The Role of Road User Costs in Benefit-Cost Analysis

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ABSTRACT

An economically and socially healthy urban region always needs to move people and goods in a timely fashion. However, with the development of urban land, many corridors in urban regions suffer from great congestion, since demand is close to or greater than the capacity of the roadways. In order to improve traffic conditions, transportation planners need to identify and select the best projects that will expand and upgrade existing facilities by using Benefit-Cost Analysis. Usually, Benefit-Cost Analysis assists transportation planners by balancing the consideration of user benefits against the total costs of the projects, by translating them into monetary terms. The principal elements in Benefit-Cost Analysis are travel time costs, vehicle operation costs, and safety costs. These elements of a Base Case are compared to those of one or more Project Alternatives that offer significant improvements. However, the Road User Costs (RUC) during construction, which have the same three components, is often ignored in Benefit Cost Analysis. When RUC is significant, it can generate different results in a Benefit Costs Analysis.

The objective of this study is to propose an improved process of Benefit-Cost Analysis, evaluating investment costs and all user costs and benefits during construction and during a facilities' lifetime. Furthermore, since comprehensive calculations of area-wide RUC during the construction phase are often lacking, this study also proposes three procedures of user cost calculation by utilizing three levels of analytical tools: one Sketch-Planning Tool (specifically, QuickZone); one Travel Demand Model (Cube Voyager); and one Microscopic Simulator (AIMSUN). In order to implement this improved procedure of Benefit-Cost Analysis, the TH-36 reconstruction project, in North St Paul, Minnesota, was utilized. Through conducting Benefit-Cost Analysis of two planned construction alternatives, Full Closure and Partial Closure, this study concluded that RUC during the construction phase are important and the selection of an optimal construction alternative can be different due to the inclusion of RUC.

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Chapter 1

Introduction

According to the 2007 Urban Mobility Report, 78 billion dollars were lost due to congestion on urban roadways in 2007[4]. Many urban corridors around the country experience demand that is close to or greater than the available capacity. Although most agree that the transportation system has matured and that we will not build ourselves out of congestion[5], existing infrastructure often requires expansion. Such expansion in an already developed system most likely does not involve new roadway construction but results in existing roadway upgrades. Such roadways normally already serve considerable demand, a fact that increases the importance of Road User Costs (RUC) (i.e. delay, vehicle operating, and accident costs) in construction projects. Unfortunately, as described in "Meeting the Customer's Needs for Mobility and Safety During Construction and Maintenance Operations"[6], RUC is rarely considered during staging and duration planning and is considered even less during Benefit Cost Analysis (BCA).

Non-inclusion of RUC in BCA is not a habit born out of negligence. The calculation of RUC, as will be discussed extensively in this study, involves either a very large number of assumptions, a set of very expensive and sophisticated tools, or both. Considering that RUC is mainly dependent on the duration of construction, in the majority of projects, and especially for projects that do not involve full reconstructions of entire corridors, project alternatives have bigger differences in terms of construction costs than impact to the road users (RUC). Unfortunately, as full reconstruction of already congested roadways becomes more and more the norm, every day that capacity is impacted imposes a penalty (e.g. delay) to society that designers cannot ignore. Proofs of the latter claim are the various ”Innovative Contracting Techniques” developed by federal and state Departments of Transportation (DOTs) [7]. These techniques, such as A+B contracting, lane rentals, etc., aim for the inclusion of the RUC into the actual cost of the project by tying it to incentives and penalties to the contractor biding for the project. In addition to new contracting methods, new, more aggressive construction operation alternatives are considered and promoted to the public.

One of these alternatives is Full Road Closure, which has the potential to accelerate the completion of a project, in addition to providing a safer environment to the public and workers in the work zone [8]. These new, aggressive alternatives for designing reconstruction projects depend highly on accurate and efficient estimation of RUC. Accuracy is essential, because RUC as a monetary parameter affects the bidding process. Additionally, the considerably shorter duration of full closures, as compared to the more traditional partial closures, render daily RUC a potentially important, often deciding factor in selecting the right construction operation alternative.

In the estimation of RUC, engineers often turn to various Traffic Analysis tools. Such tools can be the best way to obtain reliable RUC for deciding on construction alternatives and for designing traffic management plans that reduce RUC. Unfortunately, the amount, type, and quality of required information vary greatly among different traffic analysis tools, and not all data is perfect, available, or sufficient for comprehensive analysis of traffic impacts and user costs. High data-intensive tools require greater effort, increasing the cost of a traffic analysis project. Considering the available project budget, complexity, and analysis requirement, the goal is to use the most efficient methodology and tool. Although such analytical tools are available for RUC estimation, Lewis[9] suggests that many agencies empirically consider RUC in planning mitigation strategies for construction projects but do not conduct quantitative analyses.

The objective of this research is to propose improvements in the current Benefit Costs Analysis process, comprehensively evaluating the agency costs and all user costs, as well as benefits, during the construction and during the facility’s lifetime. At the same time, this work examines the available tools for RUC calculation and investigates their usability, efficiency, and accuracy. Specifically, this work examines three methodologies for the estimation of RUC in construction operations. Three tools are selected as possessing the most relevant levels of cost, complexity, and features. The selected tools are: a ”sketch-planning tool” QuickZone; a ”travel demand model”, Voyager; and a ”microscopic simulation model”, AIMSUN. For each of these tools a methodology to utilize the tool in RUC estimation is proposed, along with comparisons of the effort/data requirements and accuracy/sensitivity achieved.

In order to examine whether decisions based on Benefit Costs Analysis with RUC considered are different from those based on a more traditional procedure, a case study involving a real project, the TH-36 reconstruction in North St Paul, Minnesota, was used. For this particular project, the Full Closure construction operations that were actually implemented were compared with the hypothetical, and longer lasting, partial closure alternative. In summary, it was found that these tools all make an agreement that RUC in Full Closure is higher than Partial closure, regardless of effort requirements of these tools. Furthermore, the final decision, based on the Benefit Costs Analysis with RUC considered, can be different from the traditional process.

Thesis organization

Chapter 2 is a ”Literature Review” and it presents current procedures of Benefit Costs Analysis, the components of user costs, application of RUC, and the methods for RUC estimation. The procedure of Benefit Costs Analysis and the methods of RUC estimation are discussed in detail.

Chapter 3 is ”Need and Objective.” This chapter discusses the rationale for the study in detail.

Chapter 4 is ”Tools/Models Overview” and summarizes the major model frameworks for the three tools selected in the case study. QuickZone, Cube Voyager and AIMSUN are reviewed.

Chapter 5 is ”Methodology” and presents the improved procedure of Benefit Costs Analysis and three procedures of RUC estimation.

Chapter 6 is ”Site Description” and describes the TH-36 project and the actual traffic impact observed due to the Full Closure construction from the detector and tube count data collected.

Chapter 7 is ”Implementation” and describes the procedure of implementing each tool to estimate RUC for the two Project Alternatives of the TH-36 reconstruction. The calibration procedure of the AIMSUN simulator is described in more detail and includes freeway calibration and network calibration.

Chapter 8 is "Results" and presents the traffic diversion analysis based on Cube Voyager and AIMSUN, the RUC results from three tools, and the decisions for the Project Alternative selection based on Benefit Costs Analysis results including RUC results. In addition, a preliminary analysis of RUC is presented to analyze the sensitivity of the RUC results to model parameters and implementation for each tool.

Chapter 9 is "Conclusion" and summarizes the current research and provides recommendations for the state of practice and future research.

Chapter 2

Literature Review

The objective of this literature review is to study the current state of and current practices for Benefit Cost Analysis (BCA). The process of BCA and the components of costs and benefits are reviewed to illustrate the current study of the BCA. Here, the focus is on Road User Costs (RUC), since the objective of this study is to implement RUC into the BCA process. The definition and application of RUC, and methods of calculation, were also reviewed in greater detail.

2.1 Benefit Cost Analysis (BCA)

2.1.1 The BCA Procedure

In order to select the projects that deserve implementation, transportation planners and policy makers need to rank the candidates and plan their investment by considering the limitations of available funds. In the project selection process, Benefit Cost Analysis (BCA) is a common method used to evaluate the economic merit of a project. American Association of State Highway and Transportation Officials(AASHTO)[10] presents a BCA process that summarizes a general procedure for the economic evaluation of highway improvement projects, including building a new roadway, improvements on existing roadways, safety improvements, and highway project-management activities. Although the decision to select the most deserving projects should be part of a comprehensive evaluation system, the economic analysis of available alternative designs is essential and necessary. The manual of AASHTO illustrates the concepts and methodologies of engineering, as well as an economic analysis of the user benefits of highway projects.

In the manual of AASHTO, there are eleven steps in the entire BCA procedure. First of all, analysts need to prepare for the analysis, which includes two steps: defining the Project Alternative as well as the Base Case, and defining the level of analysis detail. The Project Alternative is defined as the improvement strategy for transportation system, while the Base Case describes the current condition without any significant improvements. The essential element in the first step is to consider what the impacted area is. In other words, the type of facilities and the portion of the roadway network that will be affected should be taken into account. In addition, the level of analytical detail should be determined as well, matching analysis effort with project benefits.

The third step, as defined in the manual, is to calculate the unit value for three types of user costs: travel time costs, vehicle-operating costs (VOC), and accident costs. There are two elements for calculating each type. One is the cost rate, which is the unit value for each type, while the other is the measure of units, which is obtained from engineering analysis by using comprehensive methods or tools.

Step four is to select the economic factors: discount rates, inflation rates, and value of life all need to be considered. The analysis period and evaluation date are also determined in this step. The user benefits and costs of each Project Alternative during the analysis period will be calculated into present value for comparability.

Step five is to analyze traffic performance for the Base Case and each Project Alternative. The manual mentions that if well-developed travel demand modeling suites are available, the effort requirements are less than analysis conducted manually. Regardless, considerable time and great effort is required even if comprehensive models are available[10].

In the next three steps, analysts calculate user costs and benefits for all Project Alternatives and the Base Case. Using the cost rate of user costs, as well as the measurements from traffic performance analysis, analysts can calculate the user costs for each alternative. The user benefits are calculated by estimating the cost savings between each Project Alternative and the Base Case. In addition, if the traffic performance is evaluated in particular years, the expansion of these values to the entire analysis period is needed.

The last three steps are to calculate the terminal value of the project, determine the present value of costs and benefits, and to make a final decision. The terminal value is a long-term benefit that estimates the present value left by the end of the life of the facility. Some projects with short-term life can have a high terminal value, while the terminal value of those projects with long-term life can be ignored. After the terminal value is calculated, the present value of costs and benefits are calculated by using the discount rate and the measurement of costs and benefits during the entire analysis period. This is the last key calculation of the procedure. Based on the results of this step, the last step is to make decisions. Benefit cost ratio and net present value are two common measures based upon which the most economically feasible project or projects can be selected.

The procedures implemented by different Departments of Transportation (DOT) have slight differences, but they are in general similar to the procedure of AASHTO [11, 12, 13].

2.1.2 Benefits and costs in BCA

To evaluate the benefit change associated with transportation investment, Consumer Surplus Analysis is an important concept. Consumer Surplus Analysis is defined as the difference between the sum that travelers have to pay and the sum that they are willing to pay[1]. In Figure 2.1, if the price falls from C1 to C2, the consumer surplus will be changed. The difference in surplus is the additional consumer surplus, since the transportation project will reduce the costs that travelers have to pay, while the travelers' willingness to pay remains the same. This additional consumer surplus is a user benefit from the transportation improvement projects.

There are four categories of benefits and costs that need to be considered in the BCA: agency costs, user costs/benefits associated with the work zone, user costs/benefits associated with facility operations, and externalities [11]. The agency costs include costs of design, construction, right of way, mitigation, future maintenance, and so on. The user costs and benefits associated with the work zone, as well as facility operations, are travel time and delay, VOC, and accident costs. Externalities are emissions, noises, and so on. In practice, benefits and costs that are considered in the BCA as performed by some DOTs do not cover all of these costs. The Minnesota Department

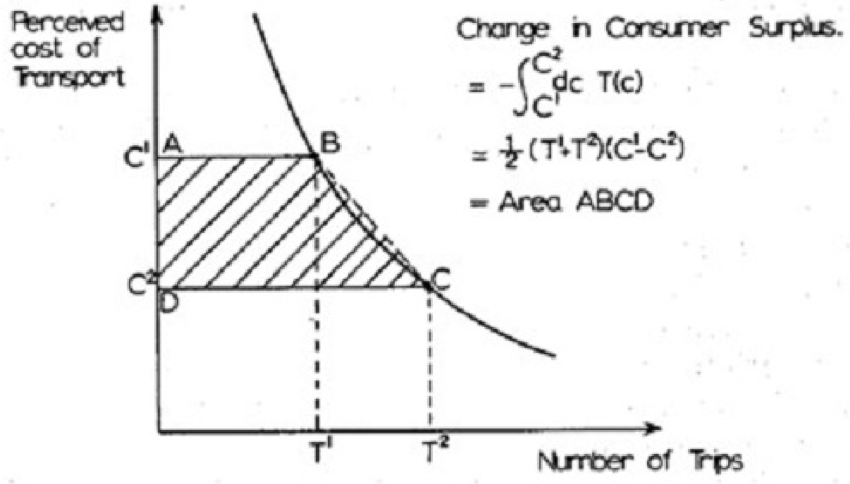

Figure 2.1: Consumer Surplus Theory. [1]

of Transportation (Mn/DOT) only takes agency costs and user costs/benefit associated with facility operations into consideration [12], while the California Department of Transportation (CALTRANS) includes also emission reductions [13]. The Virginia Department of Transportation (V/DOT) has a similar approach to CALTRANS, but takes engineering analysis of costs and benefits measures into more detailed consideration [14]. Apart of these benefits and costs, NCHRP report 456 [15] also proposes that the transportation mode choice, the accessibility of the facilities, community cohesion, economic development in that particular area, property values, and distributive effects need to be evaluated. However, this synthesis provides only general qualitative analysis of these criteria.

From the literature, it is clear that few agencies consider the quantitative evaluation of user costs/benefits associated with construction in BCA procedures. Most calculate the benefits and costs after construction of a project is completed, which only cover the facilities' lifetime.[12, 13, 14]. The user costs during the construction phase are ignored.

On the other hand, although literature such as ”User Benefits Analysis for Highways” [10] and ”Economic primer”[11] mention that user costs during the construction phase need to be considered, the economic analysis of these user costs is not clearly mentioned in the BCA process currently available in the literature.

2.2 Road user costs (RUC)

2.2.1 Definition of RUC

User costs during construction,maintenance, or rehabilitation activities are usually defined as Road User Costs (RUC), which are additional delay costs, VOC, and crashes costs for road users.[16, 17]. These are the cost discrepancies between the Base Case and Project Alternatives during the construction phase. There are many factors that affect RUC, such as the duration and characteristics of the work zone and the volume and operating characteristics within the impacted area [17].

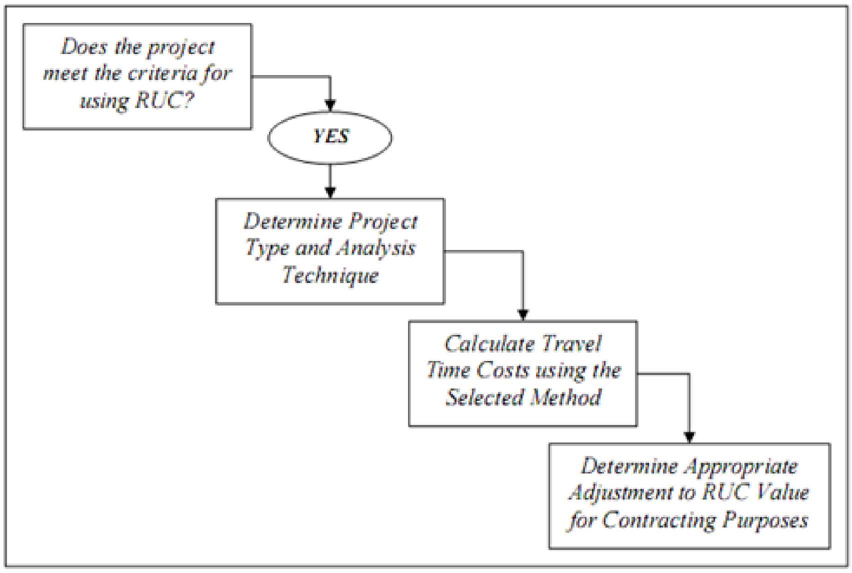

Figure 2.2: Procedure for Estimating RUC[2]

Daniels [2] suggests that RUC applies when the capacity of the roadway is added, traffic volume in construction area is very high, and economic impacts are expected. These are three main situations when RUC is important to the projects. Daniels also presents a procedure for calculating user costs, which is shown in Figure 2.2. This is a flowchart for estimating RUC. First of all, analysts need to decide whether RUC needs to be estimated. Then, the analysis methodologies are selected accordingly, to estimate the components of RUC. Last but not least, proper adjustment of RUC is needed to implement in contracting.

2.2.2 Components of RUC

Delay costs

The comprehensive delay costs can include speed change delay (due to accelerating or decelerating), reduced speed delay, queue delay (due to waiting time in a queue under forced flow conditions), and detour delay (due to additional time spent in taking different routes)[17, 16].

VOC

Vehicle Operating Costs are general concepts describing costs due to changes in vehicle operation, such as fuel, consumed tires, maintenance of the vehicles, and so on. Generally, VOC includes speed change in work zone, queue idling VOC (which is ”stop and go” issues during a queue in a work zone), and circuitry VOC, which is due to additional travel distance[17, 16].

