders can be determined by conducting a survey in the group of stakeholders. If local survey is not feasible, the importance levels can also be estimated based on the specific characteristics in each stakeholder group. A table of importance levels for the five performance attributes defined for LTP and LCUP are provided (Table 6.3) on the basis of FHWA's identifications of stakeholder interests within communities adjacent to urban signalized intersection [6]. The linguistic statements from stakeholder reflecting their specific interests and concerns summarized in Table 6.3 can be directly converted into fuzzy number by using Table 6.2.

Table 6.3 Relative Importance of Performance Attributes for LTP and LCUP

Intersection User		Performance Attributes				
		Operation	**Safety**	**Energy**	**Environment**	**Accessibility**
Performance Attributes	**Operation**	**Equally Important**	Equally Important	Moderately Important	Slightly Important	Slightly Important
	Safety		**Equally Important**	Moderately Important	Strongly Important	Strongly Important
	Energy			**Equally Important**	Moderately Important	Equally Important
	Environment				**Equally Important**	Equally Important
	Accessibility					**Equally Important**
Intersection Neighbor		**Operation**	**Safety**	**Energy**	**Environment**	**Accessibility**
Performance Attributes	**Operation**	**Equally Important**		Moderately Important	Slightly Important	Equally Important
	Safety	Slightly Important	**Equally Important**	Strongly Important	Moderately Important	Slightly Important
	Energy			**Equally Important**		
	Environment			Moderately Important	**Equally Important**	
	Accessibility					**Equally Important**
Intersection Owner		**Operation**	**Safety**	**Energy**	**Environment**	**Accessibility**
Performance Attributes	**Operation**	**Equally Important**	Equally Important	Moderately Important	Slightly Important	Slightly Important
	Safety		**Equally Important**	Moderately Important	Slightly Important	Slightly Important
	Energy			**Equally Important**	Equally Important	Equally Important
	Environment				**Equally Important**	Equally Important
	Accessibility					**Equally Important**

Note: the table is read horizontally. For example, the gray cell is read as: Safety is moderately important than Energy for Intersection User.

Intersection improvement projects involve three stakeholders, (user, neighbor and owner). Because of potential conflicting interests and various concerns, differences in their linguistic statement are possible. In addition to the vagueness of each stakeholder group in defining relative importance, the discrepancy in preferences among these groups is considered by applying additive operation of TFN values. Therefore the element $\tilde{a}_{ij}$ in comparisons matrix is estimated by:

$$\tilde{a}_{ij} = \sum_{k=1}^{n} c_k TFN_{ij}^{s_k}$$

Where *n* is the number of stakeholder groups included in the evaluation process (*n=3* for Intersection improvement projects), $TFN_{ij}^{s_k}$ is the TFN Scale defined by the k^{th} stakeholder group for comparing attributes *i* and *j* at each hierarchical level. c_k is a optional scaling factor used to identify the importance level among the stakeholder groups and usually given by decision makers . $\sum_{k=1}^{n} c_k = 1$ and $c_k = \frac{1}{n}$ if no discrepancy between the importance of stakeholder groups.

After forming a fuzzy pair-wise comparison matrix $\tilde{A}$, the normalized weight vectors of the performance attributes for intersection treatments are determined by applying the steps of FAHP extent analysis method (Step 1 to Step 4) described above. The FAHP extent analysis is demonstrated in Chapter 7 with a numerical example in a case study. It is always desirable to obtain reliable weights that reflect the importance of attributes so that the decisions can be robust.

6.5 Scale Stage of MAFU

Scale stage is one of the key aspects of the MAFU evaluation process, which is designed to establish a common unit or scale of measurements in different performance attributes, so that all MOEs can be expressed in a weighted dimensionless unit for further combination of attributes and comparison of alternatives.

CBA is commonly used to establish a common monetized unit. This method concentrates on the index of the economic efficiency by monetizing the performance MOEs to measure the costs and benefits of impacts of different stakeholders in constant dollar value. After reviewing the existing research, it became obvious that many performance MOEs defined in this research such as air quality, noise, and accessibility are not monetized, because of a lack of studies that provide reliable monetary values for them. Therefore, it is necessary to use a generic and comprehensive common metric for all the monetizeable or non-monetizeable, and quantitative or qualitative performance indicators or MOEs in the MAFU process.

In this research, for any given performance MOEs, the utility function approach based on utility theory is used to establish a dimensionless unit of desirability. The risk tolerance level is also included to provide various risk scenarios. This scaling stage also incorporates the uncertainty in estimating performance MOEs. The concept of uncertainty comes from the inability to precisely measure treatment performance in reality and to reliably predict the future response to a current improvement project. Uncertainty can be considered as objective risk due to imperfect theory, insufficient experiment or observation and unrealistic assumptions. In the case of uncertainty analysis, the decision cannot be made by relying on the outcomes of one trial. Instead, decision makers need to understand the range, the expected values and distribution of possible outcomes.

6.5.1 Generic Foundation: Measurement and Uncertainty

The analytical tools and methods utilized to identify and quantify performance MOEs have been discussed in Chapter 5. Although most of the existing methods or tools for estimating performance MOEs are deterministic and most existing decision-making processes for transportation projects use discrete fixed values for input variables, potential uncertainties of the results from the analysis of intersection performance have been recognized by traffic analysts. For example, Ji's uncertainty analysis of HCM intersection level of service estimation [125], Allsop's study on traffic delay affected by uncertainty in arrival rate and saturation flows [126], Heydecker's analysis on the variability in arrival rate for signal timing calculations[127], Park's and Kamarajugadda's estimation in the confidence interval of delay equations by taking account of the day-to-day variation of traffic volume [128], Pecheux's and Pietrucha's description of the probability distributions of delay measured at three signalized intersections [129], and Jeon's and Chang's research on incorporating uncertainty into regional transportation planning process to promote sustainability [130].

In reality, the estimates of performance MOEs inherently contain a certain amount of uncertainty. For instance, uncertainties are involved in conducting intersection delay analysis due to stochastic fluctuation in traffic volume and unpredicted traffic arrival. Quantifying the loss in business patronage may be uncertain due to the latent effects of regional economic background and unclear dependency on bypass traffic of business. In addition, a wide range of factors are also likely to change over time, some of which are beyond the control or prediction of transportation agencies. Sometimes, even the uncertainties in each model input are small, but they can accumulate and propagate, so that there may be a large uncertainty in the outcomes. Without analysis of uncertainty, the outcomes can be biased and decisions or selections made on unreliable measurement of performance cannot be robust. Therefore, it is necessary to account for the uncertainty in a deterministic analysis procedure in order to present ranges or statistical summary of the possible outputs.

Two questions need to be answered when conducting uncertainty analysis for the estimation of performance MOEs: 1) How to capture uncertainty, and 2) How to analyze uncertainty. For the latter question, if the variation (range or probabilistic distributions) of input variables is known, there are many approaches available (such as First Order Analysis, Monte Carlo Simulation, Fourier Amplitude Sensitivity Test and Point Estimate Method) to analyze uncertainty. However, capturing the uncertainty in measuring performance MOEs is not always easy. The primary purpose of this stage is to establish a suitable scale range or probability distributions, so that the uncertainty in performance measurements can be ascertained. Three commonly used approaches in capturing uncertainty are discussed below.

1. Sampling-based Approach

Sampling-based approach can be used to determine the suitable distribution type and the parameters of the distribution function. It is a useful tool if a large number of sampling data are available. The rule of thumb is the more data, the better. In most cases, in order to obtain reliable distribution fitting results, at least 75-100 data points should be available [131]. Data sampling first processes observations to generate probability plots (usually histograms) [132]. This is a graphical technique to narrow choice to a limited number of distributions before performing distribution fitting. Through comparison of the measure of the goodness of fit (i.e., the correlation coefficient associated with the linear fit to the data in the probability plot), the best fitting probability distribution can be determined and the estimates of the location and scale parameters for the distribution are given by referring to the intercept and slope. More details about the process of Goodness of Fit Test can be found in Engineering Statistics Handbook [133]. Software or statistical programming that assist in fitting distribution with exploratory data, include Matlab, @RISK, EasyFit, Frontline Solvers and The *R Project* for Statistical Computing.

2. Uncertainty Propagation Approach

A deterministic procedure provides no randomness or uncertainty and usually has a single value for each input variable. So the procedure will always produce the same output from identical starting condition or initial state. However, the single values of major input variables may have inherent variation and uncertainty and small variations in each input variable may propagate and generate a relatively large uncertainty in final outputs. Uncertainty of model inputs may come from the error in collecting input variables due to measurement errors, sampling errors, simple approximation or natural stochasticity such as the natural fluctuation of traffic flows. In addition, some input variables (e.g., accessibility or business patronage) depend on multiple choice surveys of humans making them difficult to estimate. The uncertainty considered in this research does not focus on the input errors because they can be diminished or eliminated with advanced technologies or careful measurement. In addition, the input errors are usually ignored by model developers, since the accuracy of a model is intuitively determined by its formulation and calibrated parameters [134].

The basic idea of uncertainty propagation approach is that if the uncertainty measures (such as possible range or probability distribution) of the input variable are known, the uncertainty in the outputs of the model can be captured by replicating the model with varied uncertainty levels of inputs. Many methods are available to be used to propagate the uncertainty of model inputs, such as the interval-value approach, expectation function approach, sensitivity analysis, Monte Carlo and more. There are two issues restricting the application of this approach:

Usually, the collection of detailed field data and calculation of uncertainty of input variables is not a realistic burden for practitioners. Sometimes, a national or regional database of field data is available. Such as variation of traffic volume from day to day and season to season, peak hour factor and heavy vehicle percentage for varied day or time. However, there is a shortage of available databases for examining the input uncertainty of environmental or socioeconomic variables.

Most of the existing analytical tools or models do not have an available interface or potential extension for users to conduct uncertainty analysis. The models only allow single value input for required variables at a time. In order to apply this approach and collect statistically sufficient outputs by sampling, the deterministic process may have to be replicated numerous times. It is almost impossible or extremely labor-intensive to integrate uncertainty in multiple variables.

The application of uncertainty propagation to capture uncertainty associated with the outputs requires knowledge on the uncertainty range of major inputs and the interface for conducting uncertainty analysis through an analytical model. This approach is particularly advantageous if the analytic process is straightforward and uncomplicated, such as HCM 2010 pre-timed intersection delay estimation and HSM 2010 intersection crash prediction models.

3. Empirical Selection Approach

In order to conduct uncertainty analysis under the conditions of limited data availability and uncertainty information, the probability distribution for performance MOEs can be empirically selected based on the characteristics of commonly used distributions. References from related literature or engineering experience and judgment can also be helpful. There are “rules of thumb” found in existing literature to guide an empirical selection of probability distributions for transportation projects:

- Generally if only the approximate boundaries of input variables can be estimated, a uniform distribution could be assumed. If the most probable value is also available, then a triangular distribution may be assumed [135].
- Normal, lognormal or uniform distributions have often been assumed for uncertainty analysis in traffic engineering [40].
- The binomial distribution can be considered for the discrete performance criteria that have a small range of outcomes [107].
- For performance criteria that involve continuous variables and the outcomes are spread out over a given range in a continuous fashion, the distribution of the possible outcomes can be symmetric or skewed and it can be modeled as a beta distribution to account for the degree of skewness and kurtosis [107].
- For discrete performance indicators, it was reasonable to assume that there was equal opportunity that the probability would occur at each condition rating, and this probability was not affected by any knowledge of the previous condition [136].
- According to the central limit theorem, generally the mean of a sufficiently large number of independent random variables, each with finite mean and variance, will be approximately normally distributed as the number of random variables becomes large [137].

In addition to selecting the possible fitting distribution, in practice, the distribution function may need to be truncated by varying the minimum and maximum or eliminating negative or invalid values. A truncated distribution is actually a conditional distribution by restricting the domain of probability distributions. Truncated distributions arise in many practical situations, especially in transportation systems whose performance indicators usually fall within certain tolerance limits: The values of travel time cannot be negative, the road capacity has a maximum, and there may be maximum business loss due to some access restriction. A brief introduction on the calculation process of distribution truncation is provided below [138].

Suppose we have a continuous distribution with probability density function (pdf) and cumulative distribution function (cdf) specified by *g(·)* and *G(·)*, respectively. Let *X* be a random variable representing the truncated version of this distribution over the interval *[a, b]*, where $-\infty < a < b < \infty$. The pdf ($f_X(x)$), mean (*E(X)*), variance (*Var(X)*), cdf ($F_X(x)$), quantile function ($F_X^{-1}(p)$) and the *n* random numbers of X (x_i) are given by:

$$f_X(x) = \begin{cases} \dfrac{g(x)}{G(b)-G(a)}, & if\ a \le x \le b, \\ 0, & otherwise, \end{cases}$$

$$E(X) = \int_a^b x f_X(x)dx,$$

$$Var(X) = \int_a^b [x - E(X)]^2 f_X(x)dx,$$

$$F_X(x) = \frac{G[\max(\min(x,b),a)] - G(a)}{G(b)-G(a)},$$

$$F_X^{-1}(p) = G^{-1}\{G(a) + p[G(b)-G(a)]\},$$

$$x_i = F_X^{-1}(u_i).$$

Where u_i, $i = 1, 2, \ldots, n$ are n uniform $(0, 1)$ random numbers.

6.5.2 Generic Foundation: Establishment of Utility Function and Risk

A decision-making process may have to be conducted in a complicated environment. Suppose that the analysts have effectively summarized the relative desirability of each performance attribute and estimated the values of MOEs (certain and uncertain) in each attribute for each alternative. The values of these MOEs are presented in different units and dimensions, some reflecting costs, others reflecting benefits, some deal with socioeconomic and environmental concerns, others address traffic engineering issues. These outputs cannot be simply summed into an objective formula. In addition, the decision should be made with careful consideration of tradeoffs and attitudes toward risk.

In the scale stage of MAFU, utility theory is used to convert MOE values into dimensionless utility index and to account for the subjective risk element in scaling the performance MOEs. For any given performance MOEs, a utility function developed based on utility theory can provide a uniform and generalized scale. It integrates the risk behaviors of decision maker ascertained from the function shape and parameter values. A risk-taking decision maker has a strictly convex utility function, a risk-neutral decision maker has a linear utility function, and a decision maker is risk averse if and only if his utility function in concave [107] [139]. Figure 6.7 shows examples of function curves presenting the different risk premium of their risk-taking behaviors.

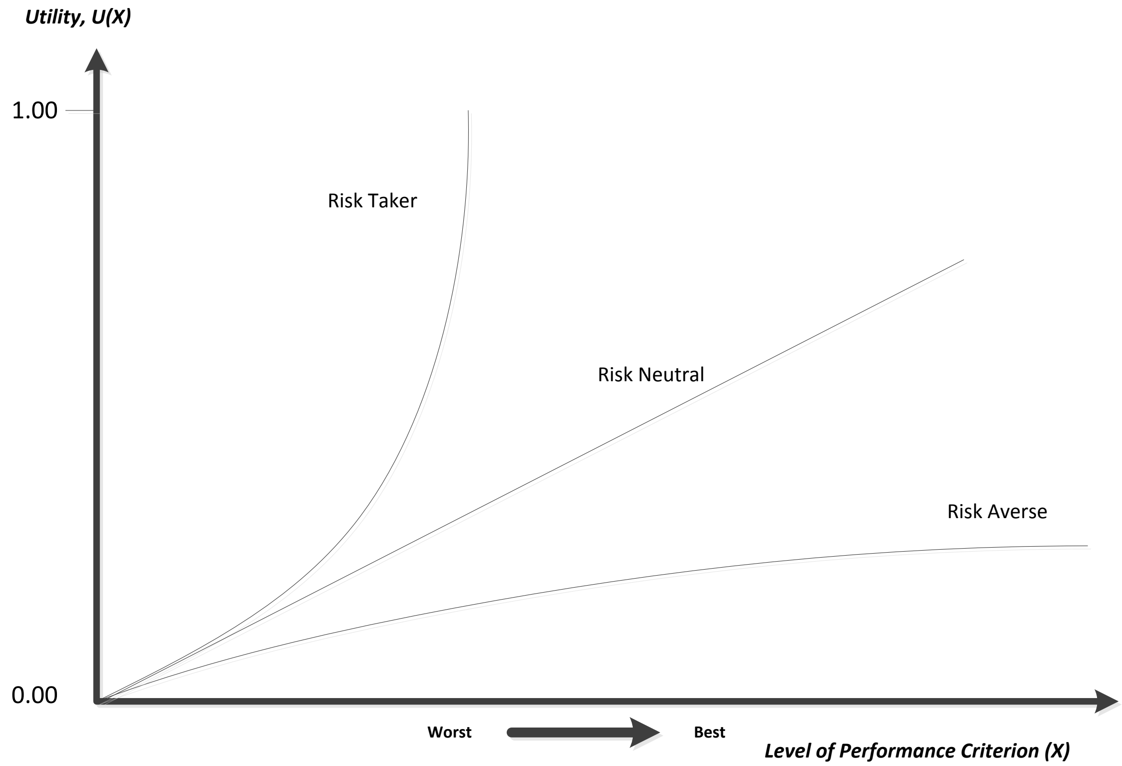


Figure 6.7 Example Function Curves Presenting Different Risk Premiums

The utility function is established by weighting and synthesizing single attribute utility functions to a multi-attribute utility function, either in additive or multiplicative form. In the scaling stage of MAFU, single attribute utility functions for an individual performance attribute are developed. In combination, system-wide multi-attribute utility functions combing all the performance attributes are defined for each alternative. The expected values of the multi-attribute utility function for project alternatives are used to rank the alternatives. Usually the alternative with the maximum expected utility value is chosen.

Questionnaire surveys can be used to develop single attribute utility functions for individual performance attributes. Two approaches are commonly used for the preparation of questionnaires: the direct questioning approach and the certainty equivalency approach. The concepts of these approaches are briefly summarized as follows [139]:

Direct Questioning (Gamble Approach)

For a performance MOE X, the best level for the MOE is defined as X_b and its worst level is X_w. Then assign the following utilities: $U(X_w)=0$ and $U(X_b)=1$. After that, two situations are compared:

(i) Risky prospect of obtaining X_w with probability p and X_b with probability $(1-p)$

(ii) Guaranteed prospect of obtaining $X= 0.5(X_b - X_w)$

Repeated back-and-forth survey need to be conducted until the probability p has reached a threshold point where the survey respondents indictate that they are indifferent between the two situations listed above. To improve the accuracy of utility function, the process can also be repeated for other levels of the criterion such as $X= 0.25(X_b - X_w)$ and $X= 0.75(X_b - X_w)$. A plot of probability (p) versus levels (e.g, 0.25, 0.5, 0.75) can yield the utility function for the MOE.

Certainty Equivalency Approach

This approach also starts with the best and worst level for one of the MOEs in a performance attribute: $U(X_w)=0$ and $U(X_b)=1$.

(i) Twp situation are compared in this step:

a. Risky prospect of obtaining X_w with probability 0.5 and X_b with probability 0.5

b. Guaranteed prospect of obtaining $X_{0.5}$ for which $U(X_{0.5})= 0.5$

Repeat until there is no difference in the value of $X_{0.5}$ between the guaranteed situation and alternative risky situation. The level at which the survey respondents are indifferent is called the certainty equivalent of the gamble.

(ii) Determine the certainty equivalent corresponding to other criteria levels such as $X_{0.25}$ and $X_{0.75}$ in a similar fashion.

(iii) Plot the utility function for the performance criterion (MOEs) and repeat the entire procedure for other criteria in the performance attributes.

As discussed above, surveys and questionnaires are suggested to be used for defining utility functions, because of their accuracy and reliability in understanding the risk tolerance level of decision makers. With limited project budget, short project schedule or poor survey responses, a simpler approach based on the mathematical technologies of normalization and risk theory can be used to construct dimensionless utility functions model.

For the performance MOE X in one of the performance attributes, the value range of the MOE estimate for alternative A_i can be denoted as $X \in [X_L^{A_i}, X_H^{A_i}]$, ($X_L^{A_i} = X_H^{A_i}$ if the value of the MOE is a single fixed value involving no uncertainty). The highest and lowest value (among all the alternatives A_1, A_2, ……., A_n) for the MOE: X_{max} and X_{min} can be computed:

$$X_{max} = \max(X_H^{A_1}, X_H^{A_2}, ..., X_H^{A_n}) \quad (6.10.a)$$

$$X_{\min} = \min(X_L^{A_1}, X_L^{A_2}, ..., X_L^{A_n}) \quad (6.10.b)$$

Then, the utility functions can be developed by using a normalization process for the following three conditions:

(1) Higher value of MOE represents more desirable performance. Assigning $U(X_{max}) = 1$ and $U(X_{min}) = 0$, the utility function with normalized value of MOE x can be obtained:

$$u(x) = \left(\frac{X - X_{\min}}{X_{\max} - X_{\min}}\right)^{\lambda} \quad (6.11)$$

(2) Lower value of MOE represents more desirable performance. Assigning $U(X_{min}) = 1$ and $U(X_{max}) = 0$, the utility function can be obtained:

$$u(x) = (\frac{X_{\max} - X}{X_{\max} - X_{\min}})^{\lambda} \tag{6.12}$$

(3) A value of MOE more toward the middle represents more desirable performance can be achieved. Assigning $U(X_{mid}) = 1$ and $U(X_{max}) = U(X_{min}) = 0$, the utility function can be obtained:

$$u(x) = \begin{cases} (\frac{X - X_{\min}}{X_{\max} - X_{\min}})^{\lambda}, if\ (X_{\min} \le X < X_{mid}) \\ (\frac{X_{\max} - X}{X_{\max} - X_{\min}})^{\lambda}, if\ (X_{mid} \le X \le X_{\max}) \end{cases} \tag{6.13}$$

As shown in Eq. 6.14, the risk parameter λ in the utility functions is a positive real number used to adjust the shape of the utility function in order to reflect the relations between decision maker single-criterion utility function and their risk attitude for the subjective risk situation.

$$\lambda \in \begin{cases} (0,1)\ \ risk\ averse \\ \quad 1\ \ \ risk\ neutral \\ (1,\infty)\ risk\ taking \end{cases} \tag{6.14}$$

Risk can be classified as objective or subjective. Subjective risk is based on a personal perception that may be related to the consequences of failure as well as the ability or inability to control the situation. Objective risk is based on theory, experiment, or observation [140]. Risk parameters in the utility functions are used to describe the implications of subjective risk associated with performance MOEs. A decision maker is risk averse if he prefers the expected consequence of any nondegenerate lottery to that lottery (a nondegrenerate lottery is one where no single consequence has P=1 of occurring). A decision maker is risk prone if he prefers any nondegenarate lottery to the expected consequence of that lottery [139]. It can also be shown in terms of the second derivative of utility function: A utility function *u(x)* has the following three basic properties: concave ($0<\lambda<1$), convex ($\lambda>1$) and linear ($\lambda=1$). Assuming that the function *u(x)* is twice differentiable; then risk taking, risk neutral and risk averse state that $u(x)/\Delta x^2>0,\ u(x)/\Delta x^2=0, and\ u(x)/\Delta x^2=0$ [139].

A decision maker can have an identical risk attitude for all the utility functions developed for each performance attribute, but most likely, the single attribute utility functions may be assigned different risk parameters to reflect the importance level of each performance attribute. Usually, the performance attributes which correspond to the primary objectives of the proposed project should be conservative and be assigned a risk-averse value, such as traffic operation and safety performance for an intersection improvement project. Other utility functions for performance attributes with moderate importance may use risk-neutral parameters.

6.5.3 Scale Stage for LTP and LCUP

In the uncertainty scaling for LTP and LCUP, the suggested uncertainty range or distributions and risk parameters (shown in Table 6.4) are established to capture the uncertainty and risk in estimation of performance MOEs in the five attributes.

Table 6.4 Uncertainty Analysis for LTP and LCUP Performance Attributes

Performance Attributes	**Suggested MOEs**	**Uncertainty Analysis Approaches**	**Risk Parameters**
Traffic Operation	Delay, Number of stops, Vehicle speed, Queue length	Uncertainty Propagation Approach	Risk Averse: λ=1/2
Traffic Safety	Accidents per one million entering vehicles, Crash rate and severity	Uncertainty Propagation Approach	Risk Averse: λ=1/2
Energy	Fuel Usage, Modal trips, Duration of truck engine Idling	Empirical Selection Approach-Beta Distribution	Risk Neutral: λ=1
Environment	Pollutant emission, Greenhouse gas emission, Noise	Empirical Selection Approach-Y Distribution	Risk Neutral: λ=1
Accessibility	Land value, Business profits	Empirical Selection Approach-Discrete or binary distribution	Risk Taking: λ=2

Accounting for uncertainty in traffic safety attributes is frequently overlooked. In examining differences in accident experience before and after an improvement, it is especially important to explicitly account for uncertainty in estimates and to properly interpret the results, since sample sizes and differences of interest are typically small [141]. In the attributes of traffic safety, the HSM prediction model is the analytical tool employed to evaluate the effects of proposed LTP and LCUP on intersection safety. Because the reliability of estimates is subject to uncertainty, as a rule, estimates are often accompanied by a description of their standard error, variance, or some manner of statistical reliability in HSM. Therefore, the standard error as a common measure of reliability is provided for all CMFs which are designed to reflect potential impacts of intersection treatment and then a confidence interval for the estimated change in expected average crash frequency can be calculated as follows:

$$CI(y\%) = CMF_x \pm SE_x \times MSE$$

Where:

$CI(y\%)$ the confidence interval for which it is y% probable that the true value of the CMF is within the interval;

CMF_x the crash modification factor for condition x or treatment x;

SE_x Standard error of the CMF_x

MSE Multiple of standard error (see Table 6.5)

Table 6.5 Values for Determining Confidence Intervals using Standard Error [63]

Desired Level of Confidence	**Confidence Interval (y)**	**Multiple of standard error**
Low	65%-70%	1
Medium	95%	2
High	99.90%	3

Once the proper confidence level is defined, the range of CMFs together with other key inputs, such as AADT and pedestrian volume can be applied into the crash prediction model for estimating the output uncertainty level according to the uncertainty propagation approach.

Other performance attributes such as the environment, energy, accessibility or project costs usually involve continuous MOEs. For example, the emission and energy consumption attributes continuously spread over a minimum and maximum range. Therefore beta distribution is empirically selected to model their uncertainty (automobile emissions may be modeled by using γ-distribution [142] [143]). The general beta distribution is actually a family of continuous probability distributions defined on the interval (0, 1) and has four parameters including lower limit (*L*), upper limit (*H*), and two shape parameters α and β. The density function is given by [107]:

$$f(x \mid \alpha, \beta, L, H) = \frac{\tau(\alpha+\beta)(x-L)^{\alpha-1}(H-x)^{\beta-1}}{\tau(\alpha)\tau(\beta)(H-L)^{\alpha+\beta-1}} \qquad \text{for } L \leq x \leq H$$

Where the gamma function factors serve to normalize the distribution, so that the area under the density function from *L* to *H* is exactly equal to 1. The mean (μ) and variance (σ^2) for the beta distribution are given by the following:

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

The properties of the Beta distribution are summarized below:

- When $0 < \alpha < \beta$ the mean is closer to L and the distribution is skewed to the right.
- When $\alpha > \beta > 0$ the mean is closer to H and the distribution is skewed to the left.
- When $\alpha = \beta$, the Beta distribution is symmetrical about $x = 0.5$.
- When both α and β are larger than 1, the Beta distribution is uni-modal, and its density is 0 at both ends of the range.
- When both α and β are smaller than 1, the density is U-shaped 1. Both vertical axes are asymptotes.

- When both α and β are equal to 1, the density is uniform in {0, 1}.

In practice, the skewness and variance (kurtosis) can be categorized as high, medium, or low based on the magnitude of α and β. Table 6.6 below presents the resulting combinations of skewness and variance (kurtosis) for beta distributions that best approximate the uncertainty situation of possible outcomes of the continuous performance indicators [107].

Table 6.6 Approximate Values of Shape Parameters for Beta Distributions

Combination Type	Variance (Kurtosis)	Skewness	α	β
1	High	To the left	1.5	0.5
2	High	Symmetric	1.35	1.35
3	High	To the right	0.5	1.5
4	Medium	To the left	3	1
5	Medium	Symmetric	2.75	2.75
6	Medium	To the right	1	3
7	Low	To the left	4.5	1.5
8	Low	Symmetric	4	4
9	Low	To the right	1.5	4.5

Note that the table above only provides approximate parameters for restricted application under conditions with limited data. The parameters of the distribution function are suggested to be calibrated to reflect site-specific condition if supporting data are available.

The process of determining uncertainty ranges and establishing utility functions are programmed in *R Project*, a free and open source software of providing a wide variety of statistical and graphical techniques with a special focus on risk and uncertainty analysis. This tool is also used in the combination and decision stages in conducting Monte Carlo simulation and developing the tradespace for tradeoff analysis.

6.6 Combination Stage of MAFU

The combination stage is a mathematical amalgamation (e.g., additive, multiplicative, or pair-wise comparison) of single-attribute utility functions of performance MOEs in different performance attributes. Since the potential uncertainty level (discrete range of variation or continuous probability distribution) is taken into account for estimating some performance MOEs, the process of combination is repeated numerous times to generate a statistical summary (output utility index) for each alternative by using Monte Carlo Simulation (MCS). The statistical summary includes mean, variance, fitting distribution factors, and confidence intervals, which can be used to develop a tradespace for tradeoff analysis and decision-making.

The main purpose of applying multi-attribute utility functions and MCS are to generate multiple dimensional scenarios for tradeoff analysis and to estimate aggregated uncertainty in outputs simultaneously. MCS is selected because it is generally applicable to any uncertainty conditions without restricting model structure. If a complete representation of population distribution is available, then the simulation results are reliable and accurate.

In order to reach convergence and produce reliable statistical results, thousands of repetitive MCS runs may be necessary. The calculation time can be quite lengthy. Therefore, in this research, a statistical programming software: *R Project* for Statistical

Computing [144] is utilized to conduct the simulation process, because it has high speed of calculation, allows statistical analysis and visualization of unlimited sophistication, can work on objects of unlimited size and complexity with a consistent, logical expression language [145], and is free because all of its source code is published.

6.6.1 Generic Foundation: Mathematical Amalgamation

The process of amalgamation in the combination stage is designed to yield a utility index and its related statistical information for each one of the alternatives. The outputs allow the alternatives to be scored, ranked and compared. There are many common technologies for combining performance measures, such as ε-constraint method, multiple attribute utility function method and evolutionary and genetic algorithms.

The combination stage was achieved by developing the multi-attribute utility function for individual alternatives (i.e., intersection treatments). The utility theory has been used to determine the single attribute function for each performance attribute in the scale stage.

The multi-attribute utility function is used to combine those single attribute functions in order to establish dimensionless units for the tradeoff analysis and decision-making. The process of developing multi-attribute utility function is shown below.

We assume that an objective hierarchy has been specified and that attributes X_1, X_2, ..., X_n have been identified and are appropriate for the problem. If x_1 designates a specific level of X_i, then the task is to assess multi-attribute utility function $u(x)=u(x_1, x_2,\dots,x_n)$ over the n attributes. The utility function to estimate the utility of a consequence $(x_1, x_2,\dots,x_n)$ can be determined by direct assessment and decomposed assessment.

Direct assessment estimates the combined utility $u(x)$ over the given values of all n attributes. If there are only a few possible consequences, it may be reasonable to directly assign a utility to each of these. The decomposed assessment considers the qualitative structuring of preferences and the basic preference attitudes of the decision maker are exploited in specifying a utility faction. This assessment estimates n conditional utility functions $u_i(X_i)$ for the given values of the n attributes and computes $u(x_1, x_2,\dots,x_n)$ by combining the $f_i = u_i(X_i)$ of all attributes [139]:

$$u(x_1, x_2,\dots,x_n)=f[f_1(x_1), f_2(x_2),\dots,f_n(x_n)], \qquad (6.15)$$

Where f_i is a function of attributes X_i and where f has a simple additive or multiplicative form. The assessment of u can be greatly simplified if possible.

The single attribute utility function for one of the performance MOEs x in the $u_i(X_i)$ of attribute X_i has been developed in the Eq. 6.11 to Eq. 6.13. Therefore, in this study, for performance attributes X_i, the utility function f_i can be defined as:

$$f_i = u(X_i) = \sum_{j=1}^{K} w_{ij} \bullet u(x_{ij}) \qquad (6.16)$$

Where

w_{ij} is the relative weight of performance MOEs x_{ij} within the performance attributes X_i (determined by using Delphi technique).

$u(x_{ij})$ is the single attribute utility function for performance MOE j in the performance attributes X_i.

K is the number of performance MOEs defined in the performance attributes X_i ($K \geq 1$).

As described before, the multiple attribute utility function can have a simple additive or multiplicative form. One of the most important results of multi-attribute utility theory specifies conditions that enable one to conclude that a utility function is either multiplicative or additive [139]. The additive utility function has the form:

$$u(x_1, x_2, \ldots, x_n) = k_1 f_1(x_1) + k_2 f_2(x_2) + \ldots\ldots + k_n f_n(x_n) \tag{6.17}$$

where k_i is positive scaling constants allowing to add the separate contributions of the attributes to obtain the total utility (usually with weights).

The additive utility function is the best known of the multi-attribute utility functions and important both because of its relevance to some real problems and its relative simplicity [139]. Use of an additive utility function is justified given the assumption of additive independence. Any two attributes X_i and X_j are additive independent, if preferences for lotteries (choices) over $X_i \times X_j$ can be established by comparing the values on one attribute at a time. More formally, if the paired preference comparison of any two lotteries (choices), defined by two joint probability distributions

($f_{X_iX_j}(X_i, X_j)$) on $X_i \times X_j$, depends only on their marginal probability distributions ($f_{X_i}(X_i)$ and $f_{X_j}(X_j)$). The relation can be shown in mathematical form:

$$f_{X_iX_j}(X_i, X_j) = f_{X_i}(X_i) + f_{X_j}(X_j)$$

The multiplicative form of the multi-attribute utility functions is used if the attributes defined in the utility function are interrelated. Multiplicative utility functions are defined below [139].

$$\begin{aligned} u(x) = \sum_{i=1}^{n} k_i u_i(x_i) + k \sum_{\substack{i=1 \\ j>i}}^{n} k_i k_j u_i(x_i) u_j(x_j) \\ + k^2 \sum_{\substack{i=1 \\ j>i \\ e>j}}^{n} k_i k_j k_e u_i(x_i) u_j(x_j) u_e(x_e) \\ + \ldots + k^{n-1} k_1 k_2 \ldots k_n u_1(x_1) u_2(x_2) \ldots u_n(x_n) \end{aligned} \tag{6.18}$$

Where

k is a scaling constant.

k_i is positive scaling constant allowing adding the separate contributions of the attributes. k_i have been determined through Fuzzy AHP process in the weight stage of the MAFU process (i.e., W computed with Eq. 6.9).

Eq. 6.18 can be simplified when $\sum_{i=1}^{n} k_i \neq 0$, then $k \neq 0$ by multipling each side by k and add one to each to obtain:

$$ku(x)+1=\prod_{i=1}^{n}[kk_i u_i(x_i)+1] \tag{6.19}$$

The scaling constant k can be determined by examining the special case where $u(x_i) = 1$ for all the attributes. As a result, Eq. 6.19 can be further simplified to

$$k+1=\prod_{i=1}^{n}(kk_i+1) \tag{6.20}$$

The additive form has been used in developing single attribute utility function of performance MOEs for LTP and LCUP (Eq. 6.17), because the MOEs in a performance attribute are independent, for example, the noise and emission MOEs in the environment attribute. The additive form is not used in the combination stage for combining all performance attributes into system-wide utility functions for an intersection improvement project, because of the existence of strong correlations between some of the performance attributes. For instance, a better traffic operation condition would be ideal for improvement of traffic safety and it also results in a reduction in vehicle air pollution and emission. The reduction of accessibility to a destination may extend average travel time so that the energy consumption may also increase. Therefore, a multiplicative form was adopted to establish the multi-attribute utility functions combing all the performance attributes for a project alternative.

The establishment of multiplicative utility function is justified only if attributes $X_1, X_2, \ldots, X_n$ are mutually independent and if every subset of $\{X_1, X_2, \ldots, X_n\}$ is utility independent of its complement [139]. Consider two attributes X_i and X_j with values x_1,

$x_2, \ldots, x_n$, $n \geq 2$, and $y_1, y_2, \ldots, y_n$, $m \geq 2$. X_i is utility independent of X_j if and only if for each value y_j of X_j. There are real functions $G > 0$ and H, such that $u(X_i, X_j) = G(X_j) \bullet u(X_i, y_j) + H(X_j)$ for all values of X_i and X_j. Utility independence means that the establishment of each attribute's utility function is independent of the level of all other attributes [146].

Another relatively weaker assumption for multi-attribute utility function is preferential independence. Utility independence concerns preference for lotteries that involve uncertainty, while preferential independence concerns the decision maker preferences for consequences where no uncertainty is involved. The utility independence condition is a stronger condition than preferential independence. If two attributes are utility independent, then they must be preferentially independent as well. Attribute X_i may be utility independent from attribute X_j, but the opposite does not necessarily hold [146].

Verification of the multi-attribute utility theory assumptions regarding utility and preferential independence of the attributes is necessary for the use of utility functions. This research specifies the performance attributes in the multi-attribute utility function. The correlation between the attributes needs to be clarified in order to develop a valid additive or multiplicative form of utility function. Because MAFU process is designed to be a generic evaluation method that could be compatible to both the additive and multiplicative form, the determination of appropriate utility function form should be carefully conducted for a specific project according to the correlations between performance attributes and indicators.

In order to justify the application of multiplicative utility functions for LTP and LCUP, preferential independence between performances attributes needs to be verified. Preferential independence implies that the conditional indifference curves over attributes X_i does not depend on its complement $\overline{X}_i$. In other words, preferential independence exists if the decision maker preference ranking for one attribute does not depend on fixed values of other attributes [147]. This independence is obviously valid for the intersection treatments LTP and LCUP, because the weighting scores assigned to each performance attribute in the weight stage were determined only based on project objectives and stakeholders perceptions. For example, assuming the decision maker or stakeholder prefers a traffic operation over traffic safety for LTP treatment, then the decision maker or stakeholder will also prefer a traffic operation over traffic safety for LCUP treatment. The preference is only dependent on the project objectives regardless of the possible treatments.

Therefore, a system-wide multiple attribute function combing these single attribute utility functions can be written as: $U(x) = u(x) * u_{adj}$, where U_{adj} in the multiattribute function is an adjustment factor to reflect the ability of a treatment to accommodate future traffic growth. It considers future traffic condition and expected growth in traffic volume within the planning horizon of project evaluation, usually 10 to 20 years.

6.6.2 Generic Foundation: Monte Carlo Simulation

Monte Carlo Simulation (MCS) is a general procedure for risk and uncertainty analysis where random sampling is used to estimate and incorporate the inherent uncertainty or risk associated with each input variable. MCS carries out a probabilistic analysis that treats some or all the inputs of a certain model as ranges of values, assigns a likelihood of occurrence to those values, and allows for simultaneous variability among inputs, so that the outputs of probabilistic analysis are presented as a range with likelihood of occurrence. Values of input variables are randomly selected from an input probability distribution and each set of sampled inputs are used to estimate single outcome iteration. The diagram of Monte Carlo Simulation is illustrated in Figure 6.8.

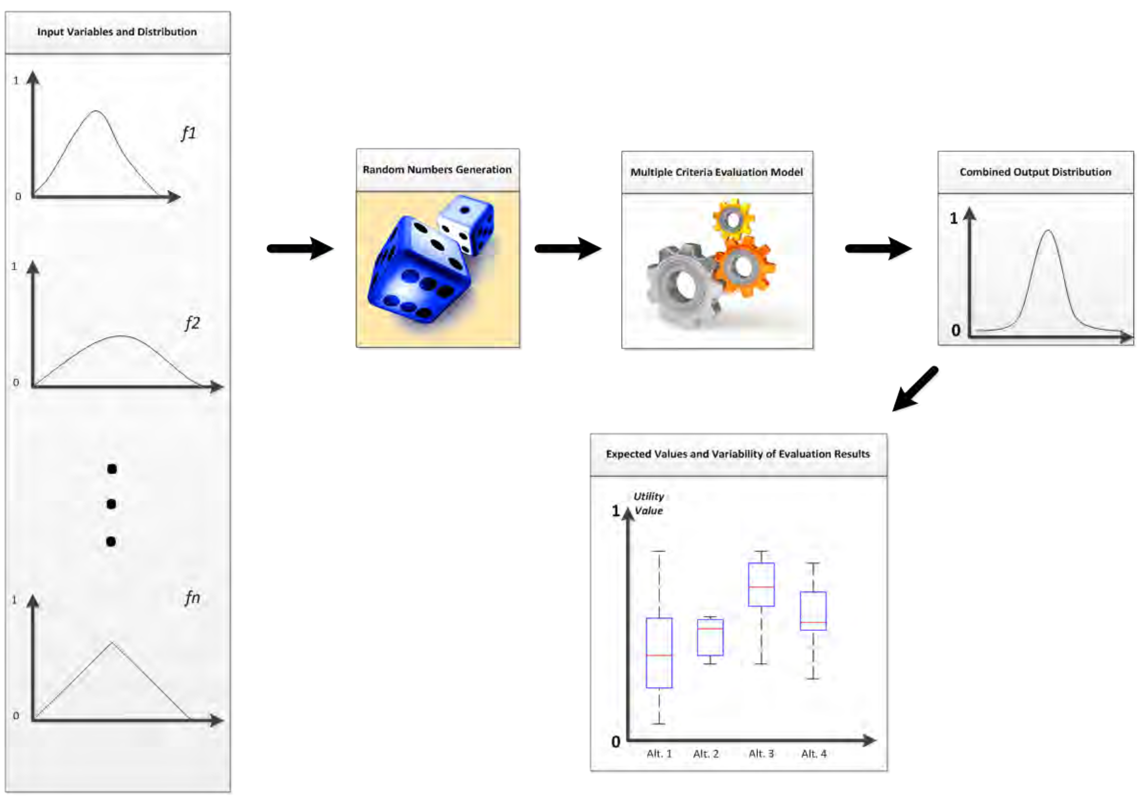


Figure 6.8 Diagram of Monte Carlo Simulation Process

The expected outcome corresponds to a given set of input variables and their variability. The distributions of the input variables need to be specified before conducting uncertainty analysis using MCS. Due to the difficulty in determining the proper probability density functions of inputs, some guidelines and approaches of selecting the appropriate distributions for an uncertain input variable were discussed in the Scaling stage. The final result of a Monte Carlo simulation is a probability distribution describing the range at output values. Because the utility functions are used to develop the combination model in MAFU process, the output would be presented as utility value confined in {0, 1}. The key factors for comparing alternatives include expected values, variability and overall range of outputs can be extracted from the simulation results (as shown in the example box plot of Figure 6.8).

Because uncertainty is considered in some performance indicators, the utility values for each attribute and the alternatives calculated using utility functions are randomly sampled in MCS process to generate the output distribution.