Accident costs

Accident Costs (AC) include fatal accidents, non-fatal injury accidents, and property damage only [18]. AC can be a function of crash rate and Vehicle Distance Travel (VDT). However, since the data for work zone crashes is limited, and the exposure of the work zone is unclear for calculation, the evaluation of this component is suspect[16].

The actual consideration of RUC usually differs from the ideal conditions mentioned above. The NJ /DOT RUC manual[17] only considers reduced speed delay, queue delay, queue idling VOC, detour delay, and circuitry VOC. The estimation methodologies of these five components are only based on a spreadsheet. Salem and Genaidy[18]in Ohio Department of Transportation (O/DOT) selected speed change delay, reduced speed delay, stopping delay, and queue delay as delay cost measures and selected speed change VOC, stopping VOC, and idling VOC as VOC measures. Both of these DOTs do not consider accident costs as part of RUC.

Adams[19] conducted a survey for DOTs about the implementation of RUC in contracting. This survey has thirteen valid samples and includes three areas: methods for applying user costs, methods for determining user costs, and adjustment. From the survey, three states do not consider RUC at all. Six consider delay and VOC, five consider delay, VOC, and accident costs, and four of them only consider delay costs. Arizona is the only state in the survey that considers social impacts as RUC. In delay estimation, seven states use the reduced speed to determine the time lost in work zones, and eight states consider time lost in detour. Among these eight states, only three calculate the time lost in detours by utilizing analysis tools. None of the agencies in the survey consider environmental impact.

Salem and Genaidy [18] also conducted a survey for 22 states. The objective of the survey was to identify the role of RUC in pavement-type selection process. Among these 22 states, 14 states do not consider RUC at all when they design or select the alternative for pavement projects. The rest considered delay costs and VOC. However, none of the states surveyed take accident costs into account, due to the difficulty of monetizing the costs of crashes.

2.2.3 Application of RUC

User costs have two major applications. One is to compare different project alternatives in economic analysis. The other one is to estimate the additional costs due to work zone activities[20]. The former is usually the user costs implemented in BCA procedure, while the latter is implemented in Life Cycle Cost Analysis (LCCA) or contracting, which is also called RUC.

In LCCA, RUC is used for selecting pavement alternatives. LCCA is also a procedure that conducts economic analysis to evaluate economic efficiency between the Base Case and Project Alternatives over a facilities' lifetime. Two cost elements are included in

LCCA: agency costs and RUC. This is distinct from BCA, where the analysis period usually starts when the project is in the operating phase; the analysis period of LCCA usually covers the construction phase and the operating phase. LCCA is implemented when the benefits of the project alternatives are essentially identical. However, if the benefits of the project alternatives are not identical, BCA should be implemented[11]. In other words, BCA is implemented when planners or policy makers need to decide which project deserves implementation, while LCCA is implemented to select the best altern ative for the project that is already being implemented. RUC during the construction phase is emphasized in LCCA process[16, 21, 18], while only a few studies[11] in the literature mention that RUC should be considered in the BCA process.

In contracting implementation, RUC can be used for incentive or disincentive methods (I/D method), A+B contracting, and lane rental[19]. The I/D method involves giving the contractor a bonus if they finish the project ahead of time, with penalties when they are delayed in the construction. The A+B method means the bid for contractors needs to include the construction costs as well as the amount of time for construction. Lane rental needs RUC as well: the contractors will be charged for the time that the lane is closed during the construction [22, 19]. In addition, RUC can be also used for determining construction scheme and staging, lane closure schedule, and project delivery method [23]. RUC in contracting methods is also mentioned in "User Benefits Analysis for Highways" [10]. The authors present different contracting methods that might generate different RUC during construction. However, this study resource does not clearly illustrate when the differences are due to different duration or due to different daily RUC.

2.2.4 Methods of RUC calculation

In order to obtain RUC, traffic analysis tools can be used. These tools should be capable of obtaining delay measures, VOC measures, and accident measures. Alexiadis [24] describes seven categories of traffic analysis tools and reviews their use, advantages, and limitations. These tools are: sketch-planning tools, travel demand models, HCM-based tools, traffic signal optimization tools, macroscopic simulation models, mesoscopic simulation models, and microscopic simulation models. In general, a sketch-planning tool is the least costly. It is better suited to preliminary proposals that do not need in-depth analysis. Travel demand models can be used for predicting future demand, obtaining origin destination data, and performing static traffic assignment. HCM-based tools can quickly estimate capacity, delay, and queues on isolated links and intersections, but do not do well in a system where congestion is a larger problem. Traffic signal optimization tools are good for designing and optimizing signal phasing and timing plans. Simulation models involve high data-intensity and effort requirements, but can potentially provide the most detailed results.

In a survey, Ellis [20] summarizes seven general methods to calculate RUC in a work zone, which are: the AASHTO Red Book method, MicroBENCOST, QUEWZ-PC, TRDF relationships, HDM-III VOC Sub-model, and the ARFCOM model. In addition the survey shows that a broad range of methods are utilized by different agencies, from simple formulas to software packages. Some DOTs do not even have a formal method for RUC calculation. No generally accepted approach of RUC calculation existed at the time the survey was conducted [20].

Adams[19] shows that QuickZone, DelayE, as well as DUCK can also be used for RUC calculation. The authors recommend DelayE and DUCK for the Utah Department of Transportation (U/DOT) for contracting evaluation. Salem [18] summarize eleven tools for RUC calculation for LCCA in pavement projects. These include WorkZone RUC, CO3, New Jersey spreadsheet, and some other models developed by other countries or the World Bank. The objective of reviewing these tools for RUC calculation was to find out a better method for O/DOT in the LCCA process, to select the best pavement alternative. Besides these tools, Edara[25] mentions that Highway Capacity Manual 1994, as well as the 2000 manual, and microscopic simulation models can be implemented for RUC calculation. This paper also visits the issues of data-intensity and effort requirement for the RUC calculation tools in short-term construction projects.

A few papers present an evaluation of these tools by using field data from work zones. Benekohal [26] compares FRESIM, QUEWZ, and QuickZone by using field data from 11 work zones in Illinois. From the results of the comparison, none of the tools achieved accurate results. Schnell [27] evaluates six traffic analysis tools with field data from four work zones in Ohio. These six tools were the Highway Capacity Software (HCS), Synchro, CORSIM, NetSim, QUEWZ 92, and a spreadsheet tool developed by the Ohio Department of Transportation. The paper indicates that the microscopic simulation models underestimate the queue length, and that they cannot estimate the oversaturated conditions of a work zone. QUEWZ 92 obtained the most accurate results among all these tools. These comparisons focus on comparing the estimation from tools within the field data, such as speed, queue length, and travel time. They do not extend the comparison into the entire impacted corridor or area.

Krammes [28] also evaluates traffic analysis tools for highway construction. They present a selection of tools for evaluating area-wide impacts due to highway construction. This paper focuses on projects involving high demand roadways, such as freeways and highways, and examines area-wide impacts due to construction activities, such as diversion and change of mode. This paper concludes that the tools that have a traffic assignment function are important for area-wide analysis in highway construction. Travel demand models are especially recommended for this kind of analysis. However, analysis effort costs are not included in this paper.

2.2.5 Summary

Reviewing the BCA process shows that current processes do not include RUC as a standard element that might affect the accuracy of BCA results. A review of RUC application and methodologies shows that most of current studies only consider RUC in work zone areas rather than estimating area-wide impact. The area-wide impact could be important when traffic diversion is significant due to work zone activities.

Chapter 3

Need and Objective

3.1 Need for this study

A healthy urban region requires a transportation system that can efficiently move both goods and people. Over the decades, even in developed areas, such transportation systems still need improvement in order to achieve a timely and efficient performance. Roadway reconstruction is a common way to improve a transportation system, i.e., repairing the pavement, adding lanes, or changing the roadway geometry to increase capacity. Safety and mobility during these improvements always concern both transportation agencies and travelers, since travelers may encounter delays due to speed reductions in work zones, additional fuel costs due to the longer distance of detours, and safety issues due to work zone activities during construction periods. These travel time, vehicle operating, and accident costs are the three general elements that make up Road User Costs (RUC). Each can be quite different due to different construction strategies for a given project.

RUC is not considered by many agencies when conducting construction planning and RUC is rarely included in the Benefit Costs Analysis (BCA) processes implemented by most DOTs. Traditionally, the analysis period for BCA starts from the first year of the operation phase of a new facility, and the user benefits are the costs saved by the new facility. RUC is not involved in BCA and is thereby considered irrelevant to the selection of economically feasible projects. However, we support that RUC should be considered during project selection, since the traffic impact during construction might cause such high costs for the users that these costs might reduce the overall user benefits of the project. Therefore, there is a need to examine whether planners could make different decisions based on a BCA process with and without RUC involved.

In order to involve RUC in the BCA, RUC should be estimated as follows. In the Literature Review Chapter of this study, several methods for estimating RUC are presented, from simple calculations to the implementation of microscopic simulation. Although several studies summarize the accuracy of these analysis tools for RUC estimation, the available literature only focuses on performance in work zones, rather than area-wide impact[26, 27, 25]. However, the user costs for the entire impacted area should be taken into account when traffic diversion is a strong issue.

Nowadays, with the development of urban land use, the existing roadways in urban areas suffer from congestion, and an expansion of these roadways is needed to maintain reasonable traffic conditions. Since these existing roadways already have high traffic demand, close to or even greater than the available capacity, reconstruction on these roadways will cause significant traffic diversion. The diverted traffic might reduce the level of service on adjacent roadways, force the initial users of those roadways to take new routes, or increase crash opportunities, thereby increasing the costs to their initial users. In such cases, diversion due to the construction activities affects not only the users in the work zone area, but also the users in adjacent roadways in the same corridor. Accordingly, RUC should take the impact of diversions into account.

Current literature does not mention the accuracy of analysis tools for evaluating RUC due to area-wide impact. There is therefore a need to examine whether currently available analysis tools are able to accurately estimate such RUC. Additionally, the data intensity and effort requirement of these tools should be examined as well, since the time and budget for BCA is usually limited. It might not be possible to spend years and millions of dollars to plan a small project, whereas simple estimation might not be sufficient for a larger project. In general, accuracy increases with the sophistication of the tools, but so does the effort for utilizing these tools. The tradeoff between accuracy and effort requirements for models should be decided before the BCA is conducted. Therefore, tools for evaluating area-wide RUC should be studied in terms of accuracy, as well as data and effort requirements. This way planners and decision makers can have a range of available options and can efficiently conduct BCA.

3.2 A comprehensive tool for RUC evaluation

Before we study the current analysis tools for evaluating area-wide RUC, the perfect tool should be defined, in order to comprehensively understand the capabilities of the available tools and the models they are based on. Ideally, if models and the input data for these models are perfect, the results can accurately emulate reality. The corresponding perfect models and respective input data are presented as follows. Although tool user-friendliness and availability are important in this study, for right now, we will focus only on the accuracy and performance of the underlying models. Evaluating the performance of specific model implementation is beyond the scope of this study, at least for models of simulator resolution and level.

3.2.1 Models

Traffic assignment

Models involved in RUC calculation should be able to conduct comprehensive traffic assignment and be able to predict the boundary of the impacted area as well as the new traffic demands for all links inside the impacted area. The traffic assignment algorithm should have many considerations, such as the capacity of the roadways and traffic management strategies. The change of origins and destinations of travelers should be considered as well. Travelers may well change their trip plans during the construction phase. For example, trips can be canceled; departure time of trips can be shifted to other times; or travelers can choose public transportation instead of driving. These behaviors have been observed and are quite common in reality; they also affect the traffic demand of roadways.

Based on the results of traffic assignment, the boundary of the impacted area can be determined, and corresponding strategies can be created to maintain reasonable traffic conditions within the impacted area. The traffic demand of all roadways inside the impacted area will be also needed for evaluating diversion due to construction.

VHT and VMT calculation

Vehicle-Miles Traveled (VMT) is the number of miles that vehicles have traveled within a particular area and time period. This element involves all road users within the impacted area, as does Vehicle-Hours Traveled (VHT). When VHT is estimated, the model should be able to consider the effect of signal control, the change of speed due to changes in the speed limit, the speed due to changes in traffic conditions, and so on.

3.2.2 Input data

Accordingly, input data are needed when the model is implemented. With this kind of information, the model should be capable of emulating the same traffic condition as in reality. Perfect input data includes the following types of information:

Network information

Network information includes roadway geometry, roadway capacities, and speed. The geometry includes lengths, widths, and number of lanes. Network information is essential for all models.

Traffic demand

Since the perfect tool requires the ability to predict traffic demands during the construction phase, the current demand should be available to start with. The traffic demand can be given in the form of the exact link flows or Origin Destination (O/D) information. Accordingly, if particular paths exist between O/Ds in reality, this kind of information should also be available for evaluation. In general, the traffic demand is an important element for any model to conduct each prediction mentioned above. The accuracy of the prediction mostly lies in the accuracy of the traffic demand.

Traffic management strategies

In reality, traffic conditions are maintained by a series of traffic management strategies, such as traffic control, ramp metering, application of an Intelligent Transportation System, Variable Message Signs, and so on. Traffic patterns could change due to different policies or different traffic management strategies. Information about what traffic management strategies are considered in the traffic assignment algorithms is essential, since those algorithms are designed to obtain the traffic demand and flows of the roadways. Without considering traffic management strategies, the obtained traffic flows cannot be the same as reality.

Limitations

However, perfect data cannot be available for all projects. It is difficult to collect information that is exactly the same as reality. If perfect inputs are not available, the models might not predict accurate results. In addition, the current available models might not be perfect as well. Therefore, it is ultimately more practical and realistic to examine the accuracy of currently available tools. As stated above, the data intensity and effort requirement of these tools should also be examined, to assist planners and policy makers in efficiently conducting the BCA process with RUC involved.

3.3 Objective of the study

The main objective of this study is to propose a comprehensive Benefit Cost Analysis process, considering all kinds of costs, including investment costs, operating costs, RUC, and all kinds of user benefits. Comprehensive RUC estimation methodologies for area-wide impact are also proposed, in order to most efficiently conduct the BCA.

The improved BCA procedure has a new timeframe for the analysis period, and a new component of user benefits, when contrasted with the traditional BCA. The new timeframe for the analysis period includes the construction phase as well as the operating phase. In the traditional BCA procedure, the benefits are calculated from the first year of the operating phase. However, the procedure in this study calculates the user benefits from the first year of the construction phase. Road User Costs are defined as user benefits in the BCA, specifically as negative user benefits.

Besides the improved BCA procedure, this study will also present methodologies of RUC estimation. As the current calculation of RUC is only for work zone areas, the new calculation procedures in this study take area-wide impact into account. In the Literature Review Chapter, various kinds of analysis tools capable of evaluating RUC are reviewed. However, only parts of them can evaluate area-wide impact, such as parts of the sketch planning tools, travel demand models, and simulation models. Since this study focuses on area-wide RUC, only tools from these three categories are selected. In addition, the accuracy and the effort requirement of these tools are examined by implementing a project in Minnesota. By calculating RUC for the same Minnesota project using different tools, the model validation and the results accuracy of the different tools are compared and illustrated. Since the model and the input data for each tool is not perfect, the objective of the comparison is to find out the capability of currently available tools that can be implemented for RUC estimation in terms of accuracy and also data and effort requirements.

Chapter 4

Model/Tool Overview

Since this study will improve several tools in the calculation of area-wide Road User Costs, the model theories as well as the inputs and outputs should be reviewed before implementation. The literature review concluded that only parts of the analytical tools are able to conduct an evaluation of area-wide impact. Although HCM-based tools and operation tools can be used for engineering analysis of user costs, they are more useful for isolated transportation facilities [24]. This study selected sketch planning, travel demand, and simulation models to conduct an engineering analysis of Road User Costs. Specifically, QuickZone was selected as the sketch planning tool; Cube Voyager was selected as the travel demand model, and AIMSUN was selected as the microscopic simulation model.

4.1 QuickZone

QuickZone, developed based on Microsoft Excel, is easy to use and quick in obtaining results. It uses a simple deterministic queuing model to estimate delay and queue length in the work zone, as well as user costs. In QuickZone, volume variation over days and seasons is considered. QuickZone takes into account various factors during the construction, such as peak spreading, trip cancelation, and route changes. The traffic impacts in QuickZone are expressed in terms of user costs, user delay, queue length, and traffic behavior, such as trip cancelation and time shift.

4.1.1 Model theory

QuickZone implements a simple queuing theory: if the demand of link exceeds its capacity, a queue is generated; otherwise, there is no queue in that link.[29].In other words, when the hourly demand is over capacity, delay is generated, due to the queue in the current link at that hour. If the demand is less than capacity, there is no delay, since there is no queue waiting. Those vehicles in queue will be considered additional demand in the next hour. In addition, the demand of the links will be limited by upstream outflow. If the upstream hourly demand is less than its link capacity, then the upstream outflow is the hourly demand. However, if the upstream hourly demand is over the link capacity, the upstream outflow is only the link capacity and the rest of demand still stays in the upstream link. Generally, these can be expressed as follows[29]:

$$\ddot{V}(l,t) = V(l,t) - V(\overleftarrow{l},t) + \dot{V}(\overleftarrow{l},t) + Q(l,t-1) \tag{4.1}$$

Where $\ddot{V}(l,t)$ is the constrained link demand, V is its initial link demand, $V(\overleftarrow{l},t)$ is the demand of the upstream link, $\dot{V}(\overleftarrow{l},t)$ is the outflow of upstream link, and Q is the queue size remaining from the previous hour. The terms $V(\overleftarrow{l},t) + \dot{V}(\overleftarrow{l},t)$ represent the difference between upstream demand and upstream outflow. Since the upstream outflow cannot be greater than upstream demand, the result of $V(\overleftarrow{l},t) + \dot{V}(\overleftarrow{l},t)$ can only be zero or negative. If is the result is zero, the demand in downstream link is not affected. However, if it is negative, some vehicles cannot pass through the upstream link, and they have to stay in that link until the capacity of the link is available for them. The vehicles constrained in the upstream link will also reduce the demand in downstream link. In QuickZone, the delay is calculated based on the queue size of the links, and the total delay is the aggregated results of all links for entire analysis period.