The sample mean and variance of a random sample of outputs can be used as estimators of the population mean and variance, which are the key factors in comparing and selecting alternatives. The law of large numbers dictates that the larger the size of the sample, the more likely it is that the sample mean and variance will be close to the population mean and variance [148]. Therefore, the sample mean and variance simply computed by using all the items in a sample of output utility values can be a good estimate of the population mean and variance if the sample size is adequate. The required sample size can be estimated by giving a confidence interval with a margin of error (*e*).

$$n = (\frac{Z_{\alpha/2}\sigma}{e})^2$$

Where $Z_{\alpha/2}$ is the standard normal deviate (Z score) for the *α/2* percentile point and *σ* is the standard deviation. Table 6.7 showes the examples of required sample size under various confidence level and variability condition:

Table 6.7 Required Sample Size for Various Confidence Levels and Variability

Std. Err	**Confidence Interval**	**90%**	**95%**	**99%**
	Margin of Error	***Sample Size****		
σ = 0.15	0.010	70	100	170
	0.005	275	385	665
	0.001	6,770	9,605	16,590
σ = 0.10	0.010	275	385	665
	0.005	1,085	1,540	2,655
	0.001	27,065	38,420	66,360
σ = 0.05	0.010	610	865	1,495
	0.005	2,440	3,460	5,975
	0.001	60,890	86,440	149,305

** Rounded up to the nearest five*

The number of simulations that should be run to reach convergence and desired accuracy is an important computational issue in applying MCS. Each utility value is one sample generated by one MCS simulation run, so the sample size is also the minimum required times of replicative calculation of MCS simulation. There are many formulas available to estimate the number of simulation runs by taking into account the standard deviation, number of input variables, confidence level and more. The results computed by using those formulas vary considerably. In general, the more runs, the more accurate the result is. As shown in Table 6.7, the number of required MCS runs is dependent on the desired level of confidence as well as the margin of error. It indicates that the number of runs increases geometrically with an increase in the level of confidence. A crude estimation summarized by Robert and Casella [149], and Raftery and Lewis [150] implies that the minimum size is about 15,000 for a precision of 99.5% and at least 250 iterations should be run to achieve a 95% precision. In practice, the sample size of MCS for different projects or research subjects varies considerably. For example, Bukowski et al. [151] used 5,000 repetitions to quantity risk assessment in an environmental application, Chen et al. [152] used 5,000 runs to assess the reliability of capacity of a road network, and Jerry Ji [40] tested various sample sizes ranging from 1,000 to 10,000 to assess the uncertainty level of intersection delay estimation and recommended that 5,000 runs be made for obtaining a converged result, if the uncertainty level of inputs is not well known.

R Project was used for the calculation of MCS for LTP and LCUP. The process is programmed using the built-in random generators for different probability distributions. It provided *"runif"* for Uniform distribution, *"rnorm"* for Normal distribution, *"rpois"* for Poisson distribution, *"rbeta"* for Beta distribution, *"rlnorm"* for Lognormal distribution and *"rexp"* for Exponential distribution. The MCS procedure conducted by R can also produce summary results of output values, diagram of box plot and best fitting distribution of outputs that can be used in the decision stage for alternative selection and project programming.

6.7 Decision Stage of MAFU

Stakeholder interests, decision maker preferences and risk attitudes can be combined to make a "best" choice among all alternatives. The "best" choice is rarely a desirable solution for achieving all the objectives and satisfying all the stakeholders and it can only be Pareto efficient. Therefore, the decision stage involves a tradeoff analysis based on the utility values and their statistical information.

The statistical information of output utility value is obtained by applying the MCS to generate a tradespace. The term "tradespace" comes from MIT's research on developing multi-attribute tradespace exploration in the aerospace domain [99] and is a combination of the words "trade-off" and "space", which is a graphical representation and database of supporting data and mathematical models of all possible solutions to an evaluation problem.

This section introduces the process of developing a tradespace and the potential application of several decision-making methods in selecting the best alternative. There is no specific method defined in the decision stage of MAFU to determine a best solution for a project, because every decision-making method has its strengths and drawbacks. A model which is effective and reasonable for one project may not be applicable for others due to evaluative complexity (i.e., multiple stakeholders exist for a system, each of whom hold different views of what are desirable and what are undesirable aspects of system performance). Analysts are suggested to cooperate with decision makers on choosing a suitable decision method.

6.7.1 Generic Foundation: Development of Tradespace

Tradespace is the tradeoff space is the solution space. The tradespace used in this research is presented as a box plot including the information of expected value, variance, and upper and lower boundary of value range, in order to explicitly describe the tradeoffs between every alternative.

Box plot is chosen to illustrate the tradespace, because it is a convenient way of graphically depicting groups of numerical data through their statistical summaries and it doesn't rely on data belonging to any particular distribution or assume any fixed structure of a model. It visually displays the differences between alternatives in final utility values without assuming the underlying statistical distribution of the output values and the spacing between the upper and lower borders of the box indicates the degree of dispersion and skewness in the output distribution.

The box plot used in developing the tradespace is not exactly identical to the traditional box plot. The traditional box plot depicts the descriptive and exploratory data summary of model outputs including the smallest observation, lower quartile (25^{th} percentile), median (50^{th} percentile), upper quartile (75^{th} percentile), and largest observation. A modified form of the box plot is used to depict the sample minimum, confidence interval with lower bound (or one standard deviation above the mean if confidence interval is not defined), sample mean, and confidence interval with upper bound (or one standard deviation below the mean), and sample maximum. The example shown in Figure 6.9 indicates the relation of the modified box plot to a probability density function of an output distribution of an alternative (confidence interval is not defined).

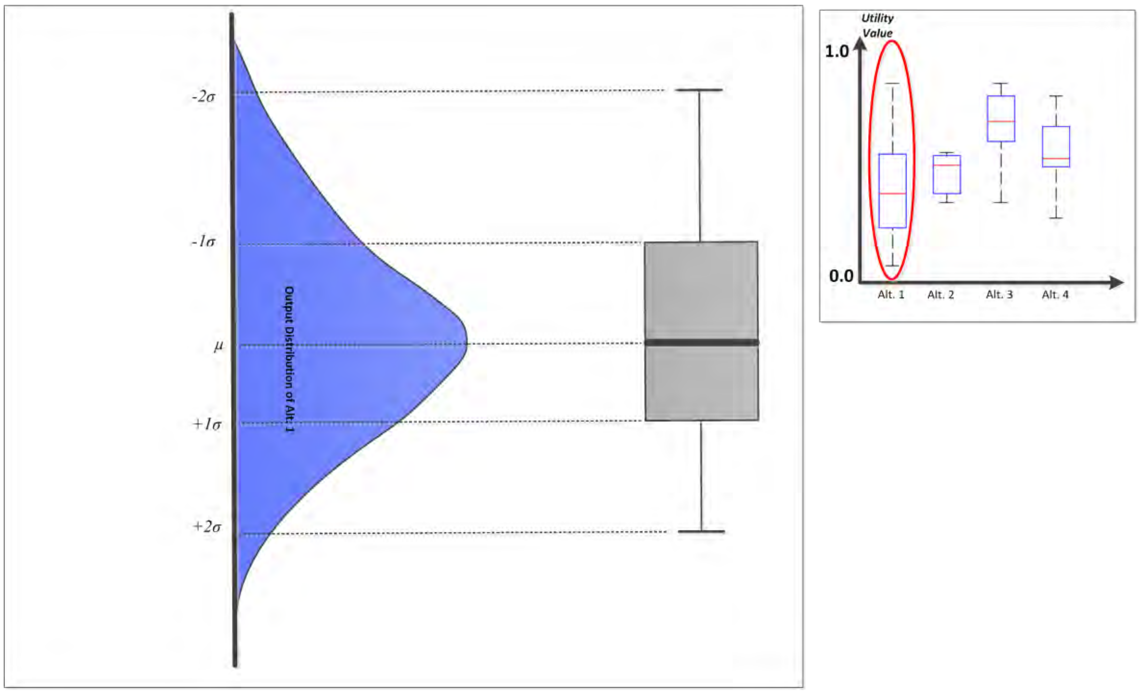


Figure 6.9 Relation of the Modified Box Plot to Output Probability Density Function

The generation of tradespace is essential in complex decision problems involving multiple conflicting objectives under uncertainty. It graphically identifies the tradeoff condition among all the alternatives. Perhaps, some of the alternatives can be eliminated from further consideration through observation of the tradeoff space because they possess maximum variability and minimum utility. Although it is not often possible, an alternative may also be selected without going through further decision-making analysis if the dominant alternative is better than all other alternatives in terms of expected utility and potential risk. The process of tradespace generation is described:

1. Identify the best-fitting distribution and compute distribution parameters for output utility generated by MCS.

Distribution fitting is the procedure of selecting a statistical distribution that can best describe the data set of output utility generated by MCS. The process was discussed in section 6.5.1, it can be done with many statistical software. It is important to know what particular distribution can be used to describe random output data. For example, the parameters of its best-fitting distribution can be used to estimate the confidence interval and a tornado graph can be developed based on the data distribution to determine the relationship of variance of each input variable to the output.

2. Identify the maximum and minimum of sample observation with or without outliers.

Identification of a sample is maximum and minimum is designed to understand the complete range of output utility. Sample maximum and minimum is the robust statistic and it provides analysts or decision makers the information about the possible extreme worst or best consequence of implementing the project alternative. Sample maximum and minimum are sensitive to outliers.

In statistics, an outlier is an observation that is numerically distant from the rest of the data [153]. Outliers can occur by chance in any random data set, but they are often indicative of measurement error or a heavy-tailed distribution population. A small number of outliers is to be expected in large samples and it usually has limited or no impacts on the entire distribution and only indicates faulty data, or erroneous procedures.

However, if extreme values can be real and are not obtained by measurement error or highly unusual conditions, then the outliers may be necessary to consider, because they may have significant impact on actual outcomes.

3. Identify sample mean and standard derivation

Sample mean is computed simply by averaging the entire collection of output utility values. Because of large sample size from thousands of simulation runs, the sample mean would greatly approximate the population mean (i.e, the expected utility value) as well as the standard derivation. The standard derivation is the measure of data variability and can be associated with risk of selection. A low standard deviation indicates that the data is distributed close to the mean (expected value), which implies a more reliable and lower risk consequence for the alternative to reach the expected value in reality.

4. Define confidence interval and compute a lower and upper limit for the mean

Confidence interval (CI) indicates the reliability of an estimate by estimating the assurance range at a given confidence level. It also describes the uncertainty surrounding an estimate and is a reminder of the limitations of the estimates. Confidence intervals used in the tradespace provide an effective way to represent how good or reliable the estimate of expected utility is. The confidence level which describes the uncertainty of a sampling method should be determined according to the evaluation target and available datasets. Although any percentage can be used as confidence level, but very low level may produce a meaningless interval covering the entire range of sampling data. A confidence level of 90% or 95% confidence levels is appropriate for statistical analysis of traffic phenomena that have large inherent variability (which, in turn makes I=99% unrealistic). In addition, if the confidence level is not defined or the computation of confidence level is costly or time-consuming in the evaluation process, mean +/- one standard derivation can be used to depict the high and low border of the box.

5. Draw box plot by using the values estimated in step 2, 3 and 4

The formation of one box plot for one alternative requires computation of five parameters: sample maximum and minimum, confidence intervals and mean, and the step 1 to 5 process for all the alternatives. Then the tradespace is generated by combining all the box plots into one diagram using an identical coordinate system.

6.7.2 Project Selection and Project Cost

In this section, several popular methods for project selection and programming are discussed based on the tradespace representing utility values and variability of all project alternatives. These methods generally assist in determining the best alternative.

The selection of best alternative is based on either 1) comparison between performance benefits, or 2) comparison between performance benefit and project cost. Performance benefits refer to the utility values generated by the MCS from multi-attribute utility model. The project cost includes initial costs, operation and maintenance costs and other direct or indirect costs for each proposed alternative.

Comparison between performance benefits may be suitable for some projects that are not associated with significant project cost or the costs of project alternatives are similar. In addition, for intersection improvement projects, since the economic feasibility of proposed intersection treatment has been examined in the second step of the entire analysis and evaluation method, all of the alternatives evaluated in the MAFU process are proved economically viable. If the decision makers intend to seek an intersection treatment with maximum performance benefits among all those economically feasible options, direct comparison of alternative performance benefits would be sufficient.

However, if the project cost of candidate alternatives varies significantly, the level of cost is suggested to be included. A quick method that can be used to normalize the project cost for conversion into a utility value is given below. All the costs used in Eq. 6.21 should consider the value of time and for conversion into net present value or equivalent uniform annual return.

$$C_x^u = \frac{C_{\max} - C_x}{C_{\max} - C_{\min}} \qquad (6.21)$$

Where

C_k^u is the normalized project cost of alternative *x*,

C_x is the project costs (monetized cost) for alternative *x,*

C_{max} (C_{min}) is the maximum (minimum) project cost value among all the alternatives.

It is important to note that if the uncertainties in project costs or discount rates are the concerns of decision makers in a project or the minimization of project cost is one of the primary project objectives, the project cost can be treated as one of the performance attributes (goal: the lower, the better) and then proceed to the weight, scale and combination stage. In this case, only the combined performance benefits of alternatives (overall utility values) need to be compared in the selection process. Table 6.8 summarizes the various forms in which project cost can be involved in determining the best alternatives.

Table 6.8 Conditions of Use of Project Cost

Conditions	Form of Project Cost
Project cost is low or not considerable and project alternatives are economically feasible	Comparison between performance benefits
Project alternatives are economically feasible, but project cost varies significantly among alternatives	Comparison between performance benefit and project cost (project cost is converted into utility value)
Minimizing project costs is one of the project objectives	Comparison between performance benefit (project cost is one of the performance attributes)
Estimation of project cost is associated with significant uncertainty	Comparison between performance benefit (project cost is one of the performance attributes)

Once the form of project cost is determined, the statistical information of the utility values summarized in the tradespace is used to compare and select the best option. The major outputs of each alternative are the expectation and variability of the alternative utility values. Two tradeoff analysis tools for selecting the "best" alternatives are introduced based on the available statistical information and the effectiveness of analysis.

1. Expected Utility Mode

If the decision maker seeks to select the best alternatives by simultaneously accounting for the uncertainty, then the expected utility value (also called sample mean) values is used. This expectation-based decision-making process was established on the basis of expected utility theory or the expected value criterion (also called the Bayesian principle) [154]. According to the expected utility hypothesis [155], a decision maker uses the expected value criterion as a rule of choice in the presence of risky outcomes, which means higher expected value investments are simply the preferred ones.

Use of expectation in making internal investment decision and profit management is very popular in financial models. This model assumes that the preferences of people with regard to uncertain and risky outcomes are represented by a function of expected payouts, the probabilities of occurrence and risk aversion. It is a simple and useful method under the condition of risk aversion. In this model, a decision maker could use the expected value criterion as a rule for selecting an alternative by direct maximization of expected utility. As shown in Eq. 6.22, alternative A is more preferred than or indifferent to B only if the expected utility of alternative A is larger or equal to expected utility of alternative B.

$$E_A^u \geq E_B^u \rightarrow A \succeq B \qquad (6.22)$$

In this model, the decision maker has well defined preferences and consistent decisions and can always decide between any two alternatives (e.g, if $A \succeq B$ and $B \succeq C$, then $A \succeq C$). In addition, if there are two alternatives mixing with another alternative, the combined alternative would maintain the same preference order as when the two are independently presented (e.g, if $A \succeq B$ and $t \in (0,1]$, $tA + (1-t)C \succeq tB + (1-t)C$).

Although this model doesn't consider the variability of expected utility and the potential risk of the expectation estimates, it does lead to realistic decisions and incorporates the probabilities of the states of nature.

2. Expected Utility-Variability Model

Mean and variance are a tradeoff in two-moment decision models or non expectation-based decision-making framework. In the process of making decisions, the decision maker considers both expected utility and the variance of utility, in this case, the alternative with the highest expected utility which also has a high variance may not be selected as the best.

This decision problem can be solved by simultaneously comparing expected value and variability associated with the expected value (can be represented by variance or confidence interval at a given confidence level). This model is designed to maximize the expected value but also minimize the associated variation. Assume the utility values for alternative *X* can be written as $U_x \in (x_L, x_{E,} x_H)$. x_L (or x_H) is the lower (or upper) boundary of the value ranges defined as lowest (or largest) value of confidence interval or one standard derivation. x_E is the expected utility value of alternative *X*. The coefficient of variation (*CV*) (i.e., a normalized measure of dispersion of the output utility distribution) is used to describe the variability and can be computed by Eq. 6.23:

$$CV_x = \frac{\sigma}{\mu} = \frac{x_H - x_L}{2x_E} \qquad (6.23)$$

In order to handle both expected utility and variance of utility, a simple method is to define the decision makers as either pessimists who seek the minimization of variance, or opportunists who seek expected value maximization.

More complex but objective method is to use distance metrics [156] for the selection process. Alternatives are ranked on the basis of the closeness of their expected values to the established thresholds or the estimated maximum expected values among alternatives and their coefficient of variation to the given goal or estimated minimum. The alternative selection is associated with the minimum value of the following distance-measuring goal programming function computed with:

$$D_x = \{(| x_E - E_{\max} |)^p + (| CV_x - CV_{\min} |)^p\}^{1/p} \qquad (6.24)$$

Where

D_x is the measure of deviation from the goals.

E_{max} is the maximal value of alternative utility. It can be the ideal/theoretical maximum *1* or the practical maximum among all alternatives.

CV_{min} is the minimal value of variation. It can be the ideal/theoretical maximum *0* or the practical minimum among all alternatives.

p is the parameter to determine the type of norm metrics used in the minimization of the goal programming function. There are three most commonly used metric norms parameter in the distance measuring function [107]:

p=1: also called city block distance is found to be more robust in statistical environments with less outliers.

p=2: also called Euclidean distance, is an isotropic metric. Distances are independent of objective orientation, subject to the limitation that the object boundary is digital. These are not easy to be calculated efficiently for complex shapes [157].

p=∞: also called min-max distance (or infinity norm), provides a way to consider the impact of the worst deviation.

These *p* values may lead to different dominant alternative.

Expected utility-variability model considered both expected utility and associated variation. The variability of expected utility is especially important and necessary to be included in the decision-making process if the distribution of input variable is assumed empirically or is not properly calibrated. In addition, if the risk-neutral or risk prone attitude is taken in the establishment of utility function, it is recommended to comprehensively use expected utility-variability model and the distance-measuring goal programming function.

6.7.3 Decision Stage for LTP and LCUP

Although the generic decision process suggests several methods in determining selection form and tradeoff analysis method, according to the project objectives, performance attributes and treatment characteristics of LTP and LCUP, the form of comparison of project costs and benefits should be used, because both treatments must be economically feasible in level 2 (feasibility and performance analysis), but the project cost associated with LTP and LCUP varies significantly.

In tradeoff analysis for LTP and LCIP, the expected utility model is too simple to be used. Expectation-based method only considers the expected utility of outcome and is only applicable under risk aversion conditions and/or if the probability distributions of input variables have been precisely defined and properly calibrated. However, several performance attributes (e.g., environment and accessibility) in LTP and LCUP evaluation were assigned risk neutral or risk-taking parameters. If the risk-neutral or risk prone attitude is taken in the establishment of attribute utility function, it is recommended to use expected utility-variability model and distance-measuring goal programming function. In the distance-measuring function, the statistical norm ($p=1$) is suggested to be used because it is a robust parameter in statistical environments of MAFU to measure the derivation between the goal and the proposed treatments. In addition, the programming functions with input of utility values (between 0 and 1) are relatively simple and easy to compute.

6.8 Variance Reduction and Optimization

Monte Carlo method in MAFU is used to capture the uncertainties in variables and generate the tradespace including expected values and variance associated with each project alternative. A main concern of using MCS to create a stochastic model is the efficiency of the simulation outputs, especially under the condition of multiple objectives and variables. Every output from the proposed method is associated with a variance which may limit the precision of the simulation results. If the uncertainty ranges associated with performance MOEs are widely distributed, the variance of the utility index assigned to each alternative may be so large that it covers the entire set of all possible values. In order to make a simulation statistically efficient and improve the precision of outputs, variance reduction techniques (VRT) are necessary to be used to obtain smaller confidence intervals for the outputs. It is important to note that, VRT is not always required when using the MAFU process. VRT may only be used if the accuracy of outputs are not satisfied or the decision among alternatives cannot be made due to extremely large variance (e.g., variance of an utility value covers all possible values in [0,1])

6.8.1 Cause of Variance in Output

The variance is a measure of precision of the estimator (i.e., the expected utility value), describing how far the set of possible values lie from the expected mean. In MCS, we estimate the mean of utility values associated with each project alternative by simulating the combination of all performance MOEs. Each uncertain performance MOE has its own variance, which can be accumulated and amplified in the MCS. According to the central limit theorem for constructing confidence interval, more replications (e.g., 10, 000) may provide a better estimator with lower variance. Although the number of iterations in a simulation can be as large as needed, the extended computation time and resource costs would be the main concerns. In addition, increase of replications cannot always be efficient in improving output accuracy. For example, some mathematical models have square root factors whose convergence is slow (e.g., derivatives pricing model in infrastructure financing), about one million sample paths are needed to obtain an accurate result [158].

Recall that the estimator "utility value" for each of the alternatives in MAFU is generated in the MCS framework combing uncertainty range or probability distribution in uncertain performance attributes. Given the uncertain performance attributes $X_1, X_2 \ldots X_n$, because the utility function used in MAFU combination stage collected each attribute has its own variance. Therefore the output variance can be written as [159]:

$$Var(X_1 + X_2 + \ldots\ldots + X_n) = Var\sum_{i=1}^{n} X_i = \sum_{i=1}^{n} \sum_{j=1}^{n} Cov(X_i, X_j) \tag{6.25}$$

As indicated in Eq. 6.25, if negative covariance among the variables X_1 $X_2 \ldots\ldots$ X_n can be induced, the generated output will have the same mean but smaller variance. The system-wide utility function is a multiplicative form because of correlations in performance attributes, thus random variables used in computing the utility index for each attribute should not be independently chosen and combined in MCS regardless of the correlation. Covariance is necessary to be addressed, because the random variables in different attributes may change together. For example, the greater values of vehicle delay in the traffic operation attribute may correspond with the higher density of air pollution in the environmental attribute. Absence of covariance deduction in estimating expected utility index produces a weak reliability of results. This issue can be mitigated by applying variance reduction techniques.

6.8.2 Variance Reduction Techniques

Variance reduction method is used to search alternative and unbiased estimator which have more accurate mean value under identical quantity of available samples or replications. The technology of variance reduction in MCS is designed to separate the simulation process from direct combination. There are many variance reduction techniques including antithetic variables, control variants, probability conditioning, stratified sampling and importance sampling [160]. All these methods involve generating alternative estimators by considering covariance in variables. MCS with variance reduction is able to simulate a more aggressive approach by identifying negative covariance and removing the unrealistic combination directly.

A method combining the techniques of stratified sampling and antithetic variables is used in MAFU to improve output accuracy. These two techniques are selected because they can be solved explicitly and are commonly used to improve MCS simulation for utility functions.

Stratified sampling method is applied at the combination stage where the system-wide utility function combining all the performance attributes is established. It is designed to remove the correlations between performance MOEs in different attributes. This techniques separates the attribute samples into each stratum and produces a more accurate sample mean with less variability. Suppose the total number of samples is equal to n and the population of samples are divided into m subgroups $n_1, n_2, \ldots, n_m$ and

$n_1+n_2+\ldots+n_m=n$. To simplify the sampling technology, assume that each group is equally separated and has n/m samples. So an unbiased alternative estimator (θ_n) is obtained by setting:

$$\theta_n = m*(\sum_{i=1}^{m}\theta_i) \quad (6.26)$$

Where θ_i is an estimate of the subgroup i using n/m samples.

The number of samples in subgroups will be used to estimate each θ_i and the total number of all the samples is equal to n. Therefore, the variance of alternative estimate can be obtained with:

$$Var(\theta_n) = m^2 * \sum_{i=1}^{m} Var(\theta_i) \quad (6.27)$$

On the other hand, the original raw simulation estimator $Var(\theta)$ can be estimated using the conditional variance formula:

$$Var(\theta) = E[Var(\theta|I)]+Var(E[\theta/I])$$

The right side of above equation is non-negative which implies that:

$$Var(\theta) \geq E\left[Var(\theta \mid I)\right] = m*\sum_{i=1}^{m} Var(\theta \mid I = n_i)$$

$$i.e., Var(\theta) \geq \frac{Var(\theta_n)}{m} \quad (6.28)$$

As a result, using an alternative estimate that leads to a variance reduction can be concluded. As shown in Eq. 6.28, the reduction will be substantial if it accounts for a large fraction (i.e., *m* is large).

In order to separate the population of samples in each attribute, the correlations among these attributes need to be qualitatively defined. As to the performance MOEs and attributes defined for LTP and LCUP, the traffic delay and emissions are positively correlated, and traffic volume and traffic safety may be negatively correlated. The number of strata depends on the needs in variance reduction. Usually two to three layers provide sufficient variance reduction. More layers provide more reduction in variance and accurate results, but they may also increase the simulation time. Compared with the antithetic variables method discussed below, the stratified sampling actually requires much less work.

Antithetic variables method is applied at the scale stage where the variances of uncertain performance MOEs are measured. Suppose the value of a performance MOE "*x*" is collected from a collection of random numbers $U_1, U_2, \ldots, U_m$ in a distribution function $f(x)$, say $x = f(U_1, U_2, \ldots, U_m)$, so the variance of *x* estimator can be written as $Var(x)$. In order to reduce the variance, x' can be another estimate based on random numbers $1 - U1, 1 - U2, \ldots, 1 - Um$, the value of x' is obtained from the same probability distribution, so $x' = f(1-U_1, 1-U_2, \ldots, 1-U_m)$. Both U and $1 - U$ are defined in the same distribution (in this example, they are uniformly distributed) and are clearly negatively correlated. Consider $\bar{x}$ is a new estimate of "*x*" and $\bar{x} = 1/2*(x + x')$. The variance of new estimate can be computed with:

$$Var(\bar{x}) = \frac{1}{4}[Var(x) + Var(x') + 2\rho\sqrt{Var(x)Var(x')}] \quad (6.29)$$

Where ρ denotes the correlation between *x* and *x'*.

Because both estimates have the identical sample number in simulation, $Var(x) = Var(x')$, therefore, the variance of new estimate can be simplified:

$$Var(\bar{x}) = \frac{1}{2}(Var(x))(1 + \rho) \quad (6.30)$$

x and *x'* will be negatively correlated, clearly, ρ is negative, a variance reduction associated with the performance MOE *x* can be achieved.

This method requires additional generation of estimators in MCS that significantly increases simulation time. Antithetic variables should only be used if variance reduction is needed and the stratified sampling method has proven insufficient in meeting the accuracy requirement. In addition, if necessary, every time, antithetic variables method should only be applied to these MOE which have the most adverse contributions to the output variance.

6.8.3 Variance Reduction Process in MAFU

Variance reduction techniques (VRT) in MAFU may cause additional computational requirements. The MAFU process should be first conducted without applying VRT to generate preliminary simulation results. If the majority of model inputs are certain variables or the uncertainties associated with model inputs are reasonably defined, the accuracy of model output will be most likely acceptable. If VRT has to be used, the key steps in conducting the VRT for refining MAFU are:

- Run MAFU without VRT and observe the variance in model outputs.
- If the variance needs to be reduced, apply stratified sampling method in the system-wide utility functions by re-running the combination stage of the MAFU model.
- If the output variance is satisfied, stop and use the results for decision-making. If not, generate a variance contribution matrix to determine variance contribution of the uncertain performance MOEs.
- Select the MOE which has the most contribution to the output variance and generate alternative sample variables using antithetic variables method (in the scale stage).
- Rerun the scale and combination stage in MAFU model with VRT, if the output variance is satisfied, stop and use the results for decision-making. If not, generate a new variance contribution matrix to identify variance contribution to the output variance calculated in step 5.
- Repeat steps 2, 3 and 4 until sufficient variance reduction is achieved.

6.9 Chapter Summary

This chapter described the process in Level 3-Evaluation and the evaluation module (MAFU) including generic foundations and specific applications in an intersection improvement project and evaluating treatments LTP and LCUP. Due to the multiplicity of project objectives, stakeholder perspectives and decision maker risk concerns in an intersection improvement project, the treatments that have been preliminarily analyzed in planning and screening level, and whose performance MOEs have been defined and measured in the feasibility and analysis level are comprehensively assessed in the evaluation level by using MAFU process. MAFU consists of four stages including initiation, weight, scale and decision. It leads to robust and reliable decision-making by taking account of stakeholder preferences on performance attributes, risk attitudes of decision makers, uncertainty in scaling performance MOEs and tradeoff analysis and selection using tradespace.

The MAFU process is a generic evaluation process that can be potentially applied to transportation projects or other areas. The process is capable of conducting tradeoff analysis in multiple scenarios and can help on structuring a rational, comprehensive and well-defined decision-making system for selecting the best alternative.

CHAPTER 7

CASE STUDY OF THE PROPOSED METHOD

7.1 Location Selection

A case study is conducted to demonstrate the application of LTP and LCUP at a congested urban arterial intersection. The prototype of study intersection is the intersection of Punchbowl Street and Vineyard Boulevard (P-V Intersection) in downtown Honolulu. The traffic volume, signal timing, safety factors and intersection geographic information are collected at the intersection, but some assumptions for the LTP rerouting network are made in order to demonstrate the application of the full method to LTP. The assumptions are detailed in Section 7.2.1.

Punchbowl Street is a 4-lane bidirectional north-south arterial with a northbound left turn lane (5-lane cross section) and no southbound left turn lane (4-lane cross section). Vineyard Boulevard is a 7-lane bidirectional west-east direction with a 1-lane left turn bay eastbound and a 2-lane left turn bay westbound.

Punchbowl Street is an urban corridor with an approximately north-south direction. The road section between the Vineyard Boulevard and Beretania Street has raised median. The northbound approach has one left-turn only lane, two through lanes and right turn channelization. The southbound approach has two through lanes and right turn channelization. Vineyard Boulevard is one of the urban principal arterials and it has a west-east direction and continuous raised median. The layout of P-V intersection is shown in Figure 7.1.

Figure 7.1 Google Map of Punchbowl St. and S. Vineyard Blvd. Intersection

This location is selected as a prototype for the case study because:

- This is an urban major intersection experiencing serious congestion during morning and afternoon peaks largely because both directions directly serve on- and off-ramps to the freeway.
- This intersection is located in a large urbanized area (only ½ mile from the city's civic center and ¾ miles from its business center) and it carries heavy traffic of vehicles and pedestrians.

- Surrounding high road density provides short and convenient rerouting paths for affected traffic.
- Various land use (e.g., residences, governmental buildings, an elementary school, businesses and a large hospital) generate moderately high pedestrian volumes.

The peak traffic volume and estimated AADT are summarized in Table 7.1. The westbound through and left-turn traffic is heavy and frequently congested during the morning peak hour due to the commuting flow to downstream highways. The eastbound through traffic is heavy during the return trips in the afternoon peak period. The proportion of heavy vehicles at the study intersection is not available; 6% for the AM peak and 8% for the PM peak were used. There were estimated from results of vehicle classification surveys in neighboring areas with similar land use characteristics (21).

Table 7.1 Summary of Traffic Volume at P-V Intersection

Morning Peak Hour				**Afternoon Peak Hour**			
NB	**526**	LT	30	**NB**	**1236**	LT	201
		TH	493			TH	1025
		RT	3			RT	9
SB	**1164**	LT	0	**SB**	**650**	LT	0
		TH	1093			TH	578
		RT	71			RT	72
EB	**1428**	LT	129	**EB**	**1839**	LT	316
		TH	816			TH	1300
		RT	483			RT	222
WB	**1559**	LT	643	**WB**	**970**	LT	322
		TH	902			TH	627
		RT	13			RT	21
Estimated AADT and %HV							
NB	**SB**	**EB**	**WB**	**Left-turn Movement**	**Average % Left-turn**	**% Heavy Vehicle AM peak**	**% Heavy Vehicle PM peak**
11383	14812	22897	14034	11363	18%	6%	8%

7.2 Planning Level Assessment

Both LTP and LCUP treatments for this intersection were investigated at the planning level. There are five deployment plans. As shown in Table 7.2, the deployment plans are LTP on eastbound only (LTP-E), LTP on westbound only (LTP-W), LTP on east and west approaches (LTP-EW), LCUP on east and west directions (LCUP-EW), LCUP on north and south approaches (LCUP-NS). All these deployment plans were subjected to level 1 planning and screening analysis with AM and PM peak traffic conditions.

Table 7.2 Deployment Plans of LTP and LCUP

Treatment	Deployment Plan	Location
LTP-E	Eastbound only	Along Vineyard Blvd.
LTP-W	Westbound only	Along Vineyard Blvd.
LTP-EW	Eastbound and Westbound	Along Vineyard Blvd.
LCUP-EW	Eastbound and Westbound	Along Vineyard Blvd.
LCUP-NS	Northbound and Southbound	Along Punchbowl St.

7.2.1 Deployment of LTP

LTP is proposed to be applied to Vineyard Blvd. only (eastbound and/or westbound). Removal of southbound and northbound left turns is not considered because there is relatively lower northbound left turning traffic from Punchbowl Street and the southbound left turn is not allowed. Therefore removal of left turn traffic doesn't contribute to the reduction of a signal phase and lost time, but instead it will aggravate the northbound through traffic congestion, especially during the afternoon peak.

As shown in Figure 7.2, a designated left turn detour route via a right turn loop at Miller Street is given for westbound left turn rerouting and the detour distance is about 0.22 miles. The alternative routes to divert left turn traffic for other deployment plans are not feasible because the nearest rerouting neighborhood at westbound downstream is blocked by the H-1 freeway, but they were assumed to exist as a means to try the method. For those reroutes, rerouting distance was estimated by using the average city block size in this area. The size is about 0.013 sq mi, so the rerouting distance is about 0.33 miles. Because most of surrounding corridors are stop controlled, the average speed of left-turn vehicles on a detour is assumed to be 20 mph.

As shown in the circular area with a radius 1,000 ft. In Figure 7.2, there are six bus stops, three schools and zero alcohol sale establishments within 1,000 ft. of this intersection. The intensity of pedestrian crossing is assessed to be “medium high”. The angle of the intersection is irregular and about 75 degrees. All of them are important inputs in the safety analysis.

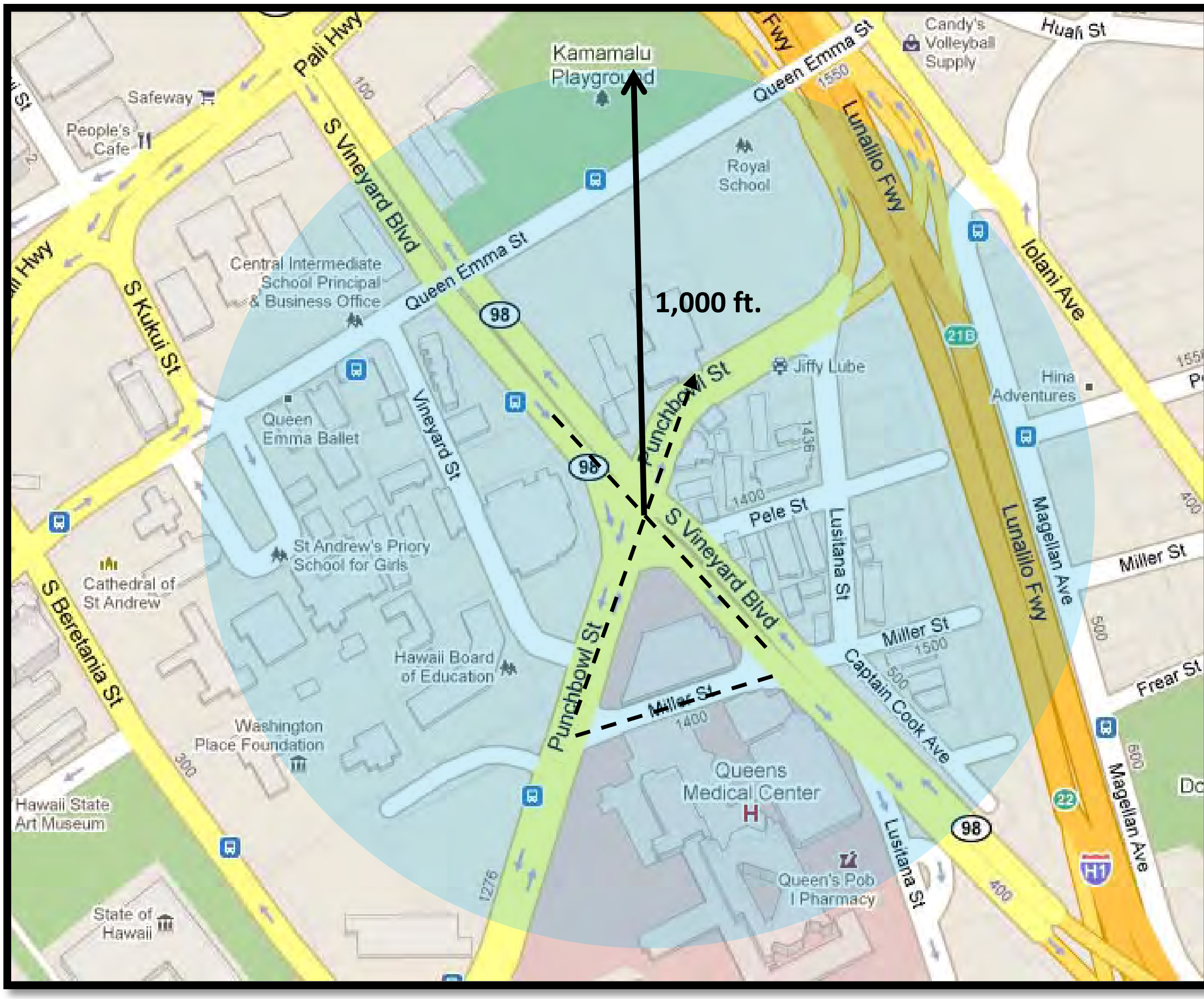


Figure 7.2 Intersection Layout and Eastbound Left-Turn Rerouting

Figure 7.3 shows the maximum rerouting distance versus average intersection delay. This figure is used to quickly check whether net benefits of travel-time savings for left-turn vehicles could be realized given an identical intersection level of service. The LOS for both eastbound and westbound left-turn is F (delay of 75 sec/veh) without treatments.

As shown in Figure 7.2, the rerouting distance is 0.22 mile for eastbound left turn via Miller Street after passing through the intersection. The rerouting roads are stop-controlled and the rerouting speed assumes to be 20 mph. Therefore, the implementation of LTP treatment could potentially produce net time savings benefits for the turning movements at this intersection.

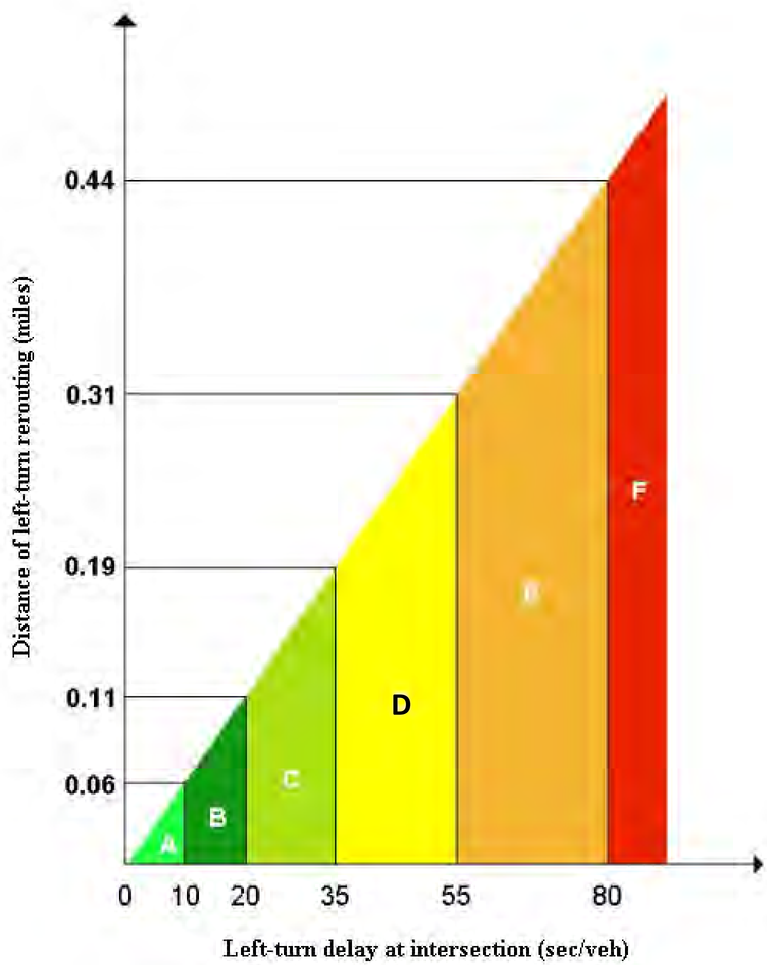


Figure 7.3 Maximum Distance of Left-Turn Rerouting Under Different Level of Service

7.2.2 Deployments of LCUP

Figure 7.4 displays a sketch representing the insertion of a one lane LCUP along the median of Vineyard Blvd. Since the deployment of underpass will occupy one at-grade lane, the lane configuration needs to be adjusted to ensure that departing and receiving lanes match and that the existing left turn lanes remain unchanged.

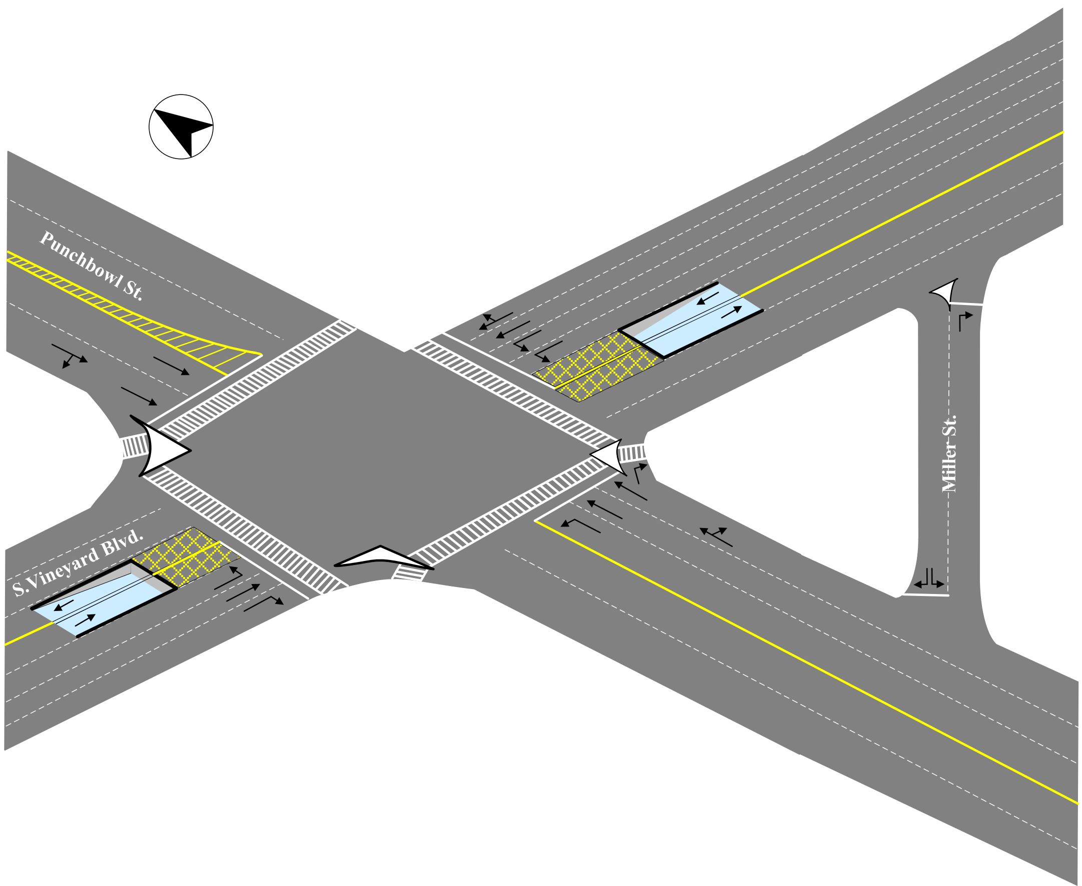


Figure 7.4 Prototype of LCUP Deployment on Vineyard Blvd.

7.2.3 Results of Planning Level Assessment

All the deployment plans of LTP and LCUP are examined in terms of operation and safety using the planning level analysis tool. In order to determine the best alternative and the best deployment plan, there are two study periods (AM and PM peak) for each deployment and an expansion factor of 2.0 is used to extrapolate a single peak hour benefits to daily benefits. The analysis results derived from spreadsheet-based planning assessment tool are summarized in Table 7. 3.