QuickZone can estimate the diversion situation due to the reduction of work zone capacity. Analysts need to define the detours for traffic diversion. At the beginning, the QuickZone model assumes that all demand will stay in the mainline after work zone capacity has been reduced. Then, QuickZone calculates the delay and decides how many vehicles need to be diverted in order to reduce the delay in the work zone area. There are two important constraints in this traffic assignment. First of all, the diverted demand from the mainline is constrained by the capacity of the detours. QuickZone will estimate the available capacity of detour links. It assumes the detour cannot suffer congestion after the traffic assignment. The diverted demand from the mainline plus initial demand in the detour cannot exceed the capacity of the links. Once the available capacity has been occupied, the rest of the vehicles still stay in the mainline, no matter how much delay they generate. In this case, the capacity of the detour is important for traffic assignment. If the detour has congestion, it cannot be used for carrying traffic diversion in QuickZone.

In addition to traffic diversion, QuickZone also takes other forms of traffic behavior into account, such as mode choice and trip cancellation. The percentages of mode choice and trip cancellation are inputs, which can be defined by analysts. According to those percentages, QuickZone will adjust the corresponding hourly demand and estimate the final delay. New hourly demand of the links will be estimated after the mode choice change, trip cancellation rate, and traffic diversion are calculated.

4.1.2 Input data

In order to obtain reliable results, four types of information are required by QuickZone: Network, Project, Travel demand, and Corridor management data. Network data includes the number of lanes, link length, capacity, jam density, and so on. Project data includes information on construction strategies, such as the duration of construction, as well as the reduction of capacity in the work zone. Travel Demand data describes the hourly demand of every link in the network. This hourly demand can be obtained either from real measurements or the AADT of the links. If only AADT is available, analysts need to estimate the hourly traffic pattern in order to calculate the hourly demand for each link. Corridor Management data include congestion mitigation strategies, such as increasing the capacity of detours or the setting up of Variable Message Signs. In addition, analysts can enter mode changes or trip cancelation fractions to reduce the traffic demand for work zone areas. In general, these inputs may be available for analysts, but the accuracy of the inputs might not be clear, since most are from engineering judgment and simple estimation.

4.1.3 Output data

The user costs in QuickZone consist of two components: delay costs and vehicle operating costs. The delay costs are the waiting time of the queue, due to capacity reduction of the work zone. QuickZone does not consider the additional travel time due to reduced speed and longer distance. The Vehicle Operating Costs are the costs for travelling longer distances. Although there are many measurements in Vehicle Operating Costs, QuickZone only considers the additional distance as the key element. It is calculated by multiplying diverted demand by additional miles between the detour and mainline. On the other hand, QuickZone cannot estimate crash costs. If analysts need to analyze the crash costs, additional tools are needed.

4.2 Voyager

Cube Voyager [30]was selected as a tool for implementing the travel demand model. It is an integrated modeling system for transportation planning. Cube Voyager can be incorporates with any model methodology: four-step models, discrete choice model, and activity based models, and so on, based on the modular and script-based structure. The four main models are: Network, Matrix, Highway, and Public Transport. Other supplementary models can be used for modeling and analysis of planning policies, as well as urban or regional improvements in transportation systems [30].

4.2.1 Networks

Networks contain utility functions to simultaneously process multiple input networks and generated one output network. The input and output network can be in many different formats: ASCII records, standard database in dBASE style, binary network format in Cube Voyager, Tp+ Tranplan, and other packages. This program creates the roadway database containing the details of network link records, node records, link speed, link capacity, and so on. The output can also be stored in an ESRI geodatabase for viewing and editing the network.

4.2.2 Matrix

Users can process zonal data and matrices based on the user script expression by using Matrix functions. Zonal data and demand matrices are inputs, and demand matrices and reports can be outputs. The flexible script language allows users to apply various types of travel demand processes, such as computing new matrix values, trip distribution, trip generation, converting different formats of matrices, reporting values from matrices, transposing matrices, generating matrices, and renumbering, aggregating, and disaggregating matrices[30].

4.2.3 Highway

The Highway model is primarily used to assign trips to network links. The input data for this model can be a highway network, zonal demand matrices, junction data, turning penalties, and so on. The output data can be a new network, new demand matrices, junction delay, and so on. In the Highway model, the primary traffic assignment is link based traffic assignment, which builds paths based on the link costs. It is iterative that paths between origins, destinations, and assigned trips on each link be updated along with the updated link costs until the criteria for termination is reached. Different criteria can be defined by users in order to decide whether the iterations for the traffic assignment are sufficient. In the traffic assignment process, paths can be built based on different methodologies, such as all-or-nothing, all-shortest paths, capacity restraint, etc.

4.2.4 Public Transport

The Public Transport model provides functions for the study of unlimited-scale transport systems. This model is able to analyze the transfers between modes, operations, and lines; to conduct traffic assignment for transit lines; to evaluate stop-to-stop movements, and so on. The public transit services can be analyzed in mixed or dedicated facilities. The inputs for this model are the transit network, including various kinds of transportation facilities, demand matrices for public transport, specific data of selected lines or links in the network, generalized cost information, and so on. The outputs include demand matrices for public transport, skim and select-link matrices, reports of input data, model results, etc.

4.3 AIMSUN

In this study, AIMSUN 6.0 (Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks) was selected as a tool to implement the microscopic simulation model. AIMSUN is able to model large-scale networks consisting different types of facilities, such as freeways, arterials, and ring roads. AIMSUN can provide a great level of detail about the network, to test transportation operations, management strategies, and traffic control systems before an actual implementation.

AIMSUN models the movement of individual vehicles based on several driving behavior models (i.e., car-following, lane changing, and gap acceptance models) and each vehicle is continuously simulated throughout the time inside the network. Vehicles entering the system (i.e., the network) follow a statistical distribution of arrivals and each vehicle is assigned certain attributes, such as a vehicle type and corresponding vehicle characteristics, following statistical distribution. Individual vehicles are tracked over short, fixed time intervals (i.e., stimulation step) through the network. AIMSUN can simulate most of the traffic equipments in reality, such as traffic lights, ramp meters, variable message signs, and loop detectors.

4.3.1 AIMSUN models

Simulation parameters

In microscopic simulation, individual vehicles are simulated in detail, based on driving behavior models: car-following, lane changing, and gap acceptance models. The functions for those models are in terms of several parameters. The values for the model parameters can be defined and calibrated by the users, based on the traffic conditions that need to be reproduced in the simulation. Setting proper values for the parameters is important in order to calibrate the driving behavior in the model.

The parameters can be defined as categories: global parameters and local parameters. [31] Global parameters are valid and implemented for all vehicles within the entire network, such as driver's reaction time, vehicle characteristics (i.e., Length, Width, Maximum desired speed, Maximum acceleration and Maximum deceleration, etc.), percentage of overtake, and queuing leaving speed. Among these parameters, the characteristics of each vehicle are assigned from a truncated normal distribution [3], whose mean and standard deviation are defined by the users. The global parameters affect the vehicle behavior throughout the entire system. Local parameters only locally affect the vehicles that enter the particular section instead of affecting the vehicle behavior all over the network. Examples of local parameters include speed limit, distance zone 1, and distance zone 2.

Models for vehicle movement

Dynamic traffic assignment model

In the AIMSUN simulator, traffic assignment is based on discrete route choice models. An individual vehicle will be assigned to a path when it is generated in an input section of the network. The paths between all OD pairs can be user-defined, or the calculated paths from the model. Vehicles follow the path based on the route choice model. A vehicle is assigned to the initial shortest path that is calculated at the moment the vehicle is generated. Nevertheless, when this vehicle travels through the network, that initial shortest path might no longer be the shortest. In the route choice model, new paths are recalculated in every time interval, which is defined by the user (i.e., 5 minutes). The vehicle can follow a new available path during its trip.

Car-following model

The car-following model implemented in AIMSUN is based on the Gipps model[3]. The AIMSUN car-following model has been modified to consider the influence of vehicles in adjacent lanes, speed limit on the sections or turnings, and the influence of grades of the section. The speed of each vehicle in a particular section is a function of current speed, maximum desired speed, reaction time, maximum acceleration and deceleration for the vehicle, and estimated desired deceleration. The maximum desired speed of each vehicle in a particular section is a function of the maximum desired speed of the vehicle, speed acceptance of the vehicle, and the speed limit of the section or the turning.

Lane-changing model

The lane-changing model is a development of the Gipps lane-changing model [32, 3]. It is modeled as a decision process, analyzing the necessity and desirability of a lane change and the feasibility conditions for the lane change. An example of a "necessity" is a lane change that is needed for turning purposes that have been predetermined by the route. An example of "desirability" is a lane change in order to reach a desired speed. The feasibility of a lane change is determined by the local traffic conditions and the location of the vehicle in the network.

Gap Acceptance model

A Gap Acceptance model is for simulating vehicle "give-way" behavior. It determines whether a vehicle with lower priority is able to cross an intersection; the decision is based on the position and speed of the vehicle with higher priority. The Gap Acceptance model considers the vehicle acceleration rate, desired speed, speed acceptance, maximum give-way time, and so on.

4.3.2 Input data

Generally, the input data for AIMSUN is of three types: network, traffic demand, and traffic control plans. The network contains the information on the network geometry, layout of roadways and intersections, location of traffic equipments.

The traffic demand in AIMSUN is defined as two different types: traffic states and time sliced Origin/Destination (O/D) matrices. Traffic states contain the traffic volumes at input sections and the turning percentages at each decision point that split the traffic flow. When traffic states are used as traffic demand, vehicles are stochastically assigned in each decision point, based on the turning percentages. In this case, there is no particular path for any vehicles and no routing issues for vehicles. Time sliced O/D matrices contain the number of trips between every pair of origin and destination. Routes between each O/D pairs are calculated and vehicles follow the routes based on the particular route choice model.

Traffic control plans are implemented to maintain the traffic condition at a reasonable level. Such input contains information about phases and the timing of signal designs for signalized intersections; priority information for un-signalized intersections; and signal information for ramp metering.

4.3.3 Output data

AIMSUN can provide detailed results of simulation in various levels as well as different periods. Statistical outputs, like traffic flows, travel times, speeds, queue length, etc., can be generated by this simulator. The statistical results can be aggregated at different levels, for an entire system or individual sections. A continuous animated graphical representation of all the vehicles in the traffic network can also be generated for traffic analysis.

4.4 Summary

This section comprehensively reviews QuickZone, Cube Voyager, and AIMSUN simulator. The objective of this section was to clearly illustrate the model theories, inputs, and outputs of these tools, which provides basic information for the engineering analysis of user costs described in the Methodology section. QuickZone, as a simple sketch planning tool, implements a queue theory to generate delay. It requires four types of inputs: Network, Project data, Travel demand, and Corridor management data, which are often readily available when analysts conduct the analysis. Cube Voyager contains four basic programs: Network, Matrix, Highway, and Public Transport, which can be used to conduct a four-step planning procedure. Analysts can achieve multiple objectives of evaluation by constructing comprehensive scripts with flexible coding language. AIMSUN is a microscopic simulator that implements dynamic traffic assignment algorithms. It typically requires three types of inputs: network, traffic demand, and traffic control plans. The outputs of AIMSUN contain detail MOE for system, as well as individual sections in the network.

Chapter 5

Methodology

Due to urban land development, today many urban corridors around the country experience demand that is often greater than capacity. Thus, existing infrastructure often requires expansion. Expanding a developed system usually does not involve new roadway construction; instead, the best option. Such roadways usually already serve considerable demand, a fact that increases the importance of Road User Costs (RUC) in construction projects. RUC expresses the additional costs to the traveling public resulting from the construction activities [33]. However, current Benefit Cost Analysis (BCA) rarely considers RUC during the construction phase. The calculation of benefits usually starts from the first year of the operation phase, after construction is finished; this ignores the traffic impact due to construction. Although this work's Literature Review shows that some procedures take user costs during the construction into account, there currently is no clear and detailed procedure for implementing RUC into BCA. If RUC is not included, the economic valuation of the projects might be biased and, therefore, the project selection decisions will be inconsistent.

This study proposes an improved BCA procedure to illustrate a new consideration of Project Alternatives and a new timeframe for the analysis period. These changes are made to better take RUC into account. This new BCA procedure is more comprehensive in benefits estimation, including the negative benefit during the construction phase and the positive benefit after the project is completed. RUC calculation involves knowing or modeling the traffic conditions during the construction period. To estimate RUC for planning purposes, one needs tools or methods that can estimate traffic conditions for a hypothetical scenario. There are many relevant tools and methods one can use for this purpose. Different tools or methods have different requirements and can achieve different levels of accuracy. In this study, three levels of traffic analysis tools will be examined for RUC calculation. Essentially, analysts need to select an efficient way to conduct engineering analysis in the BCA process, in order to obtain the most reliable results possible within budget constraints and data availability. However, the efficiency of those tools against the reliability of their results is not clear so far. It would be better to compare all of the available traffic analytical tools to find out their efficiency in a BCA procedure.

5.1 Improved BCA procedure

From the Literature Review, it is clear that the current BCA practice does not comprehensively consider RUC, which is a significant limitation, especially in the selection of alternatives that have very large differences in terms of construction time and traffic operation. This methodology section presents an improved BCA procedure that illustrates the new timeframe for the analysis period for user benefits and the additional consideration of RUC in these user benefits.

5.1.1 The improvements in BCA

In State-of-Practice BCA, RUC is not included in user costs or user benefits. Therefore, the user benefits are calculated from the first year of the operation phase. If RUC is so important that it has to be included, the user benefits need to be calculated from the first year of the construction phase until the end of the facility's life. The new BCA procedure is similar to traditional BCA; however, this study defines a new timeframe, as well as some additional considerations.

The first step in improved BCA procedure is to define the Base Case and Project Alternatives. Base Case is the scenario that retains the current situation into the future. In order to properly evaluate the traffic condition of the Base Case scenario, the roadways nearby should also be included in the evaluation. However, during the period between the planning stage and the implementation of the project, those roadways can also evolve as parts of other projects. In this case, the current situation of the entire network in the Base Case scenario might not be completely retained for the network analysis. Analysts need to make proper assumptions based on the planning information of other projects that might affect the traffic condition of the facilities during the Base Case scenario in the future. These assumptions should also be applied for Project Alternatives during the BCA procedure. Project Alternatives are the different strategies that improve the current facilities against the Base Case. In BCA, costs savings between Base Case and Project Alternatives are evaluated and defined as user benefits. Based on these user benefits, as well as agency costs, analysts will decide which Project Alternatives are worthy of implementation. In this step, analysts need to define the Projects and their alternatives. First of all, different projects that share the same budget source should be defined. They may all be implemented when they are all economically feasible and the budget is sufficient. Then, different alternatives for each project are designed. If one project is eventually ranked high for deployment, several alternatives with different strategies need to be designed; the one with highest economical feasibility is selected among these alternatives.

Obviously, if the government budget is sufficient, all projects that are economically feasible can be implemented. However, in fact, analysts need to evaluate all of the projects and select the competitive ones that have greater economic feasibility within budget constraints. Each project has its corresponding Base Case. Each project is different and is competing with other projects for the same budget resources. For example, Project A might be adding new lanes to a highway in location A, while Project B might be constructing a new freeway segment in location B. Both projects can be economically feasible. When budgets are sufficient, both alternatives can be implemented to improve the traffic condition of their respective locations. However, if the budget is limited, only the alternative that has the greater Benefit Cost Ratio or Net Present Value will be implemented first.

Once the projects are defined, their alternatives should be designed. There is only one Base Case against all Project Alternatives in each project. At most, one alternative can be selected for that particular project, although all of them may be economically feasible. The purpose of designing multiple alternatives for one project is to obtain the optimal alternative that makes the project the most economically feasible. Different Project Alternatives have different construction strategies, different contracting, and different operational improvements. Different construction strategies can be: a different number of lane closures and a different schedule of construction, such as night construction and weekend construction; different contracting can be lane rental, public-private partnering, A+B bidding, and so on. Different operational improvements include adding new lanes, improving signal timing, adding Intelligent Transportation System (ITS), etc. Analysts design a certain number of comparable alternatives and evaluate them.

Both projects and their alternatives need to be considered at the beginning of the BCA, and all alternatives are parallel-compared in the BCA procedure. For the hypothetical projects mentioned above, those two projects in two different locations also can have two different strategies (Figure 5.1). The analyst needs to evaluate four Project Alternatives to decide which one is worthy of implementation. In traditional BCA, analysts only consider one alternative for each project. Once the project with high Benefit Cost Ratio is determined, different construction alternatives for this project play a less important role in the BCA procedure, but Life Cycle Costs Analysis (LCCA) come in to evaluate different alternatives for the same project. The economic valuation of certain alternatives can be biased, if that Project Alternative is not selected as the optimal one from all comparable candidates. Therefore, when analysts define the Base Case and Project Alternatives, these two levels of alternatives need to be comprehensively considered.

In addition, the details of alternatives are important in this step. These details include impact area, engineering characteristics, project build-out schedule, project capital costs schedule, operating cost schedule, and so on. Analysts need to evaluate the impact area due to the project: it is better to select a comprehensive area that can cover all impacts for all alternatives.

After the Base Case and Project Alternative are defined, the Timeframe for BCA should be defined. Usually, user benefits are calculated from the first year of the operation phase. From the perspective of consumer surplus theory, the cost for travelers during the construction phase is higher than when there is no construction. The consumer surplus is lower, which can be defined as costs for society. However, these costs are different from the investment costs that are directly incurred by the agency. Therefore, it would be better to define them as part of user cost or negative user benefit. Its calculation should start at the first year of construction, rather than the first year of

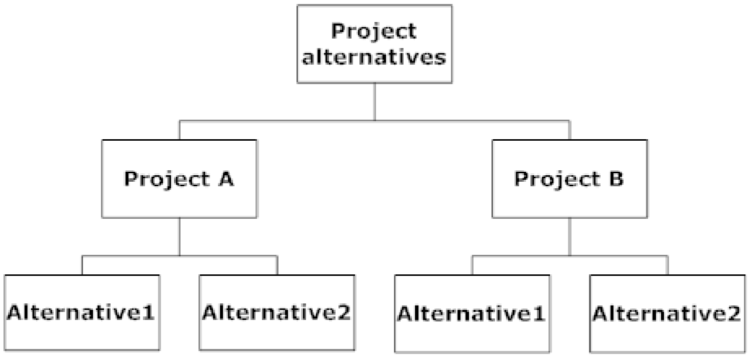

Figure 5.1: Project Alternatives

operation phase.

However, if the benefit calculation is from the first year of the construction phase, the problem of the duration of the analysis period for all alternatives arises. For the same project, different Project Alternatives might have different construction durations. In this case, if the facility lifetime is defined as the same for all alternatives, the analysis period will be the construction duration plus facility life time. The analysts need to define a unified analysis period for all Project Alternatives and all projects. This unified analysis period includes construction phases and operation phases. For example, Project A has two construction strategies. One has a construction phase of one year and the other has a construction phase of two years. The analysis period of this project is defined as 25 years. The operation phase for the first alternative is 24 years, and for the second alternative it is 23 years. Correspondingly, the Base Case also has a 25-year analysis period.

The new definition of the analysis period is shown in Figure 5.2. Cons. stands for the construction phase, while Oper. stands for the operation phase. Alternative

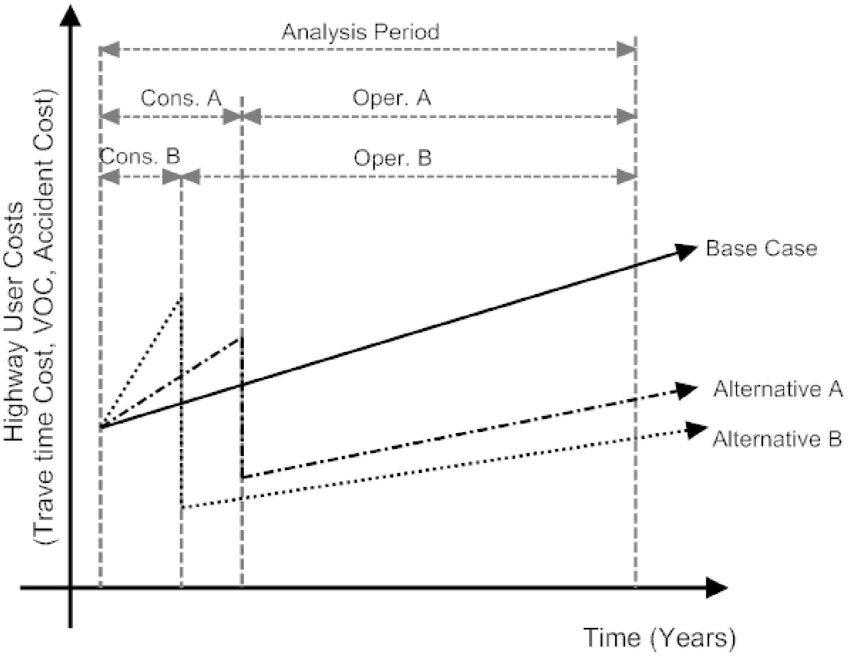

Figure 5.2: Analysis period of BCA

A and Alternative B have different construction phases and operation phases, but the total analysis period is the same as the Base Case. During the construction phase, the user costs are higher than the Base Case, since the construction activities might cause higher delay, VOC, and accident rate. However, the user costs of both alternatives in the operation phase should be less than the Base Case since the project has improved the travel time, VOC, and accident rates for travelers.

The evaluation date should be the same for all alternatives. In economic evaluation, all benefits and costs will be calculated on their present value. Based on present value, benefit and costs can be aggregated, and results of the Benefit Cost Ratio become comparable for all alternatives.

In general, two major steps are improved with the proposed BCA procedure. First of all, analysts need to define the Base Case scenario, Projects, and their alternatives. After the Project Alternatives and Base Cases are defined, the analysis period of all alternatives needs to be defined. Usually, the analysis period includes the construction phase and the operation phase. The entire analysis period is the same for all alternatives, while their corresponding construction phase and operation phase can be different. Differences of VHT and VDT in operation phase as well as during the construction phase need to be calculated, from which RUC can be calculated.

5.1.2 Improved Benefit Cost Analysis procedure

Since some steps in the BCA procedure are changed in order to take RUC into account; the new procedure is summarized below for clarity. It has four general stages for conducting the BCA: planning stage, engineering analysis stage, economic valuation stage, and evaluating results stage[12].

Stage One.Planning analysis

The first stage is planning analysis, where analysts need to define the Base Case and all Project Alternatives, the level of detail required, and the analysis period for all alternatives. For defining the Base Case and Project Alternatives, analysts need to consider the alternatives both for different projects and for the same project but with different strategies. All Project Alternatives are evaluated in parallel. Necessary information for the Base Case and Project Alternatives should be available at this stage, such as the impact area of the project, engineering characteristics like traffic volume and speed of the network, the construction schedule, and the schedules for project capital cost and operating cost.

In addition, analysts need to define the level of analytical detail. There are two limitations for defining the level of detail: the available data and available budget for the planning stage. If available data for traffic analysis is limited, analysts can decide to use a less sophisticated model that has a lesser data requirement or decide to collect the necessary data for the more sophisticated models. The data collection depends on the budget for the planning stage. If the projects have a sufficient budget and time for planning, analysts can collect as much data as necessary to build reliable, sophisticated models. Otherwise, analysts can only conduct engineering analysis in a less sophisticated way. However, the reliability of the results is greater as the tool get more sophisticated and so does the effort for corresponding traffic analysis. Once the level of detail required is defined, all alternatives should be analyzed in parallel. The same level of analytical tools should be implemented for the Base Cases as well as all Project Alternatives.

After the basic information and level of detail is defined, analysts need to decide on a unified analysis period for all alternatives. As described above, the analysis period includes the construction phase as well as the operation phase. In contrast to traditional BCA procedure, the user benefits here are calculated from the first year of construction phase, although the benefit during the construction is negative. In addition, an evaluation date is also needed for calculating the present value.

Stage Two.Engineering analysis

Once the level of detail required is determined for the planning analysis, analysts at this stage will calculate the data related to benefits and costs. In BCA, benefits are cost saving between the Base Case and the Project Alternative in terms of travel time, vehicle operation, and accident costs. If these costs in the Project Alternatives are less than the Base Case, the benefit will be positive, while in the opposite situation, the benefit will be negative. In this new BCA procedure, the calculation of benefit starts from the first year of construction. During the construction, the benefit might be generally negative due to the diversion of the traffic, and become positive when operation phase starts.

In this engineering analysis, traffic analysis tools or models are utilized to obtain VHT and VDT, which are respectively used for travel time costs and vehicle operation costs calculation. The tools and models can either be simple, such as sketch planning models and worksheets, or sophisticated, such as travel demand and simulation models. The selection of the tool depends on the level of detail that the analysts desire in the planning stage. Furthermore, these tools or models are selected to evaluate traffic conditions both in the construction phase and the operation phase within the same selected area. The outputs of the tools can be hourly or daily data, but analysts need to extrapolate them into annual data. Moreover, this annual data will take annual demand growth into account. Detailed information on extrapolating data, as well as demand prediction, can be found in[11]. In general, analysts need to select the most efficient model for the particular project.

Stage Three.Economic valuation

This stage is for transforming the benefits and costs of the projects into monetary terms.

In the previous stages, analysts obtained the VHT, VDT, and accident rate of all alternatives and their corresponding Base Cases. The economic measures of this data between each Base Case and its alternatives are calculated in this stage. Economic factors are defined, such as discount rate, inflation rates, travel time cost rate, value of life and so on. These essential factors are used to transfer those engineering characteristics into corresponding monetary terms. The evaluation date defined in the planning stage plays an important role here, providing benefit and cost results for all Project Alternatives as well as corresponding Base Cases. The present value of all benefits and costs is calculated like so[10]:

$$\text{Net Present Value} = \frac{B_0 - C_0}{(1+r)^0} + \frac{B_1 - C_1}{(1+r)^1} + \cdots + \frac{B_T - C_T}{(1+r)^T} = \sum_{t=1}^{T} \frac{B_t - C_t}{(1+r)^t} \tag{5.1}$$

Where B is the value of benefits, C is the nominal value of costs, T is the analysis period in years, and r is the nominal discount rate. There are many discussions on estimation of discount rate. However, that is out of the scope of this study.

In the BCA procedure, user benefit measures are the difference in travel time, VOC, and accident costs between Base Case and the Project Alternative during the entire analysis period. The cost refers to estimated construction costs, operation, and maintenance costs, terminal value, and other agency costs. The cost data is supposed to be obtained in the planning stage, when project alternatives are designed. For user benefits, RUC is defined as negative user benefits, since the user costs of project alternatives could be higher than that of the Base Case, due to the traffic diversion during the construction phase. However, the user benefits in the operation phase will be positive, since the improvement project can reduce the trip costs for travelers.

Stage Four.Evaluating results

The fourth stage is evaluating the results. Now, analysts can evaluate the economic feasibility of all alternatives based on net present value (NPV) or Benefit Cost Ratio. If NPV is positive, the benefit is greater than the cost. Also, if the Benefit Cost Ratio is greater than 1.0, the alternative is implementable. Eventually, analysts can make decisions based on the economic valuation results, under the conditions of budget limitation, regional allocation constraints, and other factors.

5.2 RUC calculation

In order to comprehensively conduct a Benefit Cost Analysis, the methodologies of road user costs (RUC) calculation are needed. From the literature review, one can see that although there are many analytical tools that can be used for traffic impact analysis, few of them can evaluate area-wide impact. The resolution, and the possibly accuracy, of the results are greater as the tools get more sophisticated. Unfortunately, the costs of using the tools, such as requirements for data and the need for calibration, also becomes greater with more sophisticated tools. To efficiently estimate RUC, it is beneficial to evaluate the usability of tools for RUC calculation.

This study examines three methodologies for estimating RUC. The purpose is to assist others in selecting proper traffic analysis tools for user costs calculation when they conduct Benefit Cost Analysis for highway construction. QuickZone was selected since it is a common sketch-planning tool that can directly provide RUC results. Travel demand models and microscopic simulators are also included. Those tools that are relevant to evaluating isolated facilities are not included (for example, tools based on highway capacities manual and signal optimization tools). Since this study focuses on the calculation of RUC for area-wide, tools that cannot evaluate area-wide impacts are not considered.

In order to calculate RUC, two additional terms are defined here. During Case refers to the condition during the construction phase. AsBuilt Case refers to the condition of the operation phase of a Project Alternative.

5.2.1 QuickZone

In the Review of Tools, the model theory and basic inputs/outputs, as well as limitations, were presented. In theory, QuickZone can only evaluate traffic conditions in a selected mainline and one detour carrying diverted traffic. Delay and queue length are calculated only in those links. However, in reality, all roadways around the construction site can be detours. Travelers can figure out their own detours, thus ignoring the official ones. Traffic will spread out, rather than using only one or two detours. It would be better if an evaluation of traffic conditions for other roadways were available.

In addition, QuickZone never allows the detour route to get congested due to the diverted demand. The demand in the detour cannot exceed capacity. This presents a problem: if the capacity of the work zone is significantly reduced, and many vehicles need to be diverted to the detour, it is highly probable that the capacity of the detour will not be sufficient. Based on QuickZone model theory, those vehicles that are supposed to be diverted will still stay in the mainline, no matter how much delay they cause. This assumption makes the QuickZone model theory inadequate for capturing the traffic impact of an entire corridor, and might cause high delay as a result. According to these two aspects, improvements to the QuickZone procedure are needed to comprehensively evaluate area-wide impact.

A five-step procedure is here proposed to improve QuickZone in evaluating area-wide impact. The major improvements are in traffic assignment. Initially, QuickZone does a simple traffic assignment which assigns demand from the work zone to the detour. In this improved procedure, the traffic assignment is conducted by analysts. Based on proper algorithms and assumptions that analysts make, QuickZone can calculate the user costs over an entire network. All roadways in the selected network can be the detours to take diverted demand from the work zone area. Several assumptions should be made when QuickZone is utilized, such as network selection and traffic assignment, which are mostly based on proper assumptions and engineering judgments. The five-step procedure is presented as follow.

Step One.Select project area and prepare input data

First of all, analysts need to define the network mainline where the work zone is, and the roadways that will carry all diverted traffic. The definition of the network is mainly based on engineering judgment and simple analysis. Analysts need to decide the level of analytical detail. In reality, it is impossible, not to mention time-consuming, to evaluate all roadways. In most cases, travelers might choose the routes with highest capacity or lowest travel time; or, they might simply choose those with which they are familiar. Many small roadways with low capacity might not be good choices for travelers. Once the network is defined, the demand and capacity of all links in the network are needed. If the demand and the capacity of some secondary roadways are not available, analysts need to decide whether these links still need to be included. The tradeoff can be based on the time and the budget available for planning, as well as the importance of the roadways. QuickZone is designed as a sketch-planning tool and can only be used for limited cases. Therefore, defining a network for QuickZone can be efficient if the network includes only important roadways with high capacity and the roadways that are parallel to the work zone sections.

Step Two.Calculate the Base Case costs

After selecting the network, analysts can implement QuickZone to evaluate traffic conditions of all links in the entire network. This calculation provides the existing delay on the entire network. To accomplish this, analysts need to in turn define each link as mainline and run QuickZone to obtain the delay. The delay of each link is aggregated to the total delay of the entire network. Take the following network as an example: a corridor with three roadways. Analysts firstly define the links where the work zone is located as the mainline. Then, the delay and corresponding user costs are calculated for these links. After this is finished, these links should become normal links, which are gray. Secondly, analysts choose another roadway, define it as mainline, and repeat the same calculation. So on with the third one. Finally, they aggregate the delay and the corresponding costs as the total delay and total costs of the entire network.

Step Three.Traffic assignment

In this step, the analyst needs to divert the proper amount of vehicles from the work zone demand to other roadways. Although QuickZone can theoretically assign traffic to a detour, the amount of assigned traffic is based on the capacity of that roadway. QuickZone cannot conduct either static or dynamic traffic assignment. Therefore, the traffic assignment in this step is still a simple algorithm. Analysts conduct the traffic assignment based on engineering judgment, experience, several assumptions, or some algorithms, such as All-or-Nothing (AON). It all depends on the particular projects that the analysts are dealing with.

Before the traffic assignment is conducted, analysts need to estimate the new capacity of the entire network. Work zone capacity will definitely be reduced. This new capacity of the work zone will affect the condition of diversion. If the capacity of the work zone is still adequate for initial demand, it can be assumed that all vehicles will still use the work zone links. Otherwise, a proper amount of initial demand needs to be diverted. For example, if the construction strategy is to close the entire link, all demand of the work zone links need to take new routes. Moreover, analysts also need to evaluate the capacities of adjacent roadways. Usually, improvements to the capacity of detours can relieve the congestion of the work zone and reduce the user costs. Therefore, analysts need to take additional capacity in adjacent roadways into account. Finally, analysts need to change the capacity of each link, as well as update the demand after the traffic assignment.

This is an important step in the entire improved procedure. The results of traffic assignment will affect the calculation of the next step, which is to calculate the delay and corresponding user costs during the construction phase. If the traffic assignment results have significant bias, the results of next steps will not provide trust-worthy results.

Step Four.Calculate costs during construction

Following the traffic assignment step, analysts need to calculate the delay and corresponding costs in the During Case. One important element in RUC is travel time costs. In order to obtain this cost, two kinds of data are needed. One is the user cost of the Base Case and the other one is the user cost of the Project Alternative during the construction phase. The difference between these two is the additional delay due to the construction, which is the measure of travel time cost. The procedure of Step Four is similar to Step Two. Analysts also need to define the mainline links and aggregate the results of each link for this step's final results.

Step Five.Calculate RUC

Since QuickZone does not take safety costs into account, user costs discussed here include only two components, travel time costs and vehicle operating costs. The travel time costs can be obtained by subtracting the delay costs of the Base Case by the delay costs of the During Case of the Project Alternative.

In addition to delay costs, the vehicle operating costs can be obtained by the following equation:

$$C_0 = \sum_{j=1}^{N} \frac{D_{1,j} + D_{2,j}}{2} \times L_j \times c \tag{5.2}$$

Where C_0 is the operation cost. $D_{1,j}$ is the initial demand of detour j and $D_{2,j}$ is assigned amount of traffic to detours j. is the additional distance between detour j and the initial route where the work zone is. c is the unit operation cost. N is the number of detours. The aggregation of the travel time costs and vehicle operating costs gives the final results of RUC.

These five general steps are the new procedure of implementing QuickZone as a RUC calculator. They include the procedure for network selection, traffic assignment, and calculation of RUC with two components: travel time costs and vehicle operating costs. In general, through this new procedure, analysts can obtain more comprehensive results of RUC. However, this new procedure is heavily dependent on engineering judgment. The traffic assignment step, especially, needs analysts to carefully conduct analysis based on reasonable assumptions and algorithms.