Table 7.3 Operation and Safety Analysis Results

Treatment	Intersection Only		Int. & Affected Traffic		Improvement (+)	
	AM	*PM*	*AM*	*PM*	*AM*	*PM*
Delay in Seconds per Vehicle						
Base	**73.5**	**78.3**	**73.5**	**78.3**	**-**	**-**
LTP-E	73.8	89.9	73.9	91.2	**-0.4**	**-12.9**
LTP-W	86.5	63.2	86.8	64.5	**-13.3**	**13.8**
LTP-EW	40.7	47.8	41.0	47.9	**32.5**	**30.4**
LCUP-EW	51.1	42.7	51.1	42.7	**22.4**	**35.6**
LCUP-NS	56.7	56.0	56.7	67.8	**16.8**	**10.5**
Total Annual Crash Frequency						
Base	**7.5**	**8.3**	**7.5**	**8.3**	**-**	**-**
LTP-E	3.3	3.7	3.9	5.0	**3.6**	**3.3**
LTP-W	3.7	4.2	3.8	4.4	**3.7**	**3.9**
LTP-EW	3.9	3.7	4.0	4.1	**3.5**	**4.2**
LCUP-EW	3.4	3.8	3.4	3.8	**4.1**	**4.5**
LCUP-NS	4.7	4.5	4.7	4.5	**2.8**	**3.8**

As indicated by the results, all the treatments could produce improvement on road safety. As to traffic operation, the eastbound LTP (LTP-E) slightly worsens AM delay because the already congested eastbound and northbound through movements cannot accommodate additional volume of traffic. This situation becomes critical in the PM peak analysis due to much heavier eastbound and northbound through traffic. A similar situation can be found for the westbound LTP (LTP-W). Although the rerouting distance is acceptable (about 40 to 60 seconds) and more green time is relocated to through movements, the through lanes are unable to accommodate the rerouted traffic without a substantial LOS degradation. In addition, the removal of left turn traffic at one approach does not contribute to the reduction of cycle length and the number of phases. LTP on both eastbound and westbound (LTP-EW) seems like a promising treatment for both AM and PM peak periods because the signal cycle length and phases are reduced by 2 phases down from 4 phases).

As shown in Table 7.3, if LCUP is deployed on the east and west approach, the average travel time saving is about 27 seconds per vehicle and the peak period LOS will improve to middle D from F. In addition, more than half of the crashes could be eliminated from this intersection. LCUP deployment on north and south approaches also produces benefits, but less than LCUP at east and west approaches due to lower traffic flow during peak periods.

The benefits of travel time and safety savings were monetized on an annual basis (250 workdays per year) and the results are shown in Table 7.4 below.

Table 7.4 Monetization of Travel Time and Safety Savings

Treatment	Savings in 2012 US Dollars			
	Travel Time Savings	Safety Saving	Total Savings	Further Analysis
LTP-E	-$185,992	$104,158	-$81,834	**No**
LTP-W	$6,992	$114,725	$121,717	**No**
LTP-EW	$293,205	$128,026	$421,232	Yes
LCUP-EW	$143,885	$563,250	$707,135	Yes
LCUP-NS	$67,725	$432,262	$499,987	Yes

The results reveal that the LTP treatment on eastbound would generate travel time losses of $185,992 per year, and accident savings of $104,154 per year for a net loss estimate of -$81,838. Although westbound LTP generates minimal positive savings because of PM travel time and accident savings, severe deterioration of AM traffic operational condition would not justify the deployment of westbound LTP. Therefore, the planning level analysis indicates that further analysis of the treatments LTP-E and LTP-W is unnecessary.

The planning, design and construction costs of the LTP and LCUP are used in the preliminary CBA to examine the cost benefits of selected treatments. According to existing research (17), the planning, design and construction costs with utility relocations and an automated height detection and alarm system for LCUP are approximately $5.8 million (converted $4.8 million from 2003$ to 2012$). This value adopted from existing research is used as the low cost estimation in this case study, plus $200,000 annual operation and maintenance costs and $20,000 annual miscellaneous costs. The middle cost estimation is assumed to be 20% more and the high cost estimation is 40% more than the low estimate. An annual discount rate of 3% recommended in UBA (5) is used in the cost-benefit analysis. Total after-treatment annual savings is the sum of total travel timesavings during AM and PM peak and the average of annual accident savings. The CBA is only conducted for LCUP treatments because the average costs associated with deploying LTP treatment are much less than the total savings generated by the treatment.

Table 7.5 Cost Benefit Analysis Results

Treatment	CBA Factors	Project Costs		
		Low	Middle	High
LCUP-EW	Year to Payoff	7.1	8.2	11.7
	B/C ratio	1.88	1.56	1.34
LCUP-NS	Year to Payoff	10.0	11.6	16.5
	B/C ratio	1.33	1.10	1.01

As indicated in Table 7.5, the number of years to payoff the LCUP ranges from 7 to 12 for LCUP-EW, and 10 to 17 years for LCUP-NS. Using the mid range of costs, the expected benefits for LCUP will outweigh the implementation costs in about 9 years for LCUP-EW and 12 years for LCUP-NS. The net benefits would be realized afterward. In addition, the 20 years B/C ratio provides a measure of cost-effectiveness over an extended period of time. In this case, the 20 year overall B/C ratios for both LCUP-EW and LCUP-NS are always larger than 1.0 under various scenario of project costs. Therefore, the planning level analysis clearly indicates that further analysis of these treatments is advisable.

7.3 Feasibility and Performance Analysis

Feasibility analysis is a site-specific study and the case study is not a real project in Hawaii, therefore detailed information regarding local and legal restrictions, such as project budget, construction scheduling, work zone areas are difficult to collect. However, through a general investigation of surrounding land use and road conditions along Punchbowl St. and Vineyard Blvd., LCUP deployment on north-west direction along Punchbowl St. is not a feasible solution because its narrow (4-lane) cross section cannot accommodate an underpass lane and massive construction on a road linking major urban freeway and downtown will have significant negative impacts on traffic and surrounding communities. Therefore, only the LTP and LCUP deployment plans at East-West direction are considered feasible and conducted in the performance analysis.

7.3.1 Simulation and Performance Analysis

Six scenarios of traffic simulation were programmed with AIMSUN, which are the AM and PM peak period simulations for base condition, improvement with LTP-EW, and improvement with LCUP-EW. For LTP, the eastbound and westbound left turn lanes are closed. The eastbound left turning vehicles make turning movements by passing through the intersection followed by two right turns on Miller Street for a rerouting distance of 0.22 miles. The westbound rerouting path is not designated, but all left turning traffic seeks the shortest routes to reach the southbound approach in order to complete an indirect turn left with an assumed city block length rerouting of 0.33 miles.

The influence area for LTP intersection users includes the intersection functional area and the rerouting roads consisting of road segments of Vineyard Blvd. and Punchbowl St. Because the eastbound of the subject intersection downstream connects to freeway on-ramp and the westbound downstream intersection is able to accommodate the upstream arriving traffic according to the downstream analysis conducted in planning level assessment, the LCUP influence area for intersection users will include only intersection functional area. As showed in gray area in Figure 7.5. Traffic operational performance within the area is analyzed.

Figure 7.5 Influence Area of LTP (left) and LCUP (right) at P-V Intersection

The intersection has multi-phrase signal controller. In performance analysis, the site-specific traffic signal timing before project, and the optimized signal timingafter project are used in traffic simulation and performance analysis. The signal timing is shown in Table 7.6, which indicates that the improved signal efficiency and reduced phases (shorter length of cycle) can be achieved by deploying LTP and LCUP. Note that compared with the signal timing before and after LTP, the northbound direction requires slightly longer green time to clear because the left-turn traffic is diverted to the southbound and northbound approach via rerouting routes.

Table 7.6 Signal Timings Before and After Implementation

Signal Timing Before (Sec)				Signal Timing After LTP (Sec)			Signal Timing After LCUP (Sec)		
Movement	**AM**	**Movement**	**PM**	**Movement**	**AM**	**PM**	**Movement**	**AM**	**PM**
NBT & SBT	50	NBT & SBT	65	NBT & SBT	55	68	NBT & SBT	34	30
EBL & WBL	30	EBL & WBL	11	WBT & WBL	45	34	EBL & WBL	20	12
WBT & WBL	16	EBT & EBL	14				EBT & WBT	16	18
EBT & WBT	60	EBT & WBT	30						
Cycle	156	**Cycle**	140	**Cycle**	90	75	**Cycle**	70	60
Y+AR	5	**Y+AR**	5	**Y+AR**	5	5	**Y+AR**	5	5

NBT: Northbound Through, SBT: Southbound Through, WBT: Westbound Through, EBT: Eastbound Through
WBL: Westbound Left-turn, EBL: Eastbound Left-turn
Northbound Left-turn is permitted, Southbound Left-turn is prohibited, Channelized right-turns

In this case study, due to unavailability of roadway and intersection information in surrounding road network, instead of using 0.25 mile circular area around the intersection, the influence area for intersection neighbors is only restricted within the intersection area. This assumption is just for demonstration purposes. In reality, the project should obtain information and conduct a network simulation to fully understand the impacts on the surrounding area.

Four performance attributes are defined in this case study including traffic operation, traffic safety, environment and energy. MOEs are defined to measure each of the attributes. Traffic delay defined for traffic operational attribute; PDO/injury accidents and fatal accidents defined for traffic safety attribute; NO_x emissions and greenhouse gas CO_2 defined for environmental attribute; and fuel consumption defined for energy attribute. Although the attributes of accessibility and land value are important in evaluating intersection treatment, they are not included in this case study because they are associated with site-specific conditions. Quantification of these attributes requires localized and historical data and the support from local agencies. In addition, accessibility and land value can only be evaluated if the regional road network simulation and city-wide trip distribution model are available. Street and intersection level noise are not selected as a MOE in environmental attribute because changes in street or local noise level is difficult to be modeled and a field survey was not feasible while conducting this study.

The performance analysis results are shown in Table 7.7. MOEs of each attributes are quantified for do nothing, LTP and LCUP. MOEs in Traffic operation, environment and energy attributes are quantified using AIMSUN simulation. Annual accident rates and fatal rates are estimated using accident prediction models in HSM and adjusted for urban signalized 4-leg intersection based on the statistical models developed by Midwest Research Institute for FHWA in 2000 [56].

Table 7.7 Performance Analysis Results of LTP and LCUP

Attributes	MOEs	Before Treatment		LTP			LCUP		
		AM	PM	AM	PM	Improve-ment*	AM	PM	Improve-ment*
Traffic Operation	*Traffic Delay (sec/veh)*	83.5	75.3	40.2	56.4	31,100	50.6	33.1	37,550
Traffic Safety	*PDO and Injury Accidents*	10.4		5.9		4.5	7.7		2.7
	Annual Fatal Accidents	1.3		0.4		0.9	0.6		0.7
Environment	*NOx Pollutant (kg)*	1.4	0.6	1.1	0.6	203.1	0.6	0.6	464.2
	Greenhouse Gas(kg)	983.7	917.6	790.6	792.5	159,100	404.7	420.6	538,000
Energy	*Fuel (gal)*	109.8	44.8	85.6	41.8	13,600	35.5	38.4	40,350

*Annual improvement. The AM and PM peak hour improvements are expanded to annual improvements by multiplying the daily expansion factor of 2.0 and yearly expansion factor of 250, except for traffic safety MOEs which are already on the basis of annual rate.

The results show that 8.6 vehicle-hours and 13,600 gallons gasoline could be saved after the deployment of LTP; 10.4 vehicle-hours and 40,350 gallons gasoline can be saved by deploying LCUP. Both treatments substantially reduce total and fatal accidents rates. Annually about 203 kilograms of NO_x would be reduced by applying LTP and 464 kilograms reduced by applying LCUP.

7.4 MAFU Evaluation and Selection

MAFU process involves assessment of stakeholder preferences and uncertainty in quantification of performance MOEs, in order to generate tradespace (i.e., combining all the above attributes in the decision-making process) for alternative selection and decision-making. Recall the stakeholders defined for LTP and LCUP are intersection user, neighbor and owner. The tasks of MAFU in this case study include weighing MOEs and performance attributes, defining uncertainty ranges of MOEs estimation, tradeoff analysis and alternative selection

7.4.1 MOEs and Performance Attribute Weighing

There are two MOEs in the attributes of traffic safety and environment. The Delphi method is suggested to weigh multiple MOEs in a performance attribute. However, an expert group does not really exist in this case study due to timing and budget constraints. Therefore, the weights assigned to the MOEs are found in recent research. Most states use the costs associated with accident severity as the weights to calculate the level of safety [161]. According to the accident costs in UBA (shown in Table 4.6), the normalized weights assigned to PDO/Injury accident rates and fatal accident rates are 0.03 and 0.97.

According to the EPA Environmental Fact Sheet 2012 [162], NO_x pollutant is one of the six EPA criteria air pollutants, which may adversely affect terrestrial and aquatic ecosystems through regional transport and deposition. CO_2 may not be considered as an air pollutant, but it is an environmental concern because of its global warming potential.

Therefore, a higher weight (0.8) is assigned to the NO_x pollutant and a lower weight (0.2) is assigned to the CO_2.

The FAHP technique is utilized to establish the weights for the performance attributes. The process of FAHP was introduced in Chapter 6. A small toolkit was also developed to automate the weighting process. As shown in Figure 7.6, the toolkit requests definition of stakeholders and performance attributes, triangular fuzzy numbers, and relative importance of performance attributes. This case study used the information obtained from Tables 6.2 and 6.3.

The results of FAHP weighting for performance attributes are shown in Figure 7.7. Traffic safety has the highest weighting score followed by the traffic operation attribute. Environment and energy attributes are secondary considerations of stakeholders and they are almost equally weighed.

Performance Attributes

Attribute 1	Traffic Operation
Attribute 2	Traffic Safety
Attribute 3	Environment
Attribute 4	Energy

Stakeholders

Stakeholder 1	Intersection User
Stakeholder 2	Intersection Neighbor
Stakeholder 3	Intersection Owner

Next

Stakeholders

Intersection User *weight (1~10)* 1

Importance Matrix - Linguistic

Attributes	Traffic Operation	Traffic Safety	Environment	Energy
Traffic Operation	**Equally**	Equally	Slightly+	Moderately+
Traffic Safety	Equally	**Equally**	Strongly+	Moderately+
Environment	Slightly-	Strongly-	**Equally**	Moderately+
Energy	Moderately-	Moderately-	Moderately-	**Equally**

Intersection Neighbor *weight (1~10)* 1

Importance Matrix - Linguistic

Attributes	Traffic Operation	Traffic Safety	Environment	Energy
Traffic Operation	**Equally**	Slightly-	Slightly+	Moderately+
Traffic Safety	Slightly+	**Equally**	Moderately+	Strongly+
Environment	Slightly-	Moderately-	**Equally**	Moderately-
Energy	Moderately-	Strongly-	Moderately+	**Equally**

Intersection Owner *weight (1~10)* 1

Importance Matrix - Linguistic

Attributes	Traffic Operation	Traffic Safety	Environment	Energy
Traffic Operation	**Equally**	Equally	Slightly+	Moderately+
Traffic Safety	Equally	**Equally**	Slightly+	Moderately+
Environment	Slightly-	Slightly-	**Equally**	Equally
Energy	Moderately-	Moderately-	Equally	**Equally**

Next

Figure 7.6 Definition of Performance Attributes and Stakeholders in FAHP Toolkit

Attribute	Weight
Traffic Operations	**0.351**
Traffic Safety	**0.582**
Environment	**0.037**
Energy	**0.034**
Total	**1.000**

Figure 7.7 FAHP Weighting Analysis Results

7.4.2 Uncertainty and Risk

The estimates of performance MOEs contain a certain amount of uncertainty. The uncertainty defined for each attribute is summarized in Table 7.8. Uncertainty in traffic operation and traffic safety is assumed to be a normal distribution with mean and standard derivation shown in Table 7.8 (μ, σ). The uncertainties in MOEs of the other two attributes are assumed to be uniformly distributed within a range of ± 20%. The uncertainty information in this case study is determined based on:

AIMSUN outputs traffic delay along with their standard derivation. The standard error as a common measure of reliability is available for all CMFs in HSM traffic accident prediction model. Environment and energy attributes involve continuous MOEs. For simplicity, it is assumed that they spread over a minimum (-20%) and maximum (+20%) range with a uniform distribution.

Table 7.8 Uncertainty Ranges in Performance Attributes

Attributes	MOEs	Before Treatment		LTP		LCUP	
		AM	PM	AM	PM	AM	PM
Traffic Operation	*Traffic Delay (sec/veh)*	(83.5, 7.3)	(75.3, 6.4)	(40.2, 5.5)	(56.4, 8.1)	(50.6, 7.6)	(33.1, 6.3)
Traffic Safety	*PDO and Injury Accidents*	(10.4, 0.1)		(5.9, 0.1)		(7.7, 0.1)	
	Annual Fatal Accidents	(1.3, 0.04)		(0.4, 0.04)		(0.6, 0.04)	
Environment	*NOx Pollutant (kg)*	(1.4 ± 20%)	(0.6 ± 20%)	(1.1 ± 20%)	(0.6 ± 20%)	(0.6 ± 20%)	(0.6 ± 20%)
	Greenhouse Gas(kg)	(983.7 ± 20%)	(917.6 ± 20%)	(790.6 ± 20%)	(792.5 ± 20%)	(404.7 ± 20%)	(420.6 ± 20%)
Energy	*Fuel (gal)*	(109.8 ± 20%)	(44.8± 20%)	(85.6 ± 20%)	(41.8 ± 20%)	(35.5 ± 20%)	(38.4 ± 20%)

The uncertainty ranges have to be normalized in order to establish the utility function. Utility functions are used to establish a common unit or scale of measurements cross a different performance attributes. Table 7.9 indicates the normalized uncertainty ranges given 95% confidence interval ($\mu \pm 2\sigma$).

Table 7.9 Normalized Uncertainty Ranges of Performance Attributes

Attributes	MOEs	Before Treatment		LTP		LCUP	
		AM	PM	AM	PM	AM	PM
Traffic Operation	*Traffic Delay (sec/veh)*	(0, 0.38)	(0.13, 0.46)	(0.6, 0.89)	(0.33, 0.75)	(0.42, 0.81)	(0.68, 1)
Traffic Safety	*PDO/Injury Accidents*	(0, 0.08)		(0.92, 1)		(0.55, 0.63)	
	Annual Fatal Accidents	(0, 0.15)		(0.85, 1)		(0.66, 0.81)	
Environment	*NOx Pollutant (kg)*	(0, 0.45)	(0.73, 0.94)	(0.31, 0.66)	(0.81, 0.99)	(0.82, 1)	(0.81, 0.99)
	Greenhouse Gas(kg)	(0, 0.46)	(0.09, 0.52)	(0.27, 0.64)	(0.27, 0.64)	(0.81, 1)	(0.79, 0.99)
Energy	*Fuel (gal)*	(0, 0.42)	(0.75, 0.93)	(0.28, 0.61)	(0.79, 0.95)	(0.86, 1)	(0.83, 0.98)

Risk parameters have been defined in Table 6.4 to capture the sensitivity to variance in quantification of MOEs in performance attributes. All the information regarding weights and risk parameters is summarized in Table 7.10.

Table 7.10 Summary of Weights and Risk Parameter Assignments

Attributes	MOEs	MOE Weights	Attribute Weight	Risk Parameter
Traffic Operation	*Traffic Delay (sec/veh)*	1.00	0.35	0.50
Traffic Safety	*PDO and Injury Accidents*	0.03	0.58	0.50
	Annual Fatal Accidents	0.97		
Environment	*NO_x Pollutant (kg)*	0.80	0.04	1.00
	Greenhouse Gas(kg)	0.20		
Energy	*Fuel (gal)*	1.00	0.03	1.00

Then, the utility functions for each attribute are established as follows:

$$U(X) = [\sum_{i=1}^{n} w_a w_b f(x_i)]^{\lambda}$$

Where

$f(x_i)$ is the uncertainty distribution of MOE x_i.

W_a is the weight score for MOE x_i (Table 7.10).

W_b is the weight score for AM and PM analysis period (equally weighted in this case study, $W_b = 1/2$).

λ is the risk parameter (Table 7.10).

The utility function of each attribute defined for alternatives “Do nothing”, “LTP”, “LCUP” can be written as follows, with *N(x)* as the function of normal distribution and *Z(x)* as the function of uniform distribution.

Do nothing

$$U(X_{oper}) = [0.50 \times \mathrm{N}(0, 0.38) + 0.50 \times \mathrm{N}(0.13, 0.46)]^{1/2}$$
$$U(X_{safe}) = [0.03 \times \mathrm{N}(0, 0.08) + 0.97 \times \mathrm{N}(0, 0.15)]^{1/2}$$
$$U(X_{envi}) = 0.80 \times [0.50 \times \mathrm{Z}(0, 0.45) + 0.50 \times \mathrm{Z}(0.73, 0.94)] + 0.20 \times [0.50 \times \mathrm{Z}(0, 0.46) + 0.50 \times \mathrm{Z}(0.09, 0.52)]$$
$$U(X_{ener}) = 0.50 \times \mathrm{Z}(0, 0.42) + 0.50 \times \mathrm{Z}(0.75, 0.93)$$

LTP

$$U(X_{oper}) = [0.50 \times \mathrm{N}(0.6, 0.89) + 0.50 \times \mathrm{N}(0.33, 0.75)]^{1/2}$$
$$U(X_{safe}) = [0.03 \times \mathrm{N}(0.92, 1) + 0.97 \times \mathrm{N}(0.85, 1)]^{1/2}$$
$$U(X_{envi}) = 0.80 \times [0.50 \times \mathrm{Z}(0.31, 0.66) + 0.50 \times \mathrm{Z}(0.81, 0.99)] + 0.20 \times [0.50 \times \mathrm{Z}(0.27, 0.64) + 0.50 \times \mathrm{Z}(0.27, 0.64)]$$
$$U(X_{ener}) = 0.50 \times \mathrm{Z}(0.28, 0.61) + 0.50 \times \mathrm{Z}(0.79, 0.95)$$

LCUP

$$U(X_{oper}) = [0.50 \times \mathrm{N}(0.42, 0.81) + 0.50 \times \mathrm{N}(0.68, 1)]^{1/2}$$
$$U(X_{safe}) = [0.03 \times \mathrm{N}(0.55, 0.63) + 0.97 \times \mathrm{N}(0.66, 0.81)]^{1/2}$$
$$U(X_{envi}) = 0.80 \times [0.50 \times \mathrm{Z}(0.82, 1) + 0.50 \times \mathrm{Z}(0.81, 0.99)] + 0.20 \times [0.50 \times \mathrm{Z}(0.81, 1) + 0.50 \times \mathrm{Z}(0.79, 0.99)]$$
$$U(X_{ener}) = 0.50 \times \mathrm{Z}(0.86, 1) + 0.50 \times \mathrm{Z}(0.83, 0.98)$$

The single attribute utility functions have to be combined to develop a system-wide multiple attribute function. In this case study, the multiattribute function is developed using additive form and written as follows:

$$U(X)=[\sum_{i=1}^{4}k_iU_i(X_i)]*U_{adj}=[0.35U(X_{oper})+0.58U(X_{safe})+0.04U(X_{envi})+0.03U(X_{ener})]*U_{adj}$$

Where k_i is the attribute weight obtained by using FAHP.