It is difficult to examine the QuickZone results from a mathematical perspective, since QuickZone is sensitive to the input data, especially capacity and demand of the links. The major theory of QuickZone is that if the demand exceeds capacity, there is delay in that link. Otherwise, the traffic condition is good. If analysts do not have accurate demand and capacity of the links, the RUC calculations might be not usable. For example, if analysts underestimate the capacity of the work zone, the calculated diversion situation will seem more serious than it would actually be in reality. On the other hand, if the capacity is overestimated, the delay might be too low to obtain RUC. In addition, traffic assignment that depends on the capacity of the network might also be misleading. This step relies heavily on the engineering judgment of analysts. It can only be generated under some reasonable assumptions, and the results cannot be comparable with those generated by sophisticated models, such as travel demand models and microscopic simulation models. Therefore, the model validation of QuickZone is not clear from a theoretical perspective. However, through implementing this tool to a real project, the model validation of QuickZone will be illustrated based on a comparison with the other two tools.

5.2.2 Travel demand models

The model theory and basic inputs and outputs of Voyager[30] were presented in the Tools Review chapter. There are two reasons to use Travel demand models: RUC estimation and diversion analysis. In travel demand models, only a traffic assignment model is utilized, since the model can provide the link flows in the Base Case, During Case, and AsBuilt Case. Analysts can observe the traffic diversion through comparing the link flows of either two cases. The traffic diversion is more important than other traffic behavior, such as cancelling the trip, changing the mode, changing the destination, and changing the trip time[28]. Therefore, using only a traffic assignment model is sufficient.

For RUC estimation, the results of Vehicle Hour Travel and Vehicle Distance Travel from traffic assignment model are important. For diversion analysis, link volumes from traffic assignment model are important. Difference in link volumes between the Base Case and the During Case will inform analysts about the detours that road users might take. Accordingly, analysts need to decide whether further strategies are needed to upgrade those detours. If the detours will suffer great congestion, temporary or permanent improvements for those roadways might be needed to decrease the user costs. If new diversion routes are designed, such as bypass and temporally upgraded detours, the traffic assignment model can also be utilized to evaluate the change due to the detour improvements. The traffic impact can be evaluated, along with the corresponding RUC.

The Travel Demand model for RUC estimation has three major steps: model validation, traffic diversion analysis, and RUC calculation. In model validation, statistical methods are implemented to examine the link volumes from the traffic assignment model against real data. The traffic diversion analysis is to evaluate the impact due to the construction and to capture all possible detours that drivers will choose. Strategies for improving detours can be designed based on traffic assignment model results. Last but not least, RUC is calculated based on the VHT and VDT results after detour improvements and construction strategies are decided.

Model validation

Travel demand models can be built for the general purpose of metropolitan development, and analysts can use it for their particular objectives. Building and maintaining a travel demand model for even an average sized metropolitan area is not a simple task. Such a model is usually the responsibility of the local Metropolitan Planning Organization (MPO) and is used mostly for long-term planning purposes. One negative characteristic encountered often with such models is the large discrepancies that can be contained on a link-by-link basis. It is very difficult to calibrate such big models, and often there is not sufficient data for the task. Generally, the goal of the MPO is to capture the big movements of people commuting in and out of the area. It is possible that an area of construction may not have been calibrated in a satisfactory way; therefore, the closing or capacity reduction of a single link may not be simulated adequately. To avoid such problems, recent, preferably hourly, volumes of important links in the vicinity of the planned construction should be collected and compared with the results of the travel demand model. Most additional calibration will only involve adjusting traffic assignment parameters.

Although a travel demand model might be obtained with less effort, it cannot be implemented before model validation is examined. Several statistical methodologies can be utilized for comparing the real data and simulated data. In this study, correlation coefficient, linear regression, and the Bland-Altman plot were used.

Before the data comparison, it is necessary to define the level of analytical detail. Based on time and budget constraints during the planning phase, analysts need to decide the analysis duration of the traffic volume, such as daily volume, hourly volume, or 15-min volume. In most cases, comparison of daily volumes might be sufficient, since the RUC is calculated as daily costs. Therefore, at least daily volumes from the travel demand model should be proven accurate. In addition, if the real traffic volumes of peak hours are available, it is better to compare that data with the simulated data. If the volume comparison during the peak hours is shown to be adequate from a statistical perspective, then the travel demand models can be seen as valid. Otherwise, analysts need to either improve the models by further calibration of the parameters of the traffic assignment model or use other models. It is important to examine the model validation before implementing the models. If the traffic assignment results are not acceptable, the calculation of VHT and VDT will not be reliable either, which leads to inaccurate results for RUC and Benefit Cost Analysis.

Traffic diversion analysis

In order to evaluate traffic diversion during the construction period, a traffic assignment model is needed to obtain link volumes. The difference in link volumes between the Base Case and the During Case indicate the traffic diversion during construction. The traffic diversion analysis includes three steps.

Step One.Geometry change

First of all, analysts need to prepare the change of geometry in two scenarios: the Base Case and the During Case, which have been defined above. In the Base Case, the geometry is not supposed to change. However, if there are other projects in the same corridor or network, analysts need to take them into consideration. The analysts should decide whether the influence of those projects is so important that the network analysis should include those impacts. For example, there are two Project Alternatives for one project: one involves a single-year construction period and the other one involves a year-and-a-half construction period. If other projects affect the network during the half-year difference, the RUC of the current project might be different. If other projects are finished, the network is actually improved, and the RUC of the second Project Alternative might be less than the first one, while initially the RUC of the second Project Alternative might be higher. So does the opposite situation when other projects start during that time period. Analysts should consider the influence of other projects carefully to obtain the best network that describes the real situation. Accordingly, the geometry in the During Case should be revised based on the different designs in Project Alternatives and the consideration of other projects.

Step Two.Traffic assignments for entire network

After the capacities and the geometry are changed for the respective Project Alternatives, analysts need to do traffic assignment to obtain the link flows of the entire network for the Base Case and the During Case for each Project Alternatives.

Step Three. Volume comparison

In this step, analysts compare the daily traffic volume of the Base Case with the During Case. The impact area can be defined to cover all links whose volume difference exceeds the daily volume fluctuation. To do the comparison, analysts calculate the absolute daily volume differences of all links. This calculation is expressed by the following equation:

$$d_{D,j} = (V_{B,j} - V_{D,j})/V_{B,j} \times 100\% \tag{5.3}$$

Where $d_{D,j}$ is the percentage difference of volume in link j. $V_{B,j}$ and $V_{D,j}$ is the daily volume of link j in the Base Case and the During Case.

If $d_{D,j}$ exceeds the daily volume fluctuation, the link can be defined so that it carries traffic diversion during the construction period. The daily fluctuation of every link will definitely vary, due to different traffic conditions. Nevertheless, from an engineering point of view, analysts can make assumptions to obtain an average value to simplify the procedure. All links where the volume differences exceed the defined fluctuation value should be included in the selected impact area. In addition, analysts also need engineering judgment to include important accesses to capture possible diversion.

The impact area can be selected when the volumes of all links are compared between the Base Case and the During Case. Different Project Alternatives might have different impacted areas. Analysts can make a decision in Project Alternative selection based on the influence of the impact area. For each impact area, analysts need to evaluate the significant impacts of some detours. If the level of service of these roadways is reduced significantly, improvement strategies might be needed to reduce the user costs within the network. After the improvements for detours are designed and decided, the traffic assignment model should be conducted again to obtain updated results in order to calculate RUC in the next step.

Calculation of RUC

After the model is proved valid, RUC can be calculated using the following equations:

Delay costs

$$C_d = (VHT_D - VHT_B) \times c_1 \tag{5.4}$$

Operation costs

$$C_o = (VHT_D - VHT_B) \times c_2 \tag{5.5}$$

Daily RUC

$$C = C_d + C_o \tag{5.6}$$

Total RUC

$$C_{total} = C \times d \tag{5.7}$$

Where VHT_D is the vehicle-hour-travel in the During Case, while VHT_B is in the Base Case. VDT_D is the vehicle-distance-travel in the During case, while VDT_B is in the Base Case. c_1 and c_2 are the unit costs of delay and operation respectively. d is the number of construction days.

5.2.3 Microscopic simulation model

Microscopic simulation models are the most complicated and powerful of all the traffic analysis tools. They require the greatest effort in creating a model, as well the most input data. Generally, implementing a microscopic simulation model requires a detailed knowledge of the network geometry, traffic demand, signal control plans, and so on. In order to obtain reliable results, calibration of the network is paramount and usually very time consuming. However, microscopic simulation models provide higher quality results than QuickZone and travel demand models, such as average travel time, total travel time, average delay, queue sizes, number of stops, fuel consumption, and so on. These additional results can be used for calculating the RUC in greater detail. The calculation procedure of RUC is the same as the travel demand model.

Calibration and model validation

The most important step in implementing a microscopic simulation model is calibration, which is an iterative trial-and-error process. Simulation models are reliable when the simulated results are close to reality, and calibration is the key procedure to make simulation models reliable. The real-life traffic data could be traffic volumes, speed, occupancies, travel time, queue lengths, etc., which are usually measured by detectors or manual measurements. In addition, measures of goodness-of-fit are important, since they are used to evaluate the difference between real data and simulated data. Usually, the correlation coefficient, the root mean square percent error (RMSP), and Theil's inequality coefficient are utilized[31].

Usually, if the network contains freeways and arterials, the calibration can be complicated due to the limited availability of real data. In addition, as the calculation of RUC requires the consideration of a large impact area, microscopic simulation models might be utilized to simulate large networks, including all kinds of roadways. If this is the case, freeway calibration methodologies are not sufficient. This study summarizes the procedure for the calibration of such a kind of network, which includes freeway system calibration and network calibration. In freeway calibration, the freeway system in the network will be separated as the independent system. There are two stages in this calibration procedure, volume-based and speed-based calibration. Measures of goodness-of-fit are implemented to examine the adjustment of parameters in the models, and the discrepancies between the simulated data and real data are used to improve the results. Freeway calibration is to calibrate the driving behavior model and obtain the major parameters for entire network calibration in the next step, while network calibration includes route choice model calibration and O/D adjustment. Once the accuracy is judged to be acceptable by comparing the simulation system behavior with actual system behavior, the calibration can be finished.

Before these two stages of calibration, analysts need to verify the boundary traffic conditions. No matter how excellent the model is, the boundary traffic condition should be close to reality, since all traffic demand is from the boundary sections into the freeway system. If the boundary traffic conditions are incorrect, the model will have significant problems. Calibration can be performed after this preparation is finished. For details about volume-based and speed-based calibration, one can refer to ”A Practical Procedure for Calibrating Microscopic Traffic Simulation Models” [31], which is the major procedural guide used in this study.

Freeway calibration

Freeway calibration is a calibration procedure for only the freeway network system in the network. The objective of freeway calibration is to calibrate the driving behavior models. There are two major reasons for calibrating the freeway system. First of all, the traffic data for freeway segments, such as traffic volume, speed, and occupancy, are usually more readily available than those of arterials. This traffic data plays an important role in model calibration. Secondly, running the simulation for the entire network takes a much longer time than running only the simulation for freeway segments. Calibration is an iterative process that needs to run the simulation hundreds of times to obtain reliable results. If the execution of one simulation takes a long time, it will significantly reduce the efficiency of the calibration.

Freeway calibration contains two general stages: volume-based calibration and speed-based calibration. The former is the calibration process based on the measure of goodness-of-fit between real traffic volume and simulated volume, while the latter is based on the measure of goodness-of-fit between real speed and simulated speed. As volume-based calibration is less complicated, it is usually performed first. However, these two stages are not definitely in fixed sequence. They are part of a iterative process and these two stages can be alternatively performed. In most of cases, after volume calibration is done, the speed calibration might change the model parameters that satisfy the speed calibration but reduce the reliability of volume calibration. In such cases, analysts need to perform volume calibration again until these two stages agree with each other.

Network calibration

Network calibration is needed to obtain reliable results for traffic assignment. The reliability of the traffic assignment results is based on the accuracy of traffic demand, link costs function, and the route choice models. Network calibration is conducted to obtain better O/D demand and valid route choice models for traffic assignment. Network calibration has five key steps: the details are presented as follows.

Step one.Preparation of the data

The first step in network calibration is to prepare the basic input data for the models and prepare the data for the calibration.

i. Basic inputs

The basic input data for the models include the network information, traffic control plans, traffic demand, and data for route choice.

- The network information includes information about network geometry, layout of roadways and intersections, and location of traffic equipments (e.g., loop detector and variable message sign).
- The traffic control plans contain information about signal designs for signalized intersections and priority information for un-signalized ones. Such information can be available from various resources, like the agency records (i.e., DOTs and Counties), measurement or collection from the field, the historical data from other projects, and the design by the users.
- The traffic demand is in terms of O/D matrices, which is required by microscopic simulation models for traffic assignment. Such information can be available from a regional planning model or estimated based on traffic counts. These O/D matrices can be seen as seed matrices and can be used for estimating time-dependent O/D matrices for dynamic traffic assignment.
- Data for route choice models needs to be prepared before network calibration. Such data include the parameters for route choice models (i.e., model alternatives and corresponding parameters) and the link costs parameters (e.g., link capacity, link speed, travel time, user defined costs, toll, etc). The parameters for the link costs vary based on different link costs functions used in traffic assignment.

ii. Data for calibration

Network calibration needs freeway data as well as arterial data. Freeway volume data can be available from loop detectors while arterial data might be limited due to less capital investment. However, in general, Annual Average Daily Traffic (AADT) and Automatic Traffic Recorder Data (ATR) can be available for analysis. Such information might not have the same resolution level as detector data. The selection of the available data is based on the needs of the network.

Step Two. Boundary condition verification

After all input data for the model and data for calibration are prepared, the simulation model can be run for boundary condition verification.

This step examines whether the imported O/D matrices have errors. Errors might happen during the extraction of the traversal O/D matrices from the O/D matrices of the larger network. By verifying the boundary condition, errors can be found and corrected to obtain a better start for the calibration.

Step Three. Preparation for the calibration

This step is to obtain the better default values for the parameters of the models. There are various kinds of parameters in the microscopic simulation model that affect the driving behavior and route choice behavior of the vehicles. Users can define the values for the parameters based on engineering judgment, historical data, data from similar projects, and data from other programs or methods. However, these values might not be well estimated before the network calibration, which is a time-consuming trial and error process for traffic simulation. On the other hand, if some of the parameters can be better estimated before the network calibration, such a process might be more efficient and require less effort.

In this step, the values for parameters can be estimated based on several runs of the simulation. For example, according to the traffic count data for arterials (e.g., AADT, project-orient measurements, ATR, etc.), the attraction of the roadways can be analyzed. The user can adjust selected link costs parameters (e.g., capacity and section speed) to increase or decrease the attraction. Although the link costs parameters might be calibrated in next steps, the adjustment of these parameters here is to obtain a better start for later calibration. In addition, the default traffic control plans, which are designed by the users, might need fine-tuning. The improper traffic control plans for the particular intersections, can cause lots of delay. Users need to examine those locations and redesign the traffic control plans to decrease the delay before the network calibration, since high delay in the intersections affects the route choice in dynamic traffic assignment, in which case vehicles following an initial shortest route might divert to another route to avoid the delay. After preliminary fine-tuning of traffic control plans, as well as parameters for the model, O/D adjustment can be considered.

Step Four. O/D adjustment

This is an important step to obtain better O/D demand for the model. Time dependent O/D matrices are required for a dynamic approach to traffic modeling. They are simulated as the time variability of traffic demand in the microscopic simulation model. Such O/D matrices can be adjusted from seed O/D matrices relying on the traffic count through optimization algorithms. Usually, the estimation is a static process instead of a dynamic process, since the latter does not have an effective method to obtain the solution[34]. In order to obtain the reliable new matrices, link costs parameters (i.e., capacity, travel time, speed, etc.) might be adjusted to obtain reliable static traffic assignment results during the adjustment process. Measure of goodness-of-fit can be used to decide whether new O/D matrices after adjustment are acceptable based on the discrepancies between simulated link volumes and real data. If the matrices are not acceptable, a link costs parameters calibration is still needed.

Link costs parameter calibration is to calibrate the link costs for static traffic assignment. Based on the discrepancy between the simulated volume and real volume, the parameters are adjusted until the accuracy of the simulation is acceptable. If the new O/D matrices are accepted as the best estimation in this process, O/D adjustment can be finished, and the new O/D matrices can be used for route choice model calibration.

Step Five. Route choice model calibration

Route choice model calibration is the fine-tuning process for calibrating the entire network. This step includes three sub-steps which are described as follow.

i. Route choice model parameter calibration

Model alternatives and corresponding parameters are calibrated. These parameters should be calibrated first, since they are global parameters that can affect the entire network.

ii. Redesign of traffic control plans

If traffic control plans for the intersections are from real data (i.e., records from agencies and measurements from the field), the traffic control plans cannot be changed. Otherwise, if the traffic control plans are designed by the users, proper adjustment is needed for reducing the delay in the intersections. The traffic control plans affect the link costs in dynamic traffic assignment. If the improper traffic control plans increase the travel time in the link, the link costs will increase so that vehicles might avoid choosing it. The accuracy of the traffic control plans is difficult to decide on, due to the limitation of the real data.

iii. Link costs parameter calibration

This sub-step is similar to the link costs parameters calibration in O/D adjustment. The link costs parameters of two models might be the same, have some parameters in common, or be completely different. If the parameters are different in two models, the parameter calibrations in the O/D adjustment process do not affect the results in route choice model calibration. However, the corresponding link costs parameters in the microscopic simulation model can be calibrated based on the experience in O/D adjustment process. For example, if one link has high attraction and the parameters are adjusted to reduce the attraction of the roadway in the O/D adjustment process, the corresponding link costs parameters in the microscopic simulation model should be adjusted in the same way to decrease the attraction of that link. Similarly, the experience in this step can be useful in deciding whether O/D re-adjustment is needed. If the link costs parameters for particular links are significantly adjusted in this step, and the results are still not acceptable, O/D matrices might need to be re-adjusted after calibrating the corresponding link costs parameters.

During the fine-tuning of the link costs parameters, the measure of goodness-of-fit is used to compare the simulation results to the real traffic volume. Two decisions should be made based on the comparison. First, whether O/D adjustment is needed again, since link costs parameters for that model can be improved based on the experience in this step. If O/D adjustment is needed, then users need to go back to step four; otherwise, the route choice model is calibrated again, following the three sub-steps until the accuracy of the simulation is judged to be acceptable by comparing the simulated volumes and real data.

Calculation of RUC is followed by calibration. The RUC calibration process is the same as the travel demand model process. The microscopic simulation model can also provide results for VHT and VDT, which are respectively used for calculating travel time costs and vehicle operation costs. For the details of these calculations, refer to the section on travel demand models.

5.3 Summary

This chapter presented a new Benefit Cost Analysis procedure to take Road User Costs (RUC) into account. This procedure has a new timeframe for user benefits calculation and has new considerations for Project Alternative selection. The new timeframe for the analysis period includes the construction phase as well as the operation phase, and user benefits are calculated from the first year of construction phase. In order to clearly conduct economic valuation, RUC is defined as a negative user benefit in the BCA procedure. In addition, three tools capable of area-wide impact analysis are presented for RUC calculation. The procedure of implementing these tools and the model validation are presented to illustrate how to implement these tools in BCA procedure.

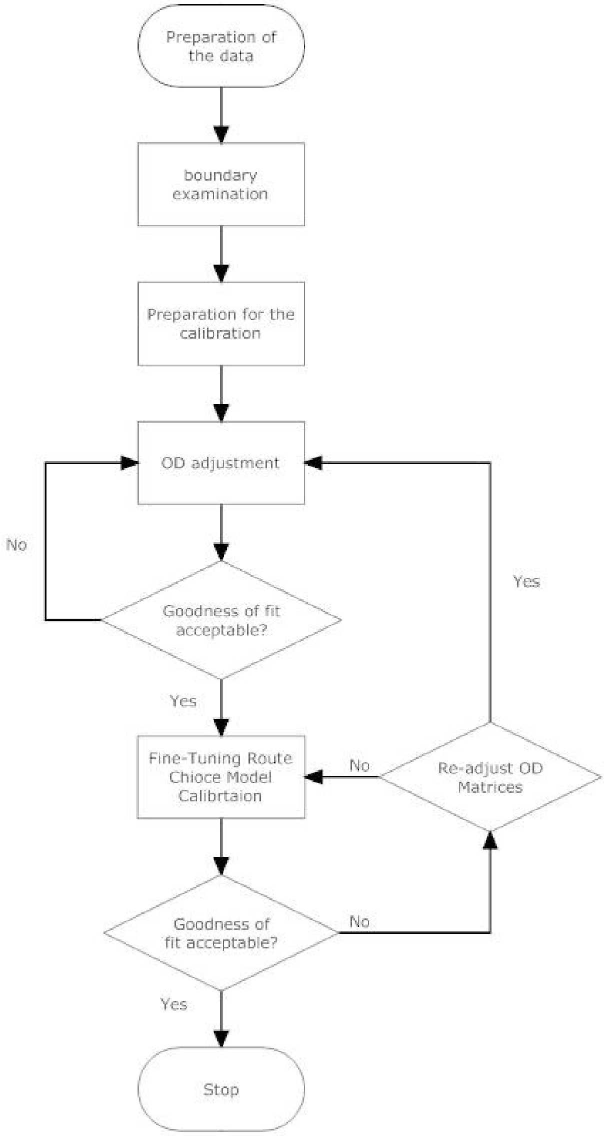

Figure 5.3: Flowchart for network calibration

Chapter 6

Project Description and Data Collection

To give a fair assessment of the aforementioned methodologies, the best choice is the implementation of an actual project. This uncovers real-world problems that affect execution, and provides before-and-after information to evaluate the process results. For this purpose, the TH-36 reconstruction project in North St Paul, Minnesota was chosen.

6.1 Test Site Description

The purpose of the TH-36 reconstruction was to improve the accessibility of the city of North St Paul. TH-36 was reconstructed for about two miles, from the interchange of White Bear Avenue to the intersection of Central Avenue (Figure 6.1). All intersections during this part of the process were removed, and the intersection of McKnight and TH-36 was changed to an interchange. After sketch planning analysis, five-month Full Closure was selected as the construction strategy, since it had lower investment costs compared to other construction strategies, and could keep the work zone area safe and mobile. The construction started on May 1st, 2007, and full closure construction was finished in August 2007.

However, after the sketch planning, in-depth traffic impact analysis was not conducted, which means that the Road User Costs (RUC) of this project were unknown.

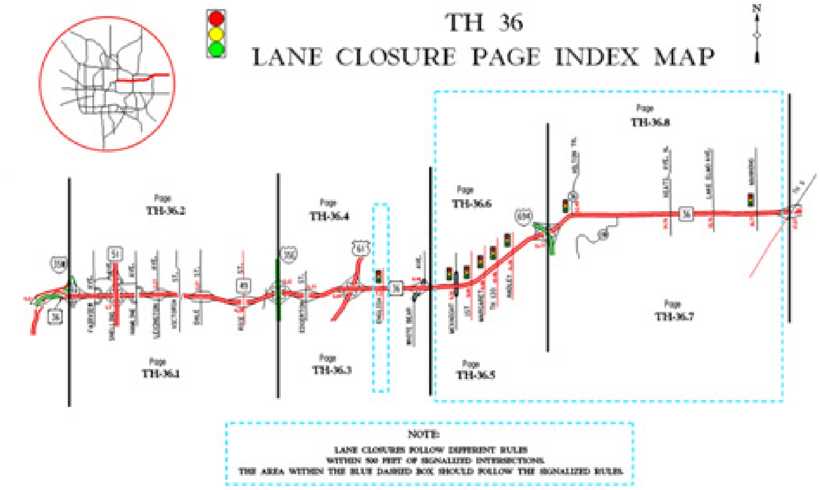

Figure 6.1: Construction site (Mn/DOT, 2006)

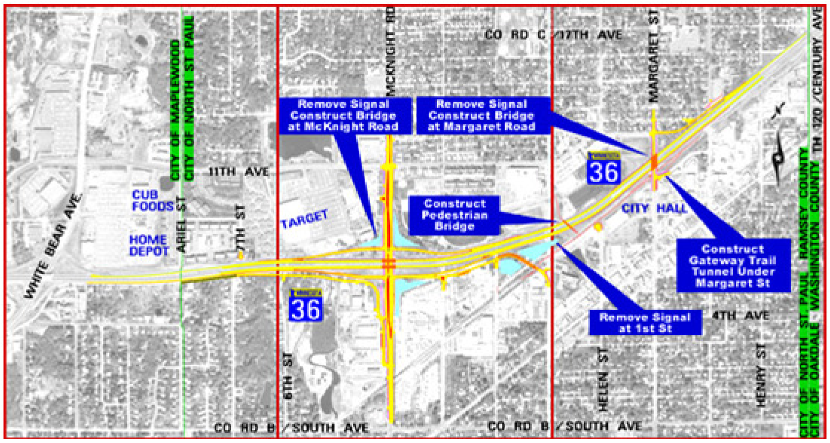

Figure 6.2: Final TH-36 geometry

It is unclear whether other construction strategies with higher investment costs than Full Closure would have had lower RUC. If this is the case, the optimal alternatives for this reconstruction might be unclear. It is possible that other alternatives, with higher investment costs but lower RUC, could have had better economic feasibility than the currently implemented construction strategy. In addition, Full Closure necessitated closing an entire link for approximately four months. All traffic needed to be diverted to other routes, which could cause high RUC during construction. A Partial Closure strategy was designed for comparison to the Full Closure strategy. The objective of the case study is to examine whether analyzing procedures with or without RUC can result in different decisions for planners.

6.2 Real data description

There are two sources of real data for TH-36. One is traffic data from loop detectors, and the other is tube count data for the project. The Minnesota Department of Transportation (Mn/DOT) has one of the most advanced freeway traffic detection systems in the country. More than 4,000 loop detectors are deployed in all Twin Cities freeways, collecting data such as traffic volume and traffic occupancy every 30 seconds. This allows for excellent analysis of the impact of the full closure in the larger area that surrounds TH-36.

Real data implemented in this study are traffic volume and speed from loop detector records, and traffic volume measurements from tube count. Loop detector data can be used to examine the change of traffic pattern in freeways, while traffic volume from the tube count can be used to evaluate arterials. In this case, data from 465 detectors and traffic volumes from 26 tube count points were selected. The data from loop detectors can be available for 30-second intervals for several years, while traffic volume from the tube count was only available for one-hour intervals for four days, which were October 25th and 26th in 2006 and later on July 26th and 27th in 2007. Since the TH-36 project has been finished, the traffic impact can be observed from this available data.

The real data analysis was to evaluate what the influence area was and how significant changes to traffic patterns were. The objective of this analysis was to provide the actual impact due to the TH-36 full closure construction, which can be used to examine the model validation of travel demand models and microscopic simulators.

6.2.1 Loop detector data analysis

Part of the scope of the analysis was to determine how far-reaching this impact was and to elaborate on the area of influence of the TH-36 full closure. Since I-694 and I-94 were the two detour routes for the TH-36 project, it was reasonable to expect that those freeway sections would experience the biggest changes. As shown in Figure 6.3, the green route includes TH-61 NB and I-694EB, which was the detour for East Bound (EB) diversion traffic. The red route includes I-694 SB, I-94WB, and I-35NB, which was the detour for West Bound (WB) diversion traffic.

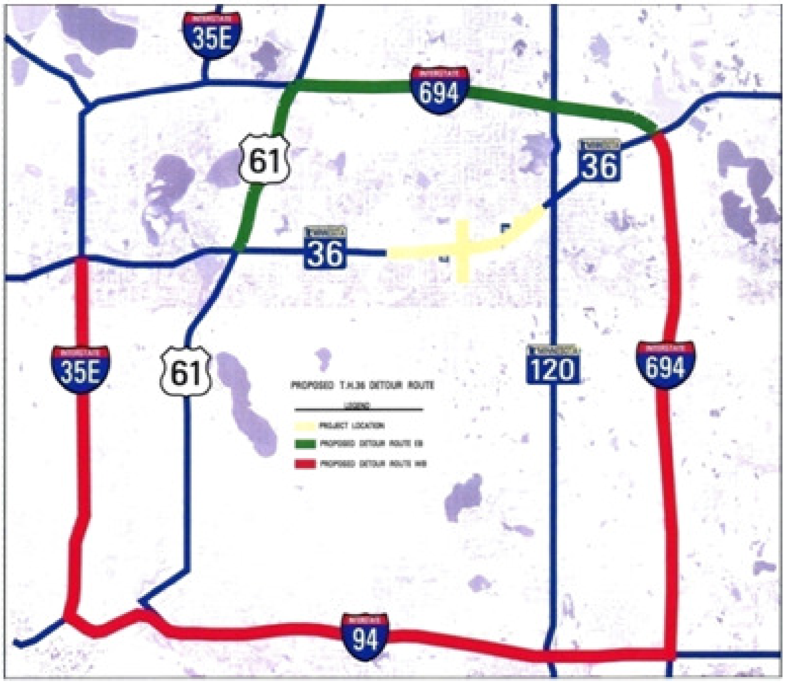

Figure 6.3: Detour Routes for TH-36 Project

Therefore, those freeways had a high possibility of suffering great changes to traffic patterns. Preliminarily, the following freeways were selected to observe the changes to traffic patterns:

- I-35E from Downtown St. Paul to North of I-694

- I-694 from I-35E to the junction with I-494
- The entire TH-36 from I-35W to I-694
- I-94 from Downtown St. Paul to the borders of Minnesota and Wisconsin

Before the analysis can be presented, there are several terms that need to be defined: "AM period", "PM period", "Before period", and "During period". This analysis was divided into two sections, corresponding to the AM period and PM period. In order to capture the effects of possible peak spreading due to departure time changes, the "AM period" denotes a time period from 6 am to 10 am, while the "PM period" denotes a time period during 2 pm to 8 pm. The traffic volumes are defined as the total traffic volume during these respective periods. In addition, "Before" period denotes the condition before full closure was implemented, while "During" period denotes the condition during the full closure construction. The volume difference was the difference between the Before period and the During period, which were the numbers calculated by the traffic volume in the During period minus those in the Before period. It was assumed that these differences in total volume were mainly diverted trips from TH-36, due to the closure, and that there was no other influence to cause those differences.

Correspondingly, the data represented in the Before period was extracted from 30 days, from February to April 2007. These days were all weekdays without significant accidents, bad weather, and large events that could change the normal traffic patterns. In order to find out these days, DataPlot[35] was implemented to observe daily traffic volumes and speeds for approximately 465 detectors. Approximately 60 days were observed before the qualified days were selected. If the traffic patterns were similar to other days and did not have any abnormal fluctuation, this day was defined as qualified. A similar procedure was conducted to select qualified days in the During period.

However, the traffic volumes in the During period were observed to be higher than in the Before period. In this case, additional observation was conducted. In order to exclude seasonal effectiveness, more observations and the following steps were needed. First, daily traffic volumes for all entrance ramps in the entire Twin Cities freeway system were collected for both the Before and the During period. Second, the traffic volumes of the two periods were respectively aggregated into total daily volumes. Finally, these two aggregated daily volumes were compared to see whether traffic volume in the During period was generally higher than the Before period. If that was the case, it would mean that the higher volume was due to seasonal factors. Comparing these two aggregated daily volumes found that traffic volumes in the During period were approximately 5% higher than in the Before period. Therefore, the traffic volumes in the During period were reduced by 5%.

Although conceptually the TH-36 closure could affect the entire system, analysis showed that only a certain subset on it displayed observable changes after the seasonal correction was applied. For this reason, the following explanation of the impact of the full closure only uses that subset.

AM period (from 6:00 am to 9:59 am)

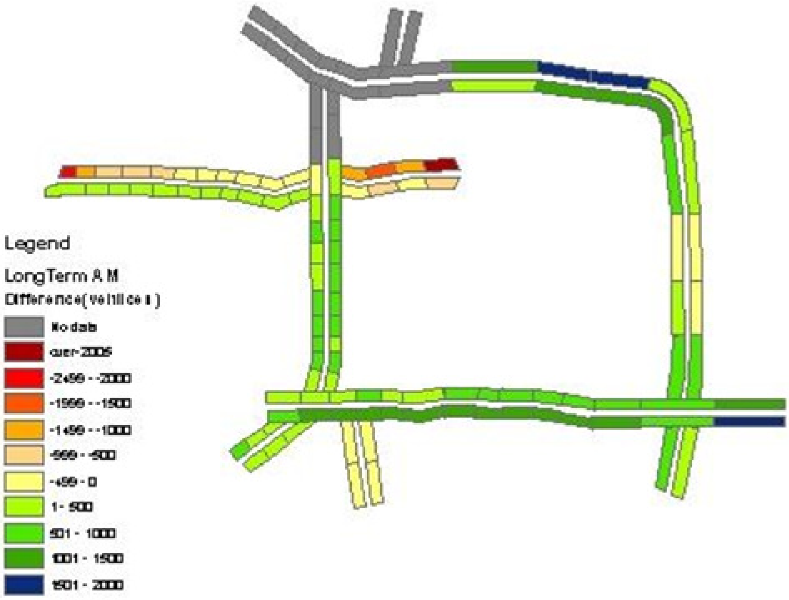

Figure 6.4: The Volume Difference in freeway sections in AM Period

The colors in Figure 6.4 represent the volume difference between the Before period and the During period, as described above. In the legend, no data means that traffic data in this area was not available during the study periods. A red to yellow color indicates that there was a decrease in the traffic volume, while light green to dark green indicates an increase in that station.

Since TH-36 is an east-west oriented highway, the study was mainly concerned with the east-west traffic flows around the area, before and during the closure of TH-36. From Figure 6.4, it can be seen that traffic on TH-36 (west of I-694) moving westward is diverted into I-694 North Bound (NB) and I-694 South Bound (SB). Even though I-694 SB is the proposed detour for westward trips, travelers preferred I-694 NB. Unfortunately, the detectors at the TH-61 interchange are not operational, due to the "unweave-the-weave" construction, so there is no clear way of knowing how many of these trips returned to TH-36 through TH-61. In the EB direction, diverted traffic due to the closure of TH-36 came into I-694 mainly from White Bear Ave. In the north-south orientation of I-694 from the midpoint (the yellow sections), there was actually a decrease in trips traversing these sections. It is highly probable that only local trips diverted to I-694 in this segment, and pass-through trips or trips destined to farther away directions on TH-36 followed a completely new route.

Both directions of I-94 exhibited volume increases, but EB I-94 had the largest. Specifically in the AM period, the diverted traffic in that direction increased more than the opposite direction, even though the total volume in the opposite direction was two times larger. This observation brings up questions regarding work-related trips to the east that are not currently captured well by the Regional Planning Model. Meanwhile, the volume in both directions of I-35E increased as well. It is safe to say that the increases in I-35E were small compared to the total volume in this period. This is reasonable because TH-36 is an east-west highway and the diverted traffic due to the closure might not affect I-35E significantly. Again, the lack of data in the segment of I-35E north of TH-36 does not allow for a clear picture on the diversion. Still, some understanding can be formed through the analysis of the Interchange with TH-36.

From Figure 6.4, it can be seen that WB TH-36 (west of I-35E) had a slight decrease in volume and the section east of I-35E had a significant one, especially in the area of the TH61 / TH36 interchange. Considering that the decrease in volume grows as one moves west on TH-36, it was suspected that the remaining traffic on TH-36 had a large percent of trips destined for the city of Roseville and its vicinity. Few trips used TH-36 to reach I-35W and beyond; they were probably diverted to I-94 or I-694 north. On the other hand, EB TH-36 (west of I-35E) exhibited a slight increase up to the I-35E interchange but decreased beyond that. The increase was less than 5% of the total volume; therefore, this area was not significantly affected by the closure of TH-36.

PM period (From 2:00 pm to 7:59 pm)

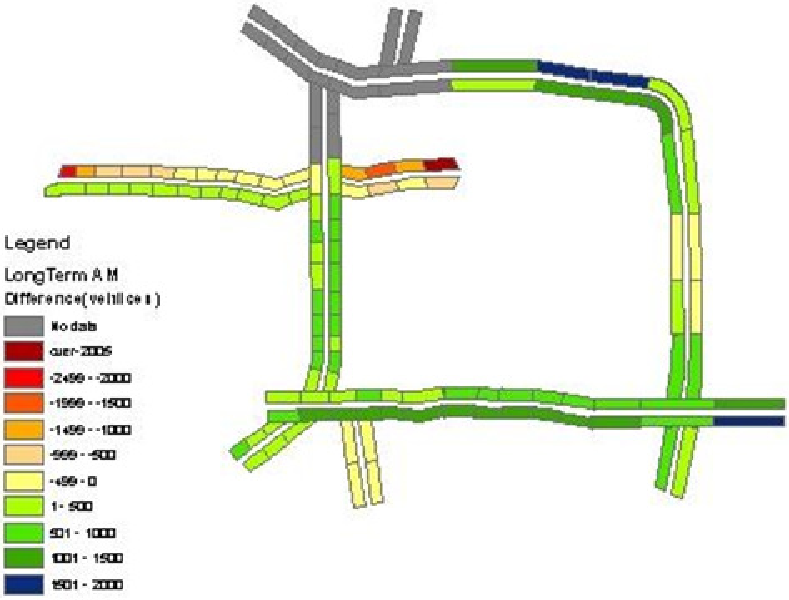

Figure 6.5: The Volume Difference in freeway sections in PM Period

The colors in Figure 6.5 represent the volume difference between the Before and the During periods during the PM peak period (6 hours, 2 pm to 8 pm). The color map has the same indication as in the AM period.

From Figure 6.5, we see that traffic on TH-36 (west of I-694) moving westward diverted into I-694 NB and I-694 SB. Similarly to the AM period, travelers preferred to follow I-694 NB instead of the proposed detour route. A large percentage of detoured travelers got out at the White Bear Ave & I-694 interchange. Additionally, in the other direction of the east-west section of I-694, the significant increases near the I-694 & TH-36 interchange indicate that travelers used this route as a detour. It also indicates that travelers used White Bear more than TH-61 as a detour to get into I-694 and go east.

In the north-south oriented section of I-694, there is a small decrease in the southbound direction, south of the TH-36 interchange. In addition, the middle point of I-694 NB had less increase than the segment near the TH-36 interchange. This indicates that only local trips diverted to I-694 in this segment and pass-through trips or trips destined to farther away directions on TH-36 followed the north route. Unfortunately, the data before the closure at interchanges of 34th St and 10th St. is not available.

Both directions of I-94 again exhibited volume increases, but differently from the AM period; for example, WB I-94 had a larger increase. Also, in EB I-94, the segments near the I-94, I-694, and I-494 interchange had significant increases. Specifically, in the westbound direction, a large volume increase was observed coming from the east. Part of that increase spread locally on I-694 and I-494. Farther down I-94, the volume increases got bigger and kept these levels till downtown St. Paul, where St. Paul seems to absorb most of the extra volume, with a smaller amount following I-35E SB. In the other direction, eastbound, there was a large decrease of volume coming to downtown St. Paul from the west, while the amount immediately after the interchange with I-35E remained relatively unchanged. As the volumes were progressing east, the volume increases grew larger and larger, peaking up around the I-494/694 interchange. It is clear that more travelers from inside the study area used I-94 to head east. Similarly to the AM period, observations in both directions of I-94 bring up questions about the assumptions used to build the Metro planning model, which does not indicate a large labor-shed for this area in the east, and why the TH-36 closure might have affected these trips.

The volume in I-35E NB decreased, while the volume in I-35E SB increased. According to the data, it is safe to say that these changes were slight. This is reasonable because TH-36 is an east-west highway, and the diverted traffic due to the closure did not utilize this segment of I-35E. Again, the lack of data in the segment of I-35E north of TH-36 does not allow for a clear picture of the diversion.

WB TH-36 (west of I-35E) exhibited a small increase in volume, but had a significant decrease in the segment east of I-35E, especially in the area of the TH-61/TH-36 interchange. This increase might indicate that travelers came from I-35E (north of TH-36) and merged into TH-36 to go westward. However, the small decrease at the end of TH-36 WB indicates that these vehicles did not use TH-36 to reach I-35W and beyond. Meanwhile, EB TH-36 (west of I-35E) exhibited a slight decrease in volume up to the I-35E interchange and a significant decrease beyond that.

6.2.2 Tube count data analysis

Tube count data was available for five important urban streets: White Bear Avenue, County Rd C, Century Avenue (TH-120), 7th Avenue, and County Rd B. Tube detectors in thirteen locations collected hourly traffic volumes on October 25th and 26th in 2006 and later on July 26th and 27th in 2007. In some locations, the days in 2006 were October 18th and 19th. A map of the data collection locations can be found in Figure 6.6. In the following analysis, the definition of AM period, PM period, Before period, and During period are the same as in the loop detector data analysis section. The differences in traffic volumes are presented in Figure 6.6 and Figure 6.7. The numbers in red on the maps indicate the approximate difference in total volume during each period between 2006 and 2007. The possible impacts due to the closure of TH-36 were highlighted in this section.

AM period (From 6:00 am to 9:59 am)

From the data on the map, the volume of SB White Bear Ave increased by 1,100 vehicles during the five hour period. This extra demand most likely originated from County Rd C WB, since the additional volume in WB Location 3 is also approximately 1,000 vehicles. The increased volume in Location 3 WB is significant, as it constitutes a 150% increase. Meanwhile, the increase of volume in WB Location 4 is also significant; an increase of 970 vehicles constitutes a 140% increase. From the increases in these two locations, one might deduce that travelers diverting from TH-36 most likely went straight from Location 4 to Location 3 without traveling out of County Rd C, and that the local traffic did not generate observable differences.

In the westbound direction, most of the diverted traffic went on SB White Bear instead of NB White Bear, since the additional vehicles in SB Location 2 were 600,

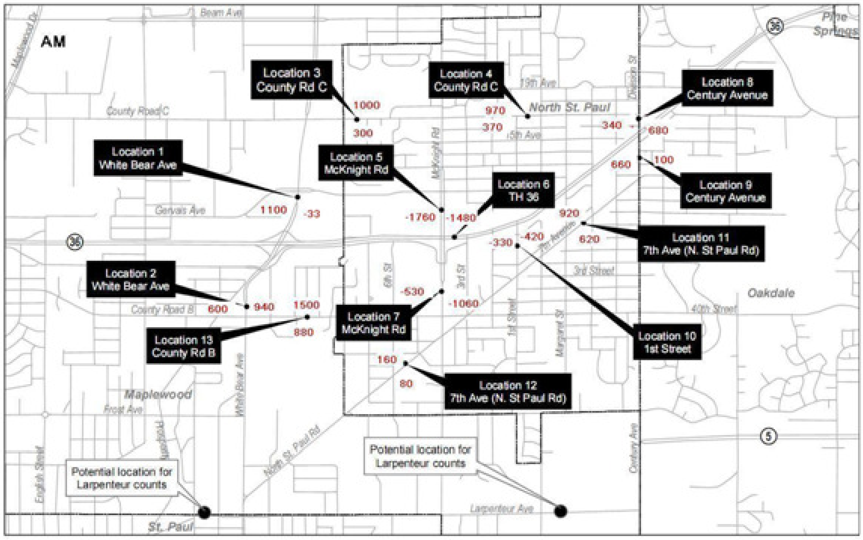

Figure 6.6: The Volume Difference of 13 Locations in AM Period

while the situation of Location 1 can be seen as no different between 2006 and 2007. These 600 veh constitute a 23% increase.

There were approximately 1,500 additional vehicles (over five hours) in County Rd B WB (Location 13), while there were only 940 additional vehicles going north on White Bear (Location 2). If it is assumed that all of the 940 veh were part of the 1,500 veh increase on County Rd B: there were more than 500 additional vehicles either continuing on County Rd B WB (towards TH-61) or on White Bear SB. However, considering the small increase registered on North St. Paul rd (Location 12), it is safe to say that drivers selected to stay on County Rd B towards TH-61. Similarly, there were approximately 600 additional vehicles on White Bear SB (Location 2). However, in Location 13 there were approximately 880 additional vehicles. If it is also assumed that all 600 veh from White Bear Ave went on County Rd B EB, there could still be approximately 280 vehicles coming from County Rd B east of White Bear or White Bear NB. A possible conclusion, later reinforced by additional data from the PM peak period, is that the diverted demand using County Rd B east of White Bear was underestimated and not measured, which leaves the operation of the County Rd B/ TH-61 intersection at a disadvantage.

The additional vehicles in WB Location 4 were approximately 970, while the additional vehicles in WB Location 3 were 1,000. These 970 veh most likely went straight to County Rd C. In the other direction, the additional vehicles in EB Location 3 were approximately 300 veh, while the additional vehicles in EB Location 4 were 370. Although the amounts of the increases were small, they constituted 90% and 100% increases. Therefore, there was no great change on Location 3 or Location 4, which means the local traffic that used McKnight Rd was small, and that the traffic that was using it to come or go from TH-36 now use other routes instead, although not County Rd C.

PM period (From 2:00 pm to 7:59 pm)

From the data on the map, we can see that the volume of SB White Bear Ave increased by approximately 700 veh during the six-hour period. This volume likely originated from County Rd C WB, since this is a proposed detour. The increased volume in Location 3 WB is higher than that in SB Location 1. Specifically, it is 920 veh, a 125% increase. There are two possible situations. One is that travelers continued on County Rd C (west of White Bear). The other possibility is that travelers might have gone to the retail services mall north of TH-36. The latter is less likely, since in the six-hour period they would be eventually counted in one of the two positions. Meanwhile, the increase of volume in WB Location 4 was 1,050 veh, a 100% increase, while the increase in Location 3 was 920 vehicles. This confirms the deduction in the AM period that travelers diverting from TH-36 most likely went straight from Location 4 to Location 3, and few of them traveled out of County Rd C.

Distinct from the AM period, the volume of NB Location 1 had an increase of 650 vehicles. The volume of EB Location 3 was increased by approximately 1,140 vehicles, a 92% increase. If some of these vehicles went to the retail mall north of TH-36, at least 500 vehicles came from County Rd C (west of White Bear) to Location 3 EB during the seven-hour period.

There were approximately 1,330 vehicles additional vehicles (over six hours) in Location 13, while there were only 740 additional vehicles going north on White Bear

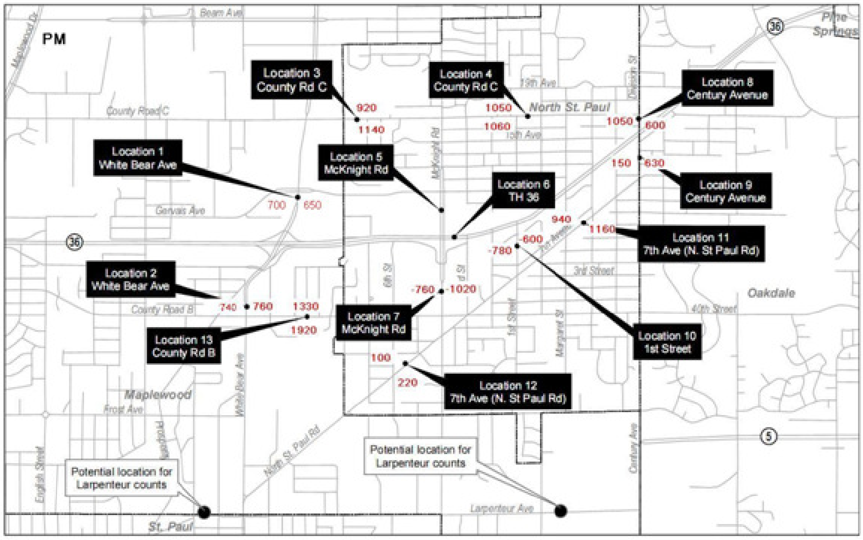

Figure 6.7: The Volume Difference of 13 locations in PM Period

(Location 2). If we assume that these 740 veh were part of 1,330 vehicles, there were approximately 600 veh either continuing on County Rd B WB (towards TH-61) or going to White Bear SB. Since the increases in Location 12 were small (Figure 14), it is safe to say that travelers selected to stay in County Rd B toward TH-61.

Similarly, there were approximately 740 additional vehicles in White Bear SB (Location 2), and there were approximately 1,920 additional vehicles in Location 13 EB. If we also assume all 740 veh went to County Rd B EB, there could still be close to 1,200 vehicles coming from County Rd B (west of White Bear) or NB White Bear (south of County Rd B). This increase is significant for traffic conditions in County Rd B (west of White Bear) and White Bear (south of County Rd B). As in the AM period, the diverted demand using County Rd B west of White was underestimated.

There were approximately 1,330 additional vehicles in Location 13 WB, while there were only 940 additional vehicles in WB Location 11. Similarly to the AM period, we can also safely assume that most of these 940 veh did not go to the North St Paul Rd, since the additional vehicles at Location 12 were only 100. Even if all 940 veh from Location 11 went to County Rd B, there were still approximately 400 veh that needed to either come from McKnight or County Rd B (east of McKnight). It is possible that these 400 veh traveled to McKnight Rd (Location 7) to reach TH-36 before the closure, since there were 1,020 less vehicles in Location 7 NB. Therefore, the 400 veh went to County Rd B instead of TH-36 to west.

In addition, there were 1,920 additional vehicles in Location 13 EB, while there were 1,160 additional vehicles in Location 11 EB. If we assume all 1,160veh were part of the 1,920 veh, there could still be 760 veh continuing on County Rd B EB or going into McKnight Rd SB.

6.3 Selection of analysis network

TH-36 was an important artery in the Twin Cities network and is now even more so. The section of TH-36 from I-35W to TH-61 is a freeway and the rest was highway with at-grade intersections. As mentioned before, the WB TH-36 freeway section experienced a slight decrease in the AM period, while EB reported a slight decrease in the PM period. These phenomena showed that the influence of the construction extended beyond I-35E. Some of the diverted traffic might have used I-35W to EB I-694 and the reverse, instead of using TH-36. Therefore, I-35W, I-694, and TH-36 from I-35W to I-35E were also included in the analysis area to capture all possible diverted traffic.

The selections of I-694 and I-94 (inside the ring) were based on the predetermined official detours, as shown in Figure 6.3. Through analyzing loop detector data, it is noted that most EB and WB diverted traffic used I-694 as their detour, rather than following the official WB detour. As mentioned in the loop detector data analysis, a large percentage of the WB diverted traffic used I-694 and White Bear Avenue. For the other detour, although the detector data showed that less traffic chose this detour, these three freeways are also important. As mentioned previously, a significant volume increase on I-94 indicated that work related trips to the east are not captured well by the Regional Planning Model. In the AM period, the diverted traffic on EB I-94 increased more than in the opposite direction, although the total traffic volume of WB I-94 was much higher. This is a bit of a mystery, since there was a large increase of diverted traffic in EB I-94 and there was no significant decrease of traffic volume in other east-west roadways, such as I-694 and TH-36.

In addition, the section of I-94, from the interchange with I-494 to the east state border, was also included. The diverted traffic that used to travel on TH-36 might have used I-94 instead, since it is the only freeway parallel with TH-36. The area between TH-36 and I-94 also needed to be included in the analysis.

According to the tube count data analysis, some important arterials were also selected, such as White Bear Avenue and TH-61, both of which were also selected based on the detector data analysis. The data at the interchange of White Bear and I-694 showed that many diverted trips exited or entered the east-west oriented section of I-694. Therefore, it is highly possible that diverted trips returned to or came from TH-36 through White Bear Avenue. Moreover, the rest of the diverted trips might either use TH-61 or I-694. Due to a significant lack of traffic data to analyze the traffic pattern, further analysis of traffic impact will be conducted by utilizing the simulation model.

Besides the two freeway detours, there were two local arterial-detours around the TH-36 construction defined in the project planning material and therefore in need of closer analysis. One detour was County Rd C and White Bear, while the other one consisted of TH-120, 7th Ave, County Rd B, and White Bear. Additionally, from the tube count data analysis, WB diverted traffic used both detours, since there were significant increases in traffic volume during the AM period. In addition, for the first detour, diverted traffic might only use White Bear to return to TH-36, but the diverted traffic in the second detour not only used White Bear but also continued traveling on County Rd B WB. From this point of view, County Rd B west of White Bear needed to be included. Meanwhile, from the tube count data in the PM period, EB diverted traffic used these two detours as well. However, these diversions were not only coming from TH-36 through White Bear Avenue, but also from County Rd C and County Rd B west of White Bear Avenue. It is possible that these diverted trips left TH-36 and used either County Rd C EB or County Rd B EB. Compared to the increases in traffic volume in 7th Ave and County Rd B, a large percent of EB diversion did not use 7th but County Rd B instead.The eventual network was defined within this area, which is shown in Figure 6.8.