U_{adj} in the multiattribute function is an adjustment factor to reflect the ability of a treatment to accommodate future traffic growth. An appropriate and long-range alternative should be chosen to facilitate future growth. The traffic growth rate of Honolulu downtown area is about 1.2% per year based on archived traffic data of Hawaii DOT. This case study examines the ability of treatment to accommodate 10-year traffic growth. The adjustment index is calculated using the increased volume from applying treatment divided by the increased traffic in 10 years. The normalized uncertainty range of the adjustment index is (0.00, 0.10) for do nothing, which means the current intersection condition cannot or can only accommodate a very small portion of the future traffic growth. The range is (0.12, 0.20) for LTP, and (0.93, 1.00) for LCUP. Higher ability is given a higher utility index.

7.4.3 Project Cost Index

Project cost index is an optional adjustment factor used in the establishment of a system-wide utility function. Section 6.7.2 and Table 6.8 have detailed the condition of applying the project cost index. In this case study, although project alternatives have been assumed to be economically feasible, the project cost varies significantly among alternatives, therefore project costs are converted into a utility value and integrated into the utility function. The project cost of do-nothing is $0 so its utility value is 1.00. The project cost ranges (low, middle and high) for LTP and LCUP have been given in the planning level analysis. The uncertainty of project costs is assumed to be a normal distribution with mean that of the medium costs. The risk parameter of ½ is assigned to project cost utility function, because cost is always a risk-sensitive factor in most transportation projects. The normalized uncertainty range of cost is (0.68, 0.85) for LTP, and (0, 0.54) for LCUP. Lower cost is given a higher utility index.

Therefore the system-wide utility function after applying project cost index can be written as:

$$U(X)_{\cos t} = U(X) * \mathrm{N}(x_{\mathrm{cost}})$$

Where $\mathrm{N}(x_i)$ is a normal distribution utility function of project cost index.

7.4.4 MCS and Tradeoff Analysis

System-wide utility functions are programmed into *R Project* to conduct MCS (R code is attached in Appendix A). This case study uses 10,000 replications and the results are shown in Table 7.11. The expected utility and standard derivation are estimated for each alternative in four analysis scenarios with and without risk parameters, and with and without costs. The results indicate that LCUP has the highest expected utility values and highest standard derivation, and "do-nothing" has the lowest expected utility values and lowest standard derivation. The results are reasonable, because no action is able to control uncertainty, but is unable to obtain any benefits.

The involvement of risk parameters does not change the order of ranking based on expected value or variance, but it causes a decrease in the variance of estimate, because the purpose of using risk parameters have reflected the sensitivity to marginal loss in the benefits associated with performance attribute.

After applying project cost index, the expected utility values of LCUP significantly reduce and the variance of estimate increases. Although the expected benefits of LCUP decrease because of its higher cost, it still has the highest expected utility value compared with other treatments (also has the highest variance).

Table 7.11 Expected Utility Index and Standard Derivation of Alternatives

Analysis Scenario	Do Nothing		LTP		LCUP	
	Expected Utility	Standard Derivation	Expected Utility	Standard Derivation	Expected Utility	Standard Derivation
Without Risk Parameter and Cost Index	0.017	**0.011**	0.141	0.105	**0.825**	0.264
With Risk Parameter and w/o Cost Index	0.008	**0.005**	0.129	0.019	**0.712**	0.037
W/o Risk Parameter and With Cost Index	0.008	**0.005**	0.098	0.016	**0.187**	0.030
With Risk Parameter and Cost Index	0.002	**0.001**	0.026	0.004	**0.051**	0.007

The results are combined into an identical coordinate system and used to develop the tradespace within 95% confidence interval. The boxplot of each alternative is shown in Figure 7.8.

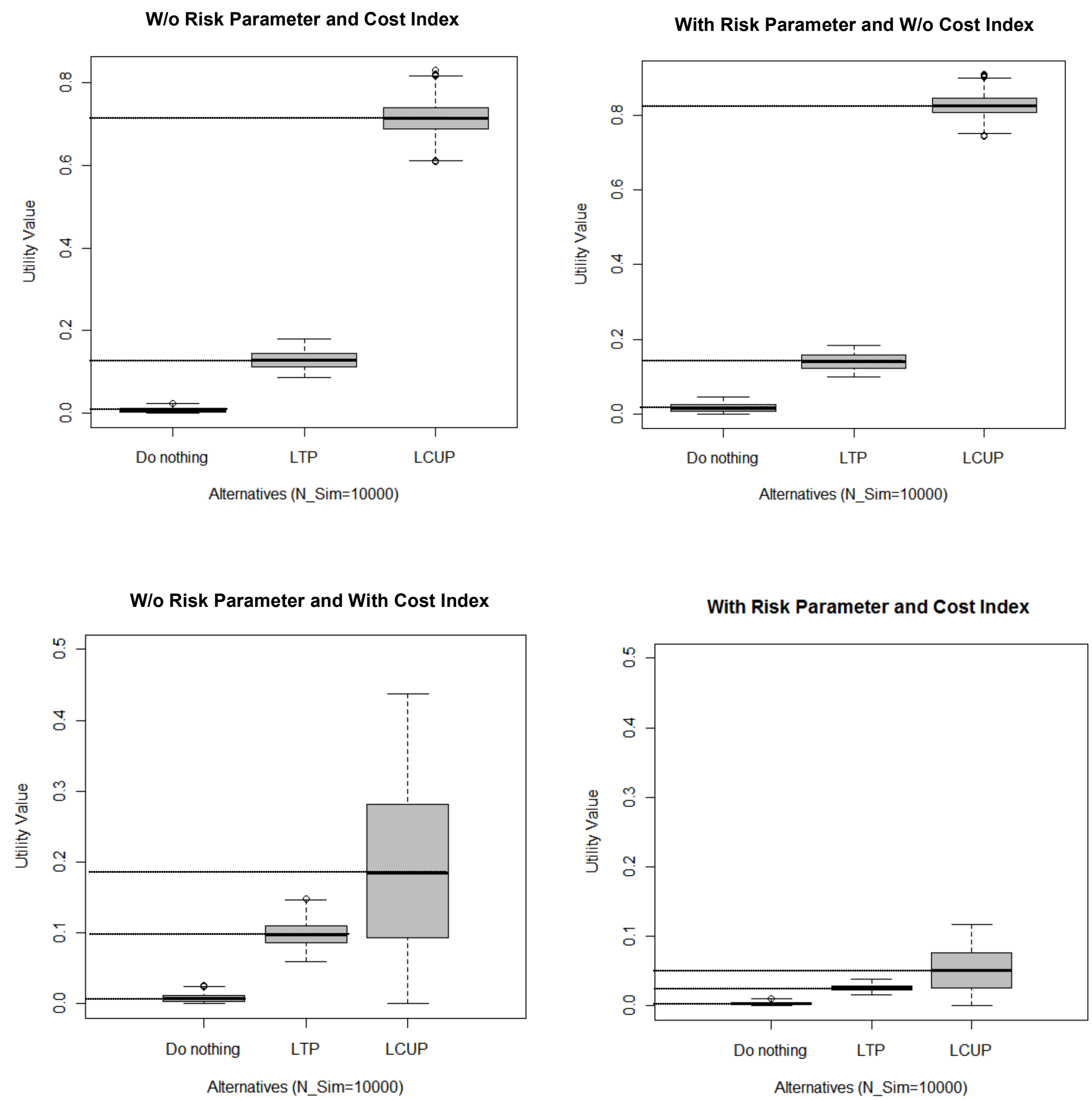


Figure 7.8 Tradespace of Combinations of Risk Parameter and Adjustments

7.4.5 Project Evaluation and Decision-making

If the decision maker seeks to select the best alternatives by using expected utility model, the expected index will be used as the only rule of choice in the presence of risky outcomes. In this case, as shown in the tradespace, the LCUP with higher expected index in any analysis scenario is the preferred one.

If the decision maker considers both expected utility and the variance of utility, then the mean and variance of the three alternatives are a tradeoff. Both the distance metrics (*Dx*) and the coefficient of variation (*CVx*) are measured and summarized in Table 7.12. Lower value of *Dx* and *CVx* are more desirable. *Dx* measures the derivation between the outputs (expected utility and variance) and the ideal condition (expected utility =1 and variance =0). *CVx* shows the extent of variability in relation to sample mean (i.e., expected utility).

Table 7.12 Analysis of Distance Metrics and Coefficient of Variation

Analysis Scenario	*Dx*			*CVx*		
	Do Nothing	LTP	LCUP	Do Nothing	LTP	LCUP
Without Risk Parameter/Without Project Cost Adjustment	0.994	0.964	**0.439**	0.647	0.745	**0.320**
With Risk Parameter/Without Project Cost Adjustment	0.997	0.890	**0.325**	0.625	0.147	**0.052**
Without Risk Parameter/With Project Cost Adjustment	0.997	0.918	**0.843**	0.625	0.163	**0.160**
With Risk Parameter/With Project Cost Adjustment	0.999	0.978	**0.956**	0.500	0.154	**0.137**

As shown in Table 7.12, LCUP has the relatively lowest *Dx* and *CVx* value among the four analysis scenarios. LTP also is a competitive candidate treatment if an project cost utility is included. LCUP is selected as the best solution by this case study.

It is important to note that this case study is developed for demonstration purposes only. Due to lack of information about road network and accessibility, study area is restricted to the intersection area and rerouting routes, so the benefits generated by LTP are overestimated, because potential negative impacts of rerouting traffic on local streets and loss of business accessibility are not considered in this case study.

A limited number of attributes were defined in this case study and the uncertainties associated with selected MOEs were reasonably defined, therefore, the reliability of model outputs is acceptable and no variance reduction process is necessary.

7.5 Scenario Analysis of Case Study

In order to examine the robustness of MAFU process, a scenario analysis was conducted to investigate the change in outputs corresponding to various scenarios of decision-making. It also demonstrates the sensitivity of MAFU process to stakeholder involvement. As summarized in Table 7.13, the analyzed scenarios include decision-making based on 1) planning level analysis without involvement of any stakeholders; 2) intersection owner objectives only; 3) intersection user objectives only; 4) intersection owner and user objectives; 5) intersection neighbor objectives or legal requirements only; 6) trade-offs in objectives by applying fuzzified weights. Cost index and risk parameters are considered in all the six scenarios. The weights are adjusted based on these scenarios of objectives. The weights on the table are logical but arbitrary values in order to demonstrate the ability of the method to be customized according to designed objectives and priorities.

Table 7.13 Summary of Decision-making Scenarios

Number	Analysis Scenario	Weights				Sum
		Safety	Operation	Environment	Energy	
1	Planning Level Only	N/A	N/A	N/A	N/A	N/A
2	Intersection Owner Objectives Only	0.75	0.25	0.00	0.00	1.00
3	Intersection User Objectives Only	0.00	1.00	0.00	0.00	1.00
4	Intersection User and Owner Objectives	0.50	0.50	0.00	0.00	1.00
5	Intersection Neighbor Objectives Only	0.00	0.00	0.50	0.50	1.00
6	Trade-off Objectives using FAHP	0.35	0.58	0.04	0.03	1.00

Scenario 1: As shown in Figure 3.2, the decision on best project alternative can be made based on the results of planning level analysis. Realistically, reliable decision-making for transportation projects implemented in urbanized area cannot be made with planning analysis alone because system-wide impacts and multiple stakeholders are neglected, the scenario may be possible for the project development in its early stage or in suburban area. Energy and environment attribute are not applicable in planning level status. MAFU is not conducted in this scenario, so there is no weight assigned to safety and operation attributes. A tradespace is generated for this scenario in order to be comparable with other scenarios. The MOEs for operation and safety are calculated by static HCM and HSM models and the values of MOEs are monetized for CBA. Therefore, instead of defining uncertainty from quantification of MOEs, the uncertainty defined in this scenario is derived from the variations (assumed to be uniformly distributed within a range of ± 20%) in interest rates (6.0%) and traffic growth rates (1.2% per year).

Scenario 2 considers only the main objectives of the intersection owner: safety and operation. Safety and operational improvement are usually the primary objectives of most intersection improvement projects. In this scenario, the weight assigned to safety (0.75) is three times higher than operation (0.25), reflecting the stronger liability of intersection owner and their commitment to traffic safety.

Scenario 3 considers only intersection user objectives. As shown in Table 5.2, intersection users are concerned with traffic delay and stoppages.

Scenario 4 represents intersection owner and user objectives, they share similar primary interests associated with an intersection improvement project. This scenario assumed equal importance on safety and operation by combing the objectives of these two stakeholders. Environment and energy attributes are neglected in this scenario.

Scenario 5 considers only intersection neighbor objectives and legal requirements (e.g, mandates) of minimizing energy consumption and environment impacts. As shown in Table 7.13, equal weighting score is assigned to the energy and environment attributes.

Scenario 6 considers the trade-offs between all the stakeholders in four performance attributes. Complete MAFU process is conducted for this scenarios including weighting stage using FAHP. The weights applied in this scenario are summarized in Figure 7.7.

The scenario analysis was coded in *R project* (Appendix B) and the tradespace for each scenario is shown in Figure 7.9. The statistical results including expected utility values and standard derivation for three alternatives are summarized in Table 7.14.

Table 7.14 Results of Scenario Analysis

No.	Analysis Scenario	Do Nothing		LTP		LCUP	
		Expected Utility	St. Dev.	Expected Utility	St. Dev.	Expected Utility	St. Dev.
1	Planning Level Only	0.051	0.028	0.199	0.017	**0.344**	0.043
2	Intersection Owner Objectives Only	0.002	0.001	0.026	0.004	**0.046**	0.027
3	Intersection User Objectives Only	0.006	0.004	0.019	0.004	**0.046**	0.028
4	Intersection User and Owner Objectives	0.003	0.002	0.019	0.004	**0.046**	0.027
5	Intersection Neighbor Objectives Only	0.012	0.007	0.040	0.007	**0.117**	0.068
6	Trade-off Objectives using FAHP	0.002	0.001	0.026	0.004	**0.051**	0.007

As shown in Figure 7.9 and Table 7.14, the maximum variance of expected utility is produced in scenario 1. Without considering stakeholder preference, the uncertainty in interest rate and traffic growth rate is unrestricted and accumulated in scenario 1.

Simple analysis results in more uncertainty. The variance of expected utility value is substantially reduced in other scenarios when stakeholder preferences are involved in MAFU process. Large variance can also be found in scenario 5, which only considered the energy and environmental attributes. The fuel consumption and vehicle emissions are estimated using a simplified linear model from the AIMSUN simulation model due to the weaknesses of current methods. The unrefined models of energy and environment analysis generate a relatively high uncertainty. Scenario 6 has the most reliable outputs and smaller variance for each alternative. It involves a complete MAFU process considering the trade-offs among stakeholder preferences on every performance attribute using fuzzy AHP.

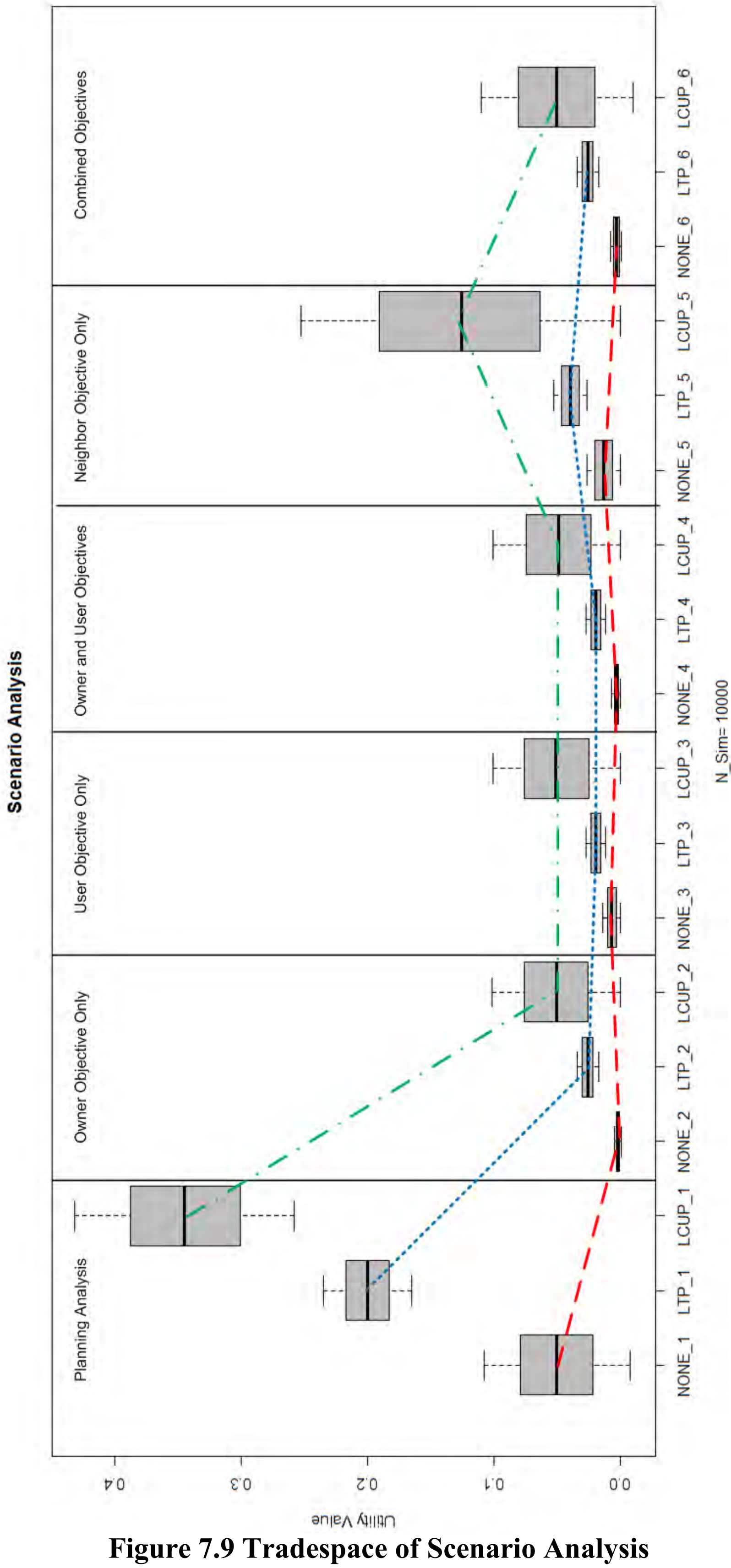


Figure 7.9 Tradespace of Scenario Analysis

Decision should be made based on expected utility and variance. For demonstration purpose, the coefficient of variation is used for final decision-making in this analysis, which shows the extent of variability in relation to the expected utility. As summarized in Table 7.15, if the decision maker seeks to select the best alternative using only the results of planning level assessment or partially considering stakeholder preferences, then the LTP which has the lowest coefficient of variance is the preferred choice. The LCUP is the chosen alternative using the comprehensive analysis.

Table 7.15 Summary of the Coefficient of Variance

No.	Analysis Scenario	*CVx*		
		Do Nothing	LTP	LCUP
1	**Planning Level Only**	0.549	0.085	0.125
2	**Intersection Owner Objective Only**	0.500	0.154	0.587
3	**Intersection User Objective Only**	0.667	0.211	0.609
4	**Intersection User and Owner Objectives**	0.667	0.211	0.587
5	**Intersection Neighbor Objective Only**	0.583	0.175	0.581
6	**Trade-off Objectives using FAHP**	0.500	0.154	0.137

The results are somewhat mixed when only do nothing and the expensive LCUP are considered. Scenarios 3, 4 and 6 recommend that the decision maker should choose the LCUP. Scenario 3 recommends Do Nothing, and Scenario 5 output is inconclusive because it yields practically identical CV.

7.6 Chapter Summary

In order to demonstrate the comprehensive methodology for intersection treatment planning, analysis, evaluation and decision-making, a case study was conducted to analyze and evaluate LTP and LCUP treatment using the data and information collected from a major urban intersection in Honolulu, Hawaii. This case study proposed five deployment plans of LTP and LCUP. Three of them (LTP-EW, LCUP-EW, LCUP-NS) were identified as promising by the planning and screening process using the spreadsheet-based planning analysis tool.

Detailed peak-hour performance analysis of Do nothing, LTP-EW and LCUP-EW alternatives was conducted using traffic simulations and other advanced traffic models. Evaluation, cross comparisons and selection of the alternatives were conducted with MAFU process. The expected utility and variance associated with each alternative were estimated for decision-making using four analysis scenarios. The findings demonstrate that the proposed method provided reliable results. It can be used by traffic engineers and decision makers for intersection improvement project evaluation and decision-making.

HAPTER 8

CONCLUSION

8.1 Summary and Findings

This research arose from the challenges in decision-making of transportation improvement projects at major intersections. Some of intersection treatments have substantial impacts on surrounding intersections and community, especially for a complex intersection in an urbanized area. The impacts may also refer to multiple stakeholders with conflicting interests. There are substantial difficulties in making robust decisions in selecting the best alternative, including how to make use of all available information, how to manage conflicting interests, and how to present performance targets and trade-offs.