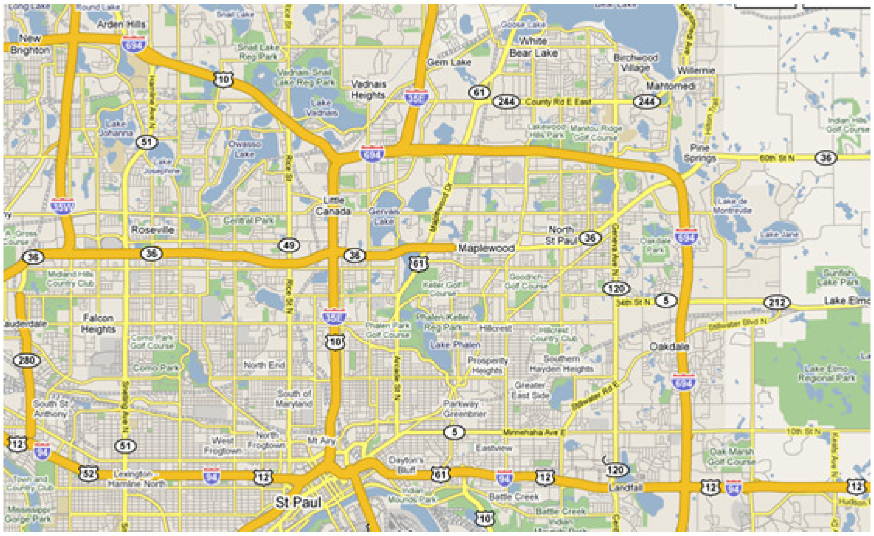

Figure 6.8: The Selected Impacted Area for TH-36 Project

6.4 Design Alternatives

Although the TH-36 project implemented a Full Road Closure construction strategy, it would be beneficial to compare multiple construction strategies to achieve the objective of this case study, which is to examine whether Road User Costs (RUC) play an important role in the Benefit/Cost Analysis (BCA). Two construction alternatives were designed in this case study. One is a Full Road Closure alternative, which was implemented for the TH-36 project in reality, and the other is a Partial Closure alternative, which was designed to be compared with the Full Closure alternative. The construction schedules and investment costs were available for both. In addition, RUC will be calculated. There will be some assumptions about the agency costs, but in general all benefits and costs will be available to conduct BCA for these two alternatives.

6.4.1 Full Road Closure alternative

There were four stages for the Full Road Closure construction alternative. First of all, the highway was closed from May 1st 2007 until August 30th 2007. During this period, both directions of TH-36 were closed and all traffic had to reroute. After Full Closure, one lane of TH-36 was open for traffic. The period for One-Lane Open was from August 31st 2007 to November 16th 2007. After November 16th, all lanes were open on TH-36. The unfinished construction did not affect the traffic.

According to the schedule of construction, there are four scenarios for RUC calculation. The first one is the Base Case scenario. This scenario has two objectives: one is to estimate the traffic condition before implementation of full closure construction, and the other objective is to estimate the traffic condition without reconstruction, which represents the case without this project. The second scenario is the Full Closure scenario, which is designed to estimate the traffic condition during full closure construction. The third option is the One-Lane Open scenario, which is designed to estimate the traffic condition during the period of one lane being open on TH-36. The last is the AsBuilt scenario, which represents the condition after the TH-36 project was finished. Generally, the Full Closure scenario lasts 18 weeks and One-Lane Open scenario lasts 12 weeks. The details of each scenario will be presented in the Implementation Chapter.

6.4.2 Partial Closure alternative

There are three corresponding sub-scenarios for the Partial Closure alternative: the Base Case scenario, the One-Lane Closure scenario, and the AsBuilt scenario. In this case, it is assumed that the final geometry of TH-36 was the same, although different construction strategies can be implemented. Therefore, the Base Case and the AsBuilt scenarios are the same as those in the Full Closure scenario. Since TH-36 is a two-lane trunk highway, the One-Lane Closure scenario is designed to estimate the traffic condition during the construction phase, which was 20 months in this case [36]. The details of each scenario will be presented in the Implementation Chapter.

6.5 Summary

The traffic impacts due to the full closure construction of TH-36 were evaluated by observing loop detector data and tube count data from 26 locations in arterials. The impacted area was captured and selected for analysis by modeling. In addition, another alternative, Partial Closure, was designed to be compared with the Full Closure alternative that was implemented and finished. Designs and assumptions of these two Project Alternatives were made for Road User Costs estimation and Benefit Costs Analysis.

Chapter 7

Implementation

In order to examine whether the selection of Project Alternatives will be changed with and without Road User Costs (RUC) in Benefit Costs Analysis (BCA), three tools are implemented to calculate user benefits and user costs for the TH-36 reconstruction project. These are QuickZone, Voyager, and AIMSUN. The data intensity, effort requirement, and accuracy of these three tools are examined. For each tool, network selection, data preparation, calculation procedure, and model validation (when possible) are presented.

7.1 QuickZone

As mentioned previously, QuickZone is a sketch-planning tool based on simple deterministic queuing theory. In order to implement QuickZone to calculate RUC, four kinds of input data are needed: Network, Project data, Travel demand, and Corridor management data. In the TH-36 case study, the network was selected by using engineering judgment and simple analysis. Project data and corridor management data were taken from ”Road-User Cost for SP 6211-81: Reconstruction of TH 36 in North Saint Paul” [37] and ”TH 36 Bid Estimate Study”[36]. The travel demand was taken from the AADT map [38]. The data preparation for QuickZone did not take long. In this case, a week was spent collecting data and running the results.

7.1.1 Problems with QuickZone

The results from QuickZone are sensitive to the input data. First of all, this model is sensitive to link capacities. If the link capacities are overestimated, the user costs are underestimated and vice-versa. The link capacities of the TH-36 project were initially taken from the Highway Capacity Manual (HCM)[39]. It is important that analysts obtain accurate link capacities in order to obtain trustworthy results. In addition, the current QuickZone model does not consider the delay due to reduced speed in the work zone area. Although some papers [40] mention this disadvantage, QuickZone has not implemented this new feature yet. The delay could be underestimated, even though model theory and all input data are assumed to be accurate. Moreover, since the traffic assignment in the improved procedure for QuickZone is almost entirely based on engineering judgment and simple algorithms, it might vary based on different perspectives from different analysts. Although QuickZone does not require high data intensity and great effort, the accuracy of the results is affected by many uncontrollable factors.

7.1.2 Calculation procedure

The procedure for implementing QuickZone is as follows:

Step One. Select project area and prepare input data

From the project information, there were two freeways detours, which are shown in Figure 6.3, and two local detours, which were Country Rd B and County Rd C. The selection of Detour Two is due to the unweave-the-weave project in I-35E and I-694. These two projects had overlapping periods of construction. However, only Detour One is selected as the freeway detour in the QuckZone network, since Detour Two has a longer distance, which vehicles might not prefer. Both directions of Detour One are selected as the detours for eastbound and westbound diversion. They are two important parallel routes for TH-36 in the local area, so they should be evaluated. The final network in QuickZone consisted of one freeway detour, two local detours, and the TH-36 mainline-shown in Figure 7.1.

In this network, four routes are defined. One route is TH-36, which consists of light blue and red links in Figure 7.1. The red links represent work zones. Links 11, 12, 13,

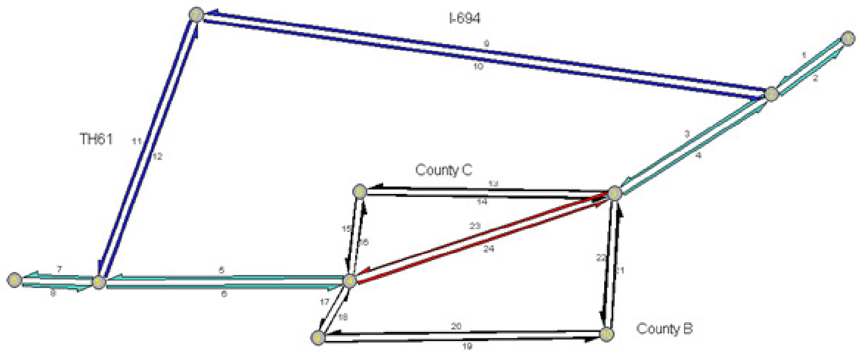

Figure 7.1: QuickZone network

and 14 are defined as freeway detours, while Links 15 to 18 are defined as Country Rd C detour and Links 19 to 24 are defined as County Rd B detour. Both County Rd C and County Rd B detours are local detours. This network is the same for both the Full Road Closure alternative and the Partial Closure alternative.

Step Two. Calculate the Base Case costs

Following Step Two in the Methodology Chapter, user costs of the four routes are calculated in sequence, and the final results are the aggregated results of those four routes. Since the Base Case represents the conditions before the construction is implemented, as well as the conditions without the project, the Base Case is the same for the Full Road Closure and Partial Closure Alternatives.

Step Three. Traffic assignment

In QuickZone, traffic assignment is based on engineering judgment, reasonable assumptions, and simple algorithms. For the Full Closure Alternative, the During Case consisted of Full Closure and One Lane Open scenarios. In the Full Closure scenario, TH-36 is completely closed, and all traffic should be diverted to other routes. It is assumed that demands in link 3 and link 4 are going through TH-36. All of these vehicles will divert to freeway detours. It is also assumed that the demand difference between link 3 and 4 and link 23 and 24 are from the local area. 50% will use the County Rd C detour, and 50% will use the County Rd B detour. For the Partial Closure alternative, 30% of the demand in link 3 and 4 are assumed to use the freeway detour and the rest are assumed to stay in TH-36. In this case, local detours are not used.

Step Four. Calculate the costs of the During Case

After traffic assignment, the traffic demand of each link needs to be updated, and the user costs can be calculated for the During Case. Before the calculation, the capacities of the work zone links are revised. Initially, these capacities of work zone links are 2,200 veh/hr. For the Full Closure scenario, the capacities of the work zone links are zero, while in the One Lane Open and One Lane Closure scenarios the capacities become 1,100 veh/hr. The eventual user costs of the During Case in the Full Road Closure alternative are the aggregated results of the Full Closure and One Lane Open scenarios. The eventual user costs of the During Case in the Partial closure alternative are the results of the One Lane Closure scenario.

Step Five. Calculate RUC

RUC contain two components: delay costs and vehicle operating costs (VOC). The difference in user costs between the Base Case and the During Case was the delay costs, while VOC is calculated by the equations explained in the Methodology Chapter. The final RUC results will be shown later.

7.2 Cube Voyager

Cube Voyager was selected as an application of a travel demand model, which is more sophisticated than QuickZone. The 2010 Twin-Cities Regional Planning Model was available for traffic analysis in this study. In order to analyze the traffic impact of the Full Closure and the Partial Closure alternatives, a traffic assignment was conducted for the entire Twin-Cities metropolitan area to capture all possible roadways impacted by the construction. In this analysis process, model validation was conducted first, and then RUC were calculated based on the results from the traffic assignment model.

7.2.1 Model validation

Before calculating RUC, a model validation is prudent. Two statistical methods are used for model validation: linear regression and a Bland-Altman plot. Real data from the Base Case and the Full Closure were used to compare the traffic assignment results of Cube Voyager. Although the traffic assignment was conducted for the entire Twin-Cities, the impact area was selected to evaluate the traffic diversion and the goodness of fit of traffic assignment.

Impact area selection

The impact area is selected based on the following procedure:

Step One. Traffic assignment of the entire Twin Cities

The 2010 Twin Cities Regional Planning Model contains the links of the entire Twin Cities metropolitan area. The link flows of the Base Case can be quickly obtained by traffic assignment for the initial model. Since there are two Project Alternatives for the TH-36 construction, the link flows of two During Cases were obtained by conducting traffic assignment for the model after the network was changed based on the design of the Project Alternatives. For the Full Road Closure, the links of the work zone were deleted, while the links of the work zone in the Partial Closure alternative were retained, but the capacities were reduced. Then, the link flows of the Base Case as well as the During Case of two Project Alternatives were obtained.

Step Two. Sub-network selection

As mentioned in the Methodology Chapter, the selection of the impacted area boundary is based on the discrepancies of the link flows between the Base Case and During Cases. However, the selection of the network for TH-36 is also based on engineering judgment.

The network selected here is similar to the one mentioned in the Site Description Chapter. The traffic impacts for the links are determined in terms of change in link volume and travel time. If the links are not impacted due to the construction, the link volume and travel time do not have a significant change. Therefore, the VDT and VHT of those links does not have a significant change. The RUC of those links can be small. For these two reasons, a slightly wider impacted area in the travel demand model might not cause significant changes to the effectiveness of the RUC results. The eventual network for Cube Voyager is shown in Figure 7.2.

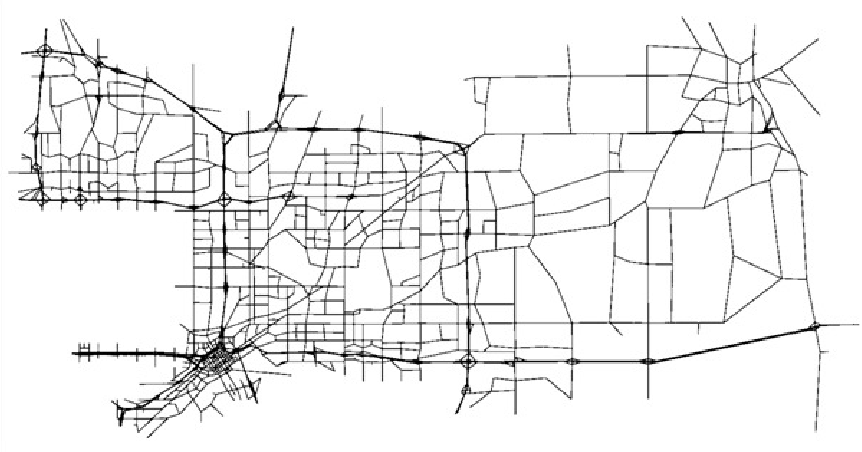

Figure 7.2: Selected impact area for Cube Voyager

7.2.2 Statistical analysis

Statistical analysis for Base Case

Linear regression was implemented to estimate the traffic assignment results of the Base Case. The regression results are shown in Figure 7.3. The real data in the figure is the average daily volume of 30 days from loop detectors before full closure was implemented.

The Cube Voyager data are the corresponding daily volumes from the traffic assignment model. As shown in Figure 7.3, the slop is 0.99. The correlation coefficient is 0.96, which indicates that the linear dependence between these two variables is strong.

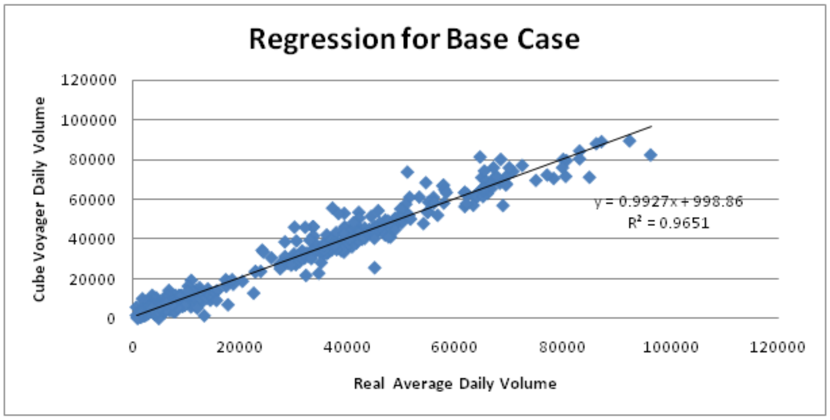

Figure 7.3: Linear regression for Base Case

The Bland-Altman plot is shown in Figure 7.4. The x-axis is the average daily volumes of 30 days from loop detectors, as well as Tube Count data and link daily volumes from Cube Voyager, while the y-axis is the volume difference between them, which is calculated by subtracting Cube Voyager data from real data. If most points are above the x-axis, it means that the Cube Voyager data is generally higher than real data. On the other hand, if most points are below the x-axis, the Cube Voyager data is generally lower than the real data. From this figure, most data points are around the x-axis, which means the Cube Voyager data achieved a good estimation of the real data. Although the regression line in the figure shows a positive slope, this is acceptable since it is only 0.01.

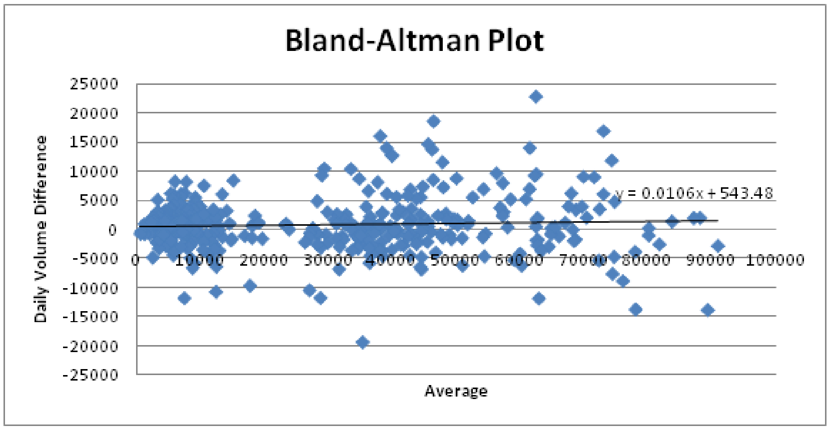

Figure 7.4: Bland-Altman Plot for Base Case

Statistical analysis for Full Closure

The model validation for Full Closure requires additional examination. In the planning stage, the real data during the construction cannot be available for the analysis. When planners conduct BCA, they can only evaluate the model validation for the Base Case and assume the model theory is accurate enough to predict the results. However, the project used in this case study was finished, and the data was available for examining whether