Currently, a definition of complete set of stakeholders in intersection improvement projects is absent. The set may include motorists, pedestrians, bicyclists, adjacent businesses, residents and other land use (church, hospital, school, government building, etc.), and responsible agencies. There is unavailability of comprehensive method of operation, safety, economic, stakeholder objective analysis. A technique to integrate the traffic performance, impacts, objectives, stakeholders and uncertainty into multi-attribute decision-making tool does not exist. This research has developed a systematic and holistic method to address this deficiency. The method consists of three levels: Level 1-planning and screening, Level 2-feasibility and performance analysis, and Level 3-multiattribute evaluation under fuzziness and uncertainty (MAFU). The study presents and demonstrates the methodology using the left-turn prohibition (LTP) and partial grade separation (1 or 2 lane low clearance underpass, i.e., LCUP) treatments. The method itself is generic and can be extended to other intersection treatments (e.g., adding lane with expansion or with lane width reduction).

The planning and screening process is used to conduct preliminary operational, safety and economic screening analysis to identify promising treatments. The level provides a simple but practical planning procedure to analyze direct benefits from delay and safety risk reduction on urban signalized intersections by combining three key manuals in traffic and transportation engineering, including HCM 2010, HSM 2010 and AASHTO's UBA. The advantages, disadvantages and tradeoffs of alternatives regarding traffic operation and safety are assessed based on the fundamental methodologies and parameter values defined in the three manuals. A preliminary cost-benefit analysis is proposed to understand the cost-effectiveness of treatments and weigh potential net benefits over a long range 20-year planning horizon. Through the planning and screening process, one or more feasible solutions that take into account safety, operational and project costs would be recommended. From that, the analyst would be able to determine the most promising treatments or locations to proceed with detailed analysis and simulation. A spreadsheet-based model was developed in this research as a quick planning analysis tool. It is designed to provide a computerized procedure to automate the process. The planning level does not include a built-in uncertainty analysis and the planning level analysis can be used to examine the potential feasibility of mitigation actions prior to conducting extended data collection and detailed analysis.

The feasibility analysis concentrated on the construction impacts and local limitations including the applicable legal requirements and roadway conditions. This is used to justify the alternatives given site-specific conditions prior to initiating the labor-intensive detailed performance analysis. Feasibility of alternatives in terms of construction, economic, and local and legal restriction is examined and a set of feasibility indicators reflecting local conditions is defined. For example, the availability of rerouting roads and potential legal restrictions on accessibility removal, and the construction impacts including construction noise, delay of lane closure, temporary accessibility blockage, and project budgets. The feasibility analysis is structured to facilitate the assessment of the viability of treatments in different locations by using a feasibility checklist. The checklist is appropriate for the application of LTP and LCUP at urban signalized intersections, but it can be potentially applicable to other intersection treatments. Traffic analysts who are considering implementing treatment feasibility analysis can use it to select analysis subjects and criteria, to help on developing the study scope, and to review the results of a complete feasibility study.

The performance analysis is an extension of planning level analysis involving the estimation of traffic operations and safety performance at the subject intersection and on the surrounding road network. In the detailed traffic analysis and impact assessment, the study intersection is treated as a non-isolated intersection in a road network. Therefore, vehicular flow has to be modeled individually and their movements are studied based on car following and gap acceptance theory by using advanced traffic modeling or simulation tools. This analysis also measures other impacts such as vehicle emissions, energy consumption, accessibility, land valuation, and visual impacts by using their corresponding models and tools. The performance indicators (i.e., MOEs) used to evaluate intersection treatment and some of the common techniques or tools used to quantify these measures are defined in this level. Identification and quantification of performance indicators for multiple attribute evaluation are the primary purpose of the detailed analysis. The results are directly used in the MAFU model for alternative evaluation and selection.

MAFU is a detailed and disaggregated multiattribute optimization model. MAFU is able to assess the magnitudes of intersection treatment performance and to integrate conflicting interests and tradeoffs among stakeholders when selecting the best treatments. This method incorporated complex tradeoffs and uncertainty analysis, but resulted in relatively simple and visual selection scenarios within specific risk and variance categories. MAFU features fuzzy mathematics (FAHP) to capture the stakeholder preferences, utility function theory (MAUT) to combine performance measures and describe risk sensitivity, and probabilistic approach (MCS) to model output uncertainties and conduct the tradeoff analysis. MAFU process has five stages: initiation, weight, scale, combination and decision. During the initiation stage of the MAFU process, candidate treatments, project objectives and stakeholders are identified. These have typically been done in the performance analysis. The identification of different performance attributes and the quantification of corresponding MOEs are also obtained from the performance analysis. In the weight stage, performance attributes of an intersection improvement project including operation, safety, accessibility, environment and more are defined along with performance MOEs. They are given weight scores using FAHP and Delphi Method. Scaling is one of the key stages in MAFU. In this stage, single attribute utility functions are established for each attribute to provide a dimensionless measurement and risk parameters are assigned to each function to describe the risk tolerance level of decision maker. In addition, the uncertainty in performance measurement and quantification is identified at this stage. The combination stage includes the development of system-wide multiattribute utility function to amalgamate the single-attribute utility functions in order to determine the utility value of each alternative. In the decision stage, the expected utility index and variance are calculated by using the system-wide multiattribute utility function. These values are used to rank the alternatives. Because of the uncertainty in MOE quantification, MCS is used to develop a tradespace to visually assist in tradeoff analysis among alternatives. The decision would be made via a tradeoff analysis by simultaneously comparing a statistical summary of utility values of each alternative including expected values, confidence interval and variance.

The FAHP weighting process of MAFU has been formulated and coded in the Excel spreadsheet for automated computation. The process of tradeoff analysis and the development of utility functions and tradeoff space are coded in *R Project*.

A case study demonstrates application of this integrated method for project evaluation and decision-making and reflects that comprehensive analysis results in less uncertainty and more reliability.

8.2 Directions for Future Research

The issue of uncertainty is common in the transportation project decision process. MAFU developed in this research has been proven to be a reliable analytical tool to conduct uncertainty and tradeoff analysis in the evaluation and selection of intersection treatments. The nature of this model has a high potential as a generic tool applicable to other large-scale transportation projects. Therefore, the following areas are recommended for future study to maximize the potential compatibility of MAFU with various transportation projects.

- Expansion of decision-making model to be applied in collaborative decision-making environment for multiple concurrent and interactive projects.
- Development of methodology for quantifying the uncertainty associated with human inputs, such as selection of performance attributes and evaluation criteria.
- In addition to considering risk factors in measuring decision maker attitudes to the possible differences between objectives and outcomes, it is recommended to develop a risk-based approach combined with fuzzy probability-driven technique for determining performance criteria.
- Develop approaches to capture potential decision errors and to identify the critical areas in which decision biases may impede reliable decision outcomes.
- Examine the sensitivity of MAFU model to the weight of attribute, risk parameters and other critical factors.

- Develop a NCHRP research topic that shows how, why and what parameters need to be established and given "central values" that are reliable and locally adjustable.

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APPENDIX A

```
## MAFU function, define the number of MCS replications: n

MAFU<-function(n){

## input Multi-state modeling package

library(msm)
## Scenario W/o Risk Parameter and Cost Index
## Attribute functions for “do nothing”

u_oper11<-a<-
(0.5*rtnorm(n,0,1,0,0.38)+0.5*rtnorm(n,0,1,0.13,0.46))
u_safe11<-a<-
(0.03*rtnorm(n,0,1,0,0.08)+0.97*rtnorm(n,0,1,0,0.15))
u_envi11<-a<-
0.8*(0.5*runif(n,0,0.45)+0.5*runif(n,0.73,0.94))+0.2*(0.5*r
unif(n,0,0.46)+0.5*runif(n,0.09,0.52))
u_ener11<-a<-0.5*runif(n,0,0.42)+0.5*runif(n,0.75,0.93)
u_future11<-rtnorm(n,0,1,0,0.10)
u11<-
(0.35*u_oper11+0.58*u_safe11+0.04*u_envi11+0.03*u_ener11)*u
_future11
```

```
## Attribute functions for "LTP"


u_oper12<-a<-
(0.5*rtnorm(n,0,1,0.6,0.89)+0.5*rtnorm(n,0,1,0.33,0.75))
u_safe12<-a<-
(0.03*rtnorm(n,0,1,0.92,1)+0.97*rtnorm(n,0,1,0.85,1))
u_envi12<-a<-
0.8*(0.5*runif(n,0.31,0.66)+0.5*runif(n,0.81,0.99))+0.2*(0.
5*runif(n,0.27,0.64)+0.5*runif(n,0.27,0.64))
u_ener12<-a<-0.5*runif(n,0.28,0.61)+0.5*runif(n,0.79,0.95)
u_future12<-rtnorm(n,0,1,0.12,0.20)
u12<-
(0.35*u_oper12+0.58*u_safe12+0.04*u_envi12+0.03*u_ener12)*u
_future12
## Attribute functions for "LCUP"


u_oper13<-a<-
(0.5*rtnorm(n,0,1,0.42,0.81)+0.5*rtnorm(n,0,1,0.68,1))
u_safe13<-a<-
(0.03*rtnorm(n,0,1,0.55,0.63)+0.97*rtnorm(n,0,1,0.66,0.81))
u_envi13<-a<-
0.8*(0.5*runif(n,0.82,1)+0.5*runif(n,0.81,0.99))+0.2*(0.5*r
unif(n,0.81,1)+0.5*runif(n,0.79,0.99))
u_ener13<-a<-0.5*runif(n,0.86,1)+0.5*runif(n,0.83,0.98)
```

```
u_future13<-rtnorm(n,0,1,0.93,1.00)

u13<-

(0.35*u_oper13+0.58*u_safe13+0.04*u_envi13+0.03*u_ener13)*u

_future13


## Scenario With Risk Parameter and W/o Costs Index

## Attribute functions for “do nothing”


u_oper21<-a<-

(0.5*rtnorm(n,0,1,0,0.38)+0.5*rtnorm(n,0,1,0.13,0.46))^0.5

u_safe21<-a<-

(0.03*rtnorm(n,0,1,0,0.08)+0.97*rtnorm(n,0,1,0,0.15))^0.5

u_envi21<-a<-

0.8*(0.5*runif(n,0,0.45)+0.5*runif(n,0.73,0.94))+0.2*(0.5*r

unif(n,0,0.46)+0.5*runif(n,0.09,0.52))

u_ener21<-a<-0.5*runif(n,0,0.42)+0.5*runif(n,0.75,0.93)

u_future21<-rtnorm(n,0,1,0,0.10)

u21<-

(0.35*u_oper21+0.58*u_safe21+0.04*u_envi21+0.03*u_ener21)*u

_future21


## Attribute functions for “LTP”
```

```
u_oper22<-a<-
(0.5*rtnorm(n,0,1,0.6,0.89)+0.5*rtnorm(n,0,1,0.33,0.75))^0.
5
u_safe22<-a<-
(0.03*rtnorm(n,0,1,0.92,1)+0.97*rtnorm(n,0,1,0.85,1))^0.5
u_envi22<-a<-
0.8*(0.5*runif(n,0.31,0.66)+0.5*runif(n,0.81,0.99))+0.2*(0.
5*runif(n,0.27,0.64)+0.5*runif(n,0.27,0.64))
u_ener22<-a<-0.5*runif(n,0.28,0.61)+0.5*runif(n,0.79,0.95)
u_future22<-rtnorm(n,0,1,0.12,0.20)
u22<-
(0.35*u_oper22+0.58*u_safe22+0.04*u_envi22+0.03*u_ener22)*u
_future22

## Attribute functions for "LCUP"
u_oper23<-a<-
(0.5*rtnorm(n,0,1,0.42,0.81)+0.5*rtnorm(n,0,1,0.68,1))^0.5
u_safe23<-a<-
(0.03*rtnorm(n,0,1,0.55,0.63)+0.97*rtnorm(n,0,1,0.66,0.81))
^0.5
u_envi23<-a<-
0.8*(0.5*runif(n,0.82,1)+0.5*runif(n,0.81,0.99))+0.2*(0.5*r
unif(n,0.81,1)+0.5*runif(n,0.79,0.99))
u_ener23<-a<-0.5*runif(n,0.86,1)+0.5*runif(n,0.83,0.98)
```

```
u_future23<-rtnorm(n,0,1,0.93,1.00)
u23<-
(0.35*u_oper23+0.58*u_safe23+0.04*u_envi23+0.03*u_ener23)*u
_future23


## Scenario With Risk Parameter and Cost Index
## Attribute functions for “do nothing”

u_oper31<-a<-
(0.5*rtnorm(n,0,1,0,0.38)+0.5*rtnorm(n,0,1,0.13,0.46))^1
u_safe31<-a<-
(0.03*rtnorm(n,0,1,0,0.08)+0.97*rtnorm(n,0,1,0,0.15))^1/2
u_envi31<-a<-
0.8*(0.5*runif(n,0,0.45)+0.5*runif(n,0.73,0.94))+0.2*(0.5*r
unif(n,0,0.46)+0.5*runif(n,0.09,0.52))^1/2
u_ener31<-a<-0.5*runif(n,0,0.42)+0.5*runif(n,0.75,0.93)
u_cost31<-1^1/2
u_future31<-rtnorm(n,0,1,0,0.10)
u31<-
(0.35*u_oper31+0.58*u_safe31+0.04*u_envi31+0.03*u_ener31)*u
_cost31*u_future31

## Attribute functions for “LTP”
```

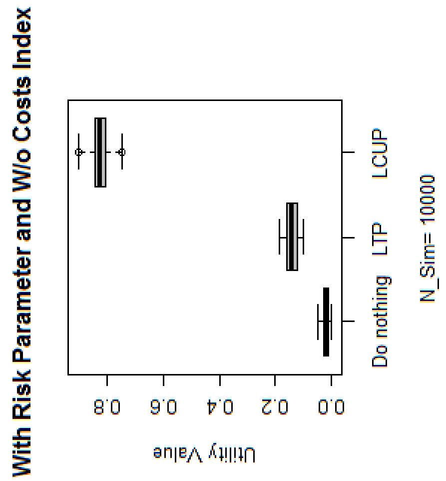
```
u_oper32<-a<-
(0.5*rtnorm(n,0,1,0.6,0.89)+0.5*rtnorm(n,0,1,0.33,0.75))^1/
2
u_safe32<-a<-
(0.03*rtnorm(n,0,1,0.92,1)+0.97*rtnorm(n,0,1,0.85,1))^1/2
u_envi32<-a<-
0.8*(0.5*runif(n,0.31,0.66)+0.5*runif(n,0.81,0.99))+0.2*(0.
5*runif(n,0.27,0.64)+0.5*runif(n,0.27,0.64))
u_ener32<-a<-0.5*runif(n,0.28,0.61)+0.5*runif(n,0.79,0.95)
u_cost32<-(rtnorm(n,0,1,0.68, 0.85))^1/2
u_future32<-rtnorm(n,0,1,0.12,0.20)
u32<-
(0.35*u_oper32+0.58*u_safe32+0.04*u_envi32+0.03*u_ener32)*u
_cost32*u_future32
## Attribute functions for "LCUP"
u_oper33<-a<-
(0.5*rtnorm(n,0,1,0.42,0.81)+0.5*rtnorm(n,0,1,0.68,1))^1/2
u_safe33<-a<-
(0.03*rtnorm(n,0,1,0.55,0.63)+0.97*rtnorm(n,0,1,0.66,0.81))
^1/2
u_envi33<-a<-
0.8*(0.5*runif(n,0.82,1)+0.5*runif(n,0.81,0.99))+0.2*(0.5*r
unif(n,0.81,1)+0.5*runif(n,0.79,0.99))
u_ener33<-a<-0.5*runif(n,0.86,1)+0.5*runif(n,0.83,0.98)
```

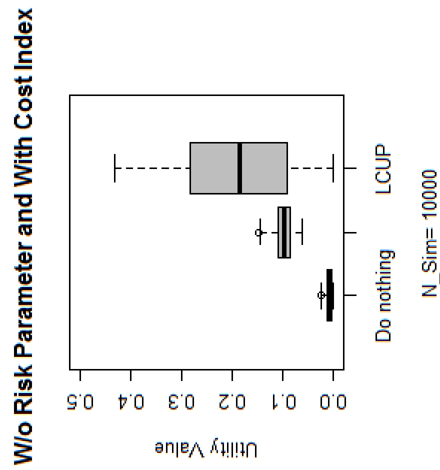
```
u_cost33<-(rtnorm(n,0,1,0, 0.54))^1/2
u_future33<-rtnorm(n,0,1,0.93,1.00)
u33<-
(0.35*u_oper33+0.58*u_safe33+0.04*u_envi33+0.03*u_ener33)*u
_cost33*u_future33

## Scenario W/o Risk Parameter and With Cost Index
## Attribute functions for "do nothing"

u_oper41<-a<-
(0.5*rtnorm(n,0,1,0,0.38)+0.5*rtnorm(n,0,1,0.13,0.46))
u_safe41<-a<-
(0.03*rtnorm(n,0,1,0,0.08)+0.97*rtnorm(n,0,1,0,0.15))
u_envi41<-a<-
0.8*(0.5*runif(n,0,0.45)+0.5*runif(n,0.73,0.94))+0.2*(0.5*r
unif(n,0,0.46)+0.5*runif(n,0.09,0.52))
u_ener41<-a<-0.5*runif(n,0,0.42)+0.5*runif(n,0.75,0.93)
u_cost41<-1
u_future41<-rtnorm(n,0,1,0,0.10)
u41<-
(0.35*u_oper41+0.58*u_safe41+0.04*u_envi41+0.03*u_ener41)*u
_cost41*u_future41

## Attribute functions for "LTP"
```

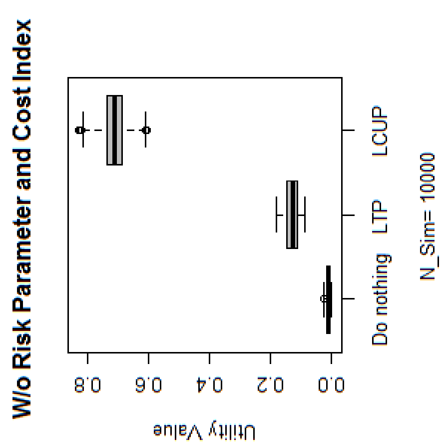
```
u_oper42<-a<-
(0.5*rtnorm(n,0,1,0.6,0.89)+0.5*rtnorm(n,0,1,0.33,0.75))
u_safe42<-a<-
(0.03*rtnorm(n,0,1,0.92,1)+0.97*rtnorm(n,0,1,0.85,1))
u_envi42<-a<-
0.8*(0.5*runif(n,0.31,0.66)+0.5*runif(n,0.81,0.99))+0.2*(0.
5*runif(n,0.27,0.64)+0.5*runif(n,0.27,0.64))
u_ener42<-a<-0.5*runif(n,0.28,0.61)+0.5*runif(n,0.79,0.95)
u_cost42<-(rtnorm(n,0,1,0.68, 0.85))
u_future42<-rtnorm(n,0,1,0.12,0.20)
u42<-
(0.35*u_oper42+0.58*u_safe42+0.04*u_envi42+0.03*u_ener42)*u
_cost42*u_future42

## Attribute functions for "LCUP"
u_oper43<-a<-
(0.5*rtnorm(n,0,1,0.42,0.81)+0.5*rtnorm(n,0,1,0.68,1))
u_safe43<-a<-
(0.03*rtnorm(n,0,1,0.55,0.63)+0.97*rtnorm(n,0,1,0.66,0.81))
u_envi43<-a<-
0.8*(0.5*runif(n,0.82,1)+0.5*runif(n,0.81,0.99))+0.2*(0.5*r
unif(n,0.81,1)+0.5*runif(n,0.79,0.99))
u_ener43<-a<-0.5*runif(n,0.86,1)+0.5*runif(n,0.83,0.98)
```

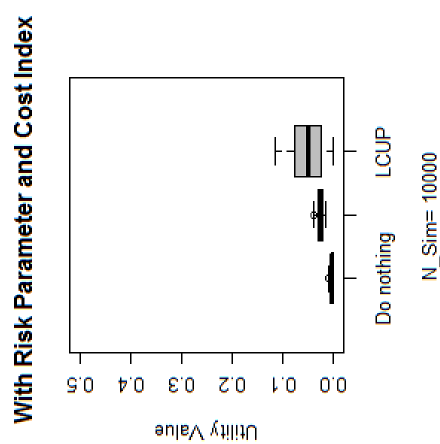
```
u_cost43<-(rtnorm(n,0,1,0, 0.54))

u_future43<-rtnorm(n,0,1,0.93,1.00)

u43<-
(0.35*u_oper43+0.58*u_safe43+0.04*u_envi43+0.03*u_ener43)*u
_cost43*u_future43


## Generate Tradspace


par(mfrow=c(2,2), pty = "s")

boxplot(u11,u12,u13, names=c("Do nothing", "LTP", "LCUP"),
xlab=paste("N_Sim=",n), ylab="Utility Value", main="W/o
Risk Parameter and Cost Index ", col="gray")

boxplot(u21,u22,u23, names=c("Do nothing", "LTP", "LCUP"),
xlab=paste("N_Sim=",n), ylab="Utility Value", main="With
Risk Parameter and W/o Costs Index ", col="gray")

boxplot(u31,u32,u33, names=c("Do nothing", "LTP", "LCUP"),
xlab=paste("N_Sim=",n), ylab="Utility Value", main="With
Risk Parameter and Cost Index ", col="gray",xlim = c(0, 4),
ylim = c(0, 0.5))

boxplot(u41,u42,u43, names=c("Do nothing", "LTP", "LCUP"),
xlab=paste("N_Sim=",n), ylab="Utility Value", main="W/o
Risk Parameter and With Cost Index ", col="gray",xlim = c(0,
4), ylim = c(0, 0.5))

}
```

```
## EXAMPLE

MAFU(10000)
```









APPENDIX B

```
## Scenario analysis function, define the number of MCS
replications: n

SCEN<-function(n){

## input Multi-state modeling package

library(msm)

## Planning Level only
## Attribute functions for “do nothing”
u01<-runif(n,0,0.1)
## Attribute functions for “LTP”
u02<-runif(n,0.17, 0.23)
## Attribute functions for “LCUP”
u03<-runif(n,0.27, 0.42)

## Owner Objectives Only (75% safety and 25% operation)
## Scenario With Risk Parameter and Cost Index
## Attribute functions for “do nothing”
```

```
u_oper11<-a<-
(0.5*rtnorm(n,0,1,0,0.38)+0.5*rtnorm(n,0,1,0.13,0.46))^1
u_safe11<-a<-
(0.03*rtnorm(n,0,1,0,0.08)+0.97*rtnorm(n,0,1,0,0.15))^1/2
u_envi11<-a<-
0.8*(0.5*runif(n,0,0.45)+0.5*runif(n,0.73,0.94))+0.2*(0.5*r
unif(n,0,0.46)+0.5*runif(n,0.09,0.52))^1/2
u_ener11<-a<-0.5*runif(n,0,0.42)+0.5*runif(n,0.75,0.93)
u_cost11<-1^1/2
u_future11<-rtnorm(n,0,1,0,0.10)
u11<-
(0.25*u_oper11+0.75*u_safe11+0.00*u_envi11+0.00*u_ener11)*u
_cost11*u_future11

## Attribute functions for “LTP”
u_oper12<-a<-
(0.5*rtnorm(n,0,1,0.6,0.89)+0.5*rtnorm(n,0,1,0.33,0.75))^1/
2
u_safe12<-a<-
(0.03*rtnorm(n,0,1,0.92,1)+0.97*rtnorm(n,0,1,0.85,1))^1/2
u_envi12<-a<-
0.8*(0.5*runif(n,0.31,0.66)+0.5*runif(n,0.81,0.99))+0.2*(0.
5*runif(n,0.27,0.64)+0.5*runif(n,0.27,0.64))
u_ener12<-a<-0.5*runif(n,0.28,0.61)+0.5*runif(n,0.79,0.95)
```

```
u_cost12<-(rtnorm(n,0,1,0.68, 0.85))^1/2

u_future12<-rtnorm(n,0,1,0.12,0.20)

u12<-

(0.25*u_oper12+0.75*u_safe12+0.00*u_envi12+0.00*u_ener12)*u

_cost12*u_future12


## Attribute functions for "LCUP"

u_oper13<-a<-

(0.5*rtnorm(n,0,1,0.42,0.81)+0.5*rtnorm(n,0,1,0.68,1))^1/2

u_safe13<-a<-

(0.03*rtnorm(n,0,1,0.55,0.63)+0.97*rtnorm(n,0,1,0.66,0.81))

^1/2

u_envi13<-a<-

0.8*(0.5*runif(n,0.82,1)+0.5*runif(n,0.81,0.99))+0.2*(0.5*r

unif(n,0.81,1)+0.5*runif(n,0.79,0.99))

u_ener13<-a<-0.5*runif(n,0.86,1)+0.5*runif(n,0.83,0.98)

u_cost13<-(rtnorm(n,0,1,0, 0.54))^1/2

u_future13<-rtnorm(n,0,1,0.93,1.00)

u13<-

(0.25*u_oper13+0.75*u_safe13+0.00*u_envi13+0.00*u_ener13)*u

_cost13*u_future13


## Intersection User Oejective Only (100% operation)

## Scenario With Risk Parameter and Cost Index
```

```
## Attribute functions for "do nothing"

u_oper21<-a<-
(0.5*rtnorm(n,0,1,0,0.38)+0.5*rtnorm(n,0,1,0.13,0.46))^1
u_safe21<-a<-
(0.03*rtnorm(n,0,1,0,0.08)+0.97*rtnorm(n,0,1,0,0.15))^1/2
u_envi21<-a<-
0.8*(0.5*runif(n,0,0.45)+0.5*runif(n,0.73,0.94))+0.2*(0.5*r
unif(n,0,0.46)+0.5*runif(n,0.09,0.52))^1/2
u_ener21<-a<-0.5*runif(n,0,0.42)+0.5*runif(n,0.75,0.93)
u_cost21<-1^1/2
u_future21<-rtnorm(n,0,1,0,0.10)
u21<-
(1.00*u_oper21+0.00*u_safe21+0.00*u_envi21+0.00*u_ener21)*u
_cost21*u_future21

## Attribute functions for "LTP"
u_oper22<-a<-
(0.5*rtnorm(n,0,1,0.6,0.89)+0.5*rtnorm(n,0,1,0.33,0.75))^1/
2
u_safe22<-a<-
(0.03*rtnorm(n,0,1,0.92,1)+0.97*rtnorm(n,0,1,0.85,1))^1/2
```

```
u_envi22<-a<-
0.8*(0.5*runif(n,0.31,0.66)+0.5*runif(n,0.81,0.99))+0.2*(0.
5*runif(n,0.27,0.64)+0.5*runif(n,0.27,0.64))
u_ener22<-a<-0.5*runif(n,0.28,0.61)+0.5*runif(n,0.79,0.95)
u_cost22<-(rtnorm(n,0,1,0.68, 0.85))^1/2
u_future22<-rtnorm(n,0,1,0.12,0.20)
u22<-
(1.00*u_oper22+0.00*u_safe22+0.00*u_envi22+0.00*u_ener22)*u
_cost22*u_future22

## Attribute functions for "LCUP"
u_oper23<-a<-
(0.5*rtnorm(n,0,1,0.42,0.81)+0.5*rtnorm(n,0,1,0.68,1))^1/2
u_safe23<-a<-
(0.03*rtnorm(n,0,1,0.55,0.63)+0.97*rtnorm(n,0,1,0.66,0.81))
^1/2
u_envi23<-a<-
0.8*(0.5*runif(n,0.82,1)+0.5*runif(n,0.81,0.99))+0.2*(0.5*r
unif(n,0.81,1)+0.5*runif(n,0.79,0.99))
u_ener23<-a<-0.5*runif(n,0.86,1)+0.5*runif(n,0.83,0.98)
u_cost23<-(rtnorm(n,0,1,0, 0.54))^1/2
u_future23<-rtnorm(n,0,1,0.93,1.00)
```

```
u23<-
(1.00*u_oper23+0.00*u_safe23+0.00*u_envi23+0.00*u_ener23)*u
_cost23*u_future23

## Intersection Owner and User Objectives (50% operation
and 50% safety)
## Scenario With Risk Parameter and Cost Index
## Attribute functions for “do nothing”

u_oper_c1<-a<-
(0.5*rtnorm(n,0,1,0,0.38)+0.5*rtnorm(n,0,1,0.13,0.46))^1
u_safe_c1<-a<-
(0.03*rtnorm(n,0,1,0,0.08)+0.97*rtnorm(n,0,1,0,0.15))^1/2
u_envi_c1<-a<-
0.8*(0.5*runif(n,0,0.45)+0.5*runif(n,0.73,0.94))+0.2*(0.5*r
unif(n,0,0.46)+0.5*runif(n,0.09,0.52))^1/2
u_ener_c1<-a<-0.5*runif(n,0,0.42)+0.5*runif(n,0.75,0.93)
u_cost_c1<-1^1/2
u_future_c1<-rtnorm(n,0,1,0,0.10)
u_c1<-
(0.50*u_oper_c1+0.00*u_safe_c1+0.00*u_envi_c1+0.00*u_ener_c
1)*u_cost_c1*u_future_c1

## Attribute functions for “LTP”
```

```
u_oper_c2<-a<-
(0.5*rtnorm(n,0,1,0.6,0.89)+0.5*rtnorm(n,0,1,0.33,0.75))^1/
2
u_safe_c2<-a<-
(0.03*rtnorm(n,0,1,0.92,1)+0.97*rtnorm(n,0,1,0.85,1))^1/2
u_envi_c2<-a<-
0.8*(0.5*runif(n,0.31,0.66)+0.5*runif(n,0.81,0.99))+0.2*(0.
5*runif(n,0.27,0.64)+0.5*runif(n,0.27,0.64))
u_ener_c2<-a<-0.5*runif(n,0.28,0.61)+0.5*runif(n,0.79,0.95)
u_cost_c2<-(rtnorm(n,0,1,0.68, 0.85))^1/2
u_future_c2<-rtnorm(n,0,1,0.12,0.20)
u_c2<-
(1.00*u_oper_c2+0.00*u_safe_c2+0.00*u_envi_c2+0.00*u_ener_c
2)*u_cost_c2*u_future_c2

## Attribute functions for "LCUP"
u_oper_c3<-a<-
(0.5*rtnorm(n,0,1,0.42,0.81)+0.5*rtnorm(n,0,1,0.68,1))^1/2
u_safe_c3<-a<-
(0.03*rtnorm(n,0,1,0.55,0.63)+0.97*rtnorm(n,0,1,0.66,0.81))
^1/2
u_envi_c3<-a<-
0.8*(0.5*runif(n,0.82,1)+0.5*runif(n,0.81,0.99))+0.2*(0.5*r
unif(n,0.81,1)+0.5*runif(n,0.79,0.99))
```

```
u_ener_c3<-a<-0.5*runif(n,0.86,1)+0.5*runif(n,0.83,0.98)
u_cost_c3<-(rtnorm(n,0,1,0, 0.54))^1/2
u_future_c3<-rtnorm(n,0,1,0.93,1.00)
u_c3<-
(1.00*u_oper_c3+0.00*u_safe_c3+0.00*u_envi_c3+0.00*u_ener_c
3)*u_cost_c3*u_future_c3


## Intersection Neighbor Oejective Only (50% Enviroment and
50% Energy)
## Scenario With Risk Parameter and Cost Index

## Attribute functions for "do nothing"

u_oper31<-a<-
(0.5*rtnorm(n,0,1,0,0.38)+0.5*rtnorm(n,0,1,0.13,0.46))^1
u_safe31<-a<-
(0.03*rtnorm(n,0,1,0,0.08)+0.97*rtnorm(n,0,1,0,0.15))^1/2
u_envi31<-a<-
0.8*(0.5*runif(n,0,0.45)+0.5*runif(n,0.73,0.94))+0.2*(0.5*r
unif(n,0,0.46)+0.5*runif(n,0.09,0.52))^1/2
u_ener31<-a<-0.5*runif(n,0,0.42)+0.5*runif(n,0.75,0.93)
u_cost31<-1^1/2
u_future31<-rtnorm(n,0,1,0,0.10)
```

```
u31<-
(0.00*u_oper31+0.00*u_safe31+0.50*u_envi31+0.50*u_ener31)*u
_cost31*u_future31

## Attribute functions for "LTP"
u_oper32<-a<-
(0.5*rtnorm(n,0,1,0.6,0.89)+0.5*rtnorm(n,0,1,0.33,0.75))^1/
2
u_safe32<-a<-
(0.03*rtnorm(n,0,1,0.92,1)+0.97*rtnorm(n,0,1,0.85,1))^1/2
u_envi32<-a<-
0.8*(0.5*runif(n,0.31,0.66)+0.5*runif(n,0.81,0.99))+0.2*(0.
5*runif(n,0.27,0.64)+0.5*runif(n,0.27,0.64))
u_ener32<-a<-0.5*runif(n,0.28,0.61)+0.5*runif(n,0.79,0.95)
u_cost32<-(rtnorm(n,0,1,0.68, 0.85))^1/2
u_future32<-rtnorm(n,0,1,0.12,0.20)
u32<-
(0.00*u_oper32+0.00*u_safe32+0.50*u_envi32+0.50*u_ener32)*u
_cost32*u_future32

## Attribute functions for "LCUP"
u_oper33<-a<-
(0.5*rtnorm(n,0,1,0.42,0.81)+0.5*rtnorm(n,0,1,0.68,1))^1/2
```

```
u_safe33<-a<-
(0.03*rtnorm(n,0,1,0.55,0.63)+0.97*rtnorm(n,0,1,0.66,0.81))
^1/2
u_envi33<-a<-
0.8*(0.5*runif(n,0.82,1)+0.5*runif(n,0.81,0.99))+0.2*(0.5*r
unif(n,0.81,1)+0.5*runif(n,0.79,0.99))
u_ener33<-a<-0.5*runif(n,0.86,1)+0.5*runif(n,0.83,0.98)
u_cost33<-(rtnorm(n,0,1,0, 0.54))^1/2
u_future33<-rtnorm(n,0,1,0.93,1.00)
u33<-
(0.00*u_oper33+0.00*u_safe33+0.50*u_envi33+0.50*u_ener33)*u
_cost33*u_future33




## Combined Objective (Fuzzified weights applied)
## Scenario With Risk Parameter and Cost Index

## Attribute functions for "do nothing"
u_oper41<-a<-
(0.5*rtnorm(n,0,1,0,0.38)+0.5*rtnorm(n,0,1,0.13,0.46))^1
u_safe41<-a<-
(0.03*rtnorm(n,0,1,0,0.08)+0.97*rtnorm(n,0,1,0,0.15))^1/2
```

```
u_envi41<-a<-
0.8*(0.5*runif(n,0,0.45)+0.5*runif(n,0.73,0.94))+0.2*(0.5*r
unif(n,0,0.46)+0.5*runif(n,0.09,0.52))^1/2
u_ener41<-a<-0.5*runif(n,0,0.42)+0.5*runif(n,0.75,0.93)
u_cost41<-1^1/2
u_future41<-rtnorm(n,0,1,0,0.10)
u41<-
(0.35*u_oper41+0.58*u_safe41+0.04*u_envi41+0.03*u_ener41)*u
_cost41*u_future41


## Attribute functions for “LTP”
u_oper42<-a<-
(0.5*rtnorm(n,0,1,0.6,0.89)+0.5*rtnorm(n,0,1,0.33,0.75))^1/
2
u_safe42<-a<-
(0.03*rtnorm(n,0,1,0.92,1)+0.97*rtnorm(n,0,1,0.85,1))^1/2
u_envi42<-a<-
0.8*(0.5*runif(n,0.31,0.66)+0.5*runif(n,0.81,0.99))+0.2*(0.
5*runif(n,0.27,0.64)+0.5*runif(n,0.27,0.64))
u_ener42<-a<-0.5*runif(n,0.28,0.61)+0.5*runif(n,0.79,0.95)
u_cost42<-(rtnorm(n,0,1,0.68, 0.85))^1/2
u_future42<-rtnorm(n,0,1,0.12,0.20)
```

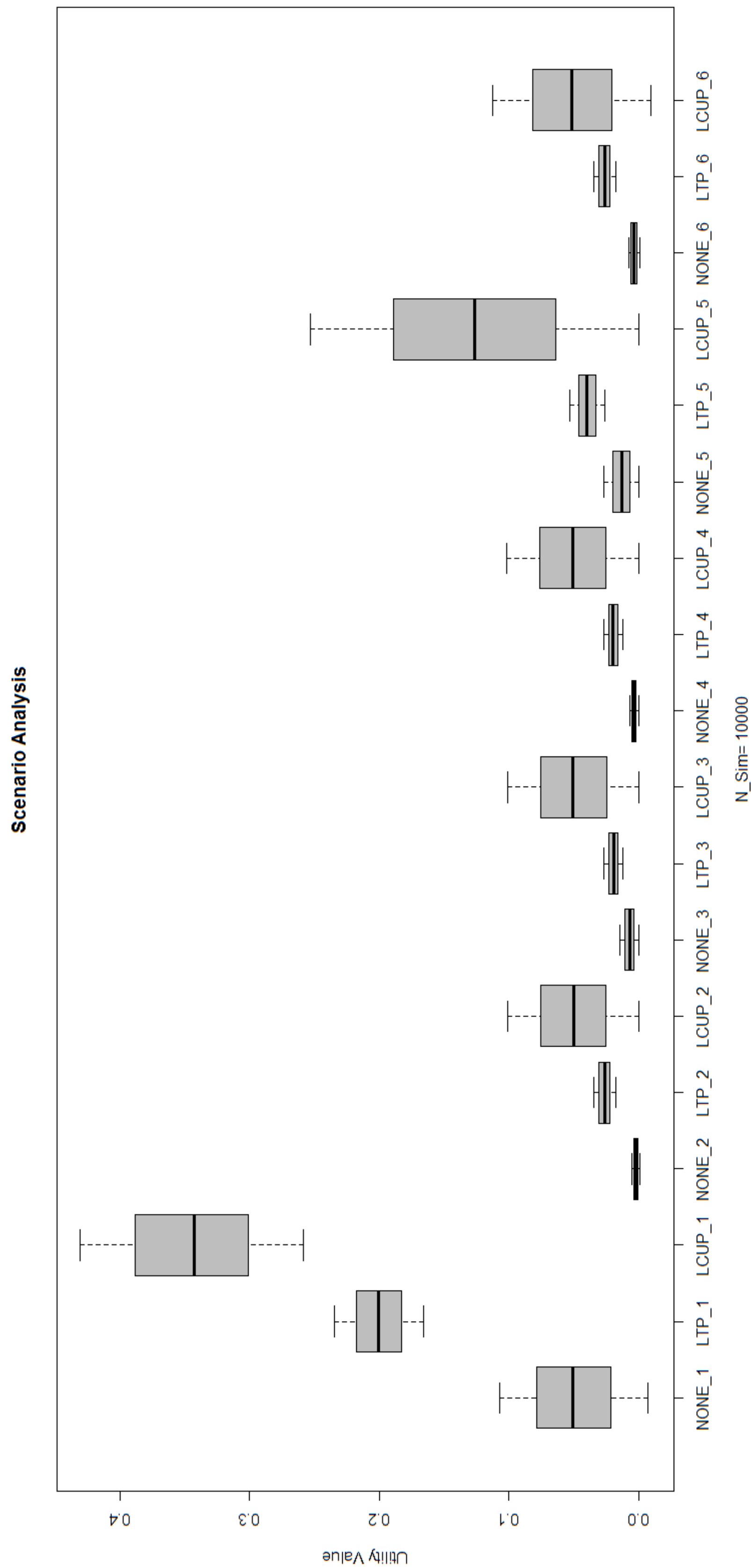
```
u42<-
(0.35*u_oper42+0.58*u_safe42+0.04*u_envi42+0.03*u_ener42)*u
_cost42*u_future42

## Attribute functions for "LCUP"
u_oper43<-a<-
(0.5*rtnorm(n,0,1,0.42,0.81)+0.5*rtnorm(n,0,1,0.68,1))^1/2
u_safe43<-a<-
(0.03*rtnorm(n,0,1,0.55,0.63)+0.97*rtnorm(n,0,1,0.66,0.81))
^1/2
u_envi43<-a<-
0.8*(0.5*runif(n,0.82,1)+0.5*runif(n,0.81,0.99))+0.2*(0.5*r
unif(n,0.81,1)+0.5*runif(n,0.79,0.99))
u_ener43<-a<-0.5*runif(n,0.86,1)+0.5*runif(n,0.83,0.98)
u_cost43<-(rtnorm(n,0,1,0, 0.54))^1/2
u_future43<-rtnorm(n,0,1,0.93,1.00)
u43<-
(0.35*u_oper43+0.58*u_safe43+0.04*u_envi43+0.03*u_ener43)*u
_cost43*u_future43

## Generate Tradspace
b01<-runif(n, mean(u01)-2*sd(u01), mean(u01)+2*sd(u01))
b02<-runif(n, mean(u02)-2*sd(u02), mean(u02)+2*sd(u02))
b03<-runif(n, mean(u03)-2*sd(u03), mean(u03)+2*sd(u03))
```

```
b11<-runif(n, mean(u11)-2*sd(u11), mean(u11)+2*sd(u11))
b12<-runif(n, mean(u12)-2*sd(u12), mean(u12)+2*sd(u12))
b13<-runif(n, 0, mean(u13)+2*sd(u13))

b21<- runif(n, 0, mean(u21)+2*sd(u21))
b22<-runif(n, mean(u22)-2*sd(u22), mean(u22)+2*sd(u22))
b23<- runif(n, 0, mean(u23)+2*sd(u23))

bc1<- runif(n, 0, mean(u_c1)+2*sd(u_c1))
bc2<-runif(n, mean(u_c2)-2*sd(u_c2), mean(u_c2)+2*sd(u_c2))
bc3<- runif(n, 0, mean(u_c3)+2*sd(u_c3))

b31<- runif(n, 0, mean(u31)+2*sd(u31))
b32<-runif(n, mean(u32)-2*sd(u32), mean(u32)+2*sd(u32))
b33<- runif(n, 0, mean(u33)+2*sd(u33))

b41<-runif(n, mean(u41)-2*sd(u41), mean(u41)+2*sd(u41))
b42<-runif(n, mean(u42)-2*sd(u42), mean(u42)+2*sd(u42))
b43<-runif(n, mean(u43)-2*sd(u43), mean(u43)+2*sd(u43))
boxplot(b01,b02,b03,b11,b12,b13,b21,b22,b23,bc1,bc2,bc3,b31
,b32,b33,b41,b42,b43, names=c("NONE_1", "LTP_1",
"LCUP_1","NONE_2", "LTP_2", "LCUP_2","NONE_3", "LTP_3",
"LCUP_3","NONE_4", "LTP_4", "LCUP_4","NONE_5", "LTP_5",
```

```
"LCUP_5", "NONE_6", "LTP_6", "LCUP_6"),
xlab=paste("N_Sim=",n), ylab="Utility Value",
main="Scenario Analysis", col="gray")
return(list(mean(u01), sd(u01), mean(u02), sd(u02),
mean(u03), sd(u03), mean(u11), sd(u11), mean(u12), sd(u12),
mean(u13), sd(u13), mean(u21), sd(u21), mean(u22), sd(u22),
mean(u23), sd(u23), mean(u31), sd(u31), mean(u32), sd(u32),
mean(u33), sd(u33), mean(u41), sd(u41), mean(u42), sd(u42),
mean(u43), sd(u43)))
}
```

EXAMPLE

SCEN(10000)


Scenario Analysis
Utility Value
0.0
0.1
0.2
0.3
0.4
NONE_1
LTP_1
LCUP_1
NONE_2
LTP_2
LCUP_2
NONE_3
LTP_3
LCUP_3
NONE_4
LTP_4
LCUP_4
NONE_5
LTP_5
LCUP_5
NONE_6
LTP_6
LCUP_6
N_Sim= 10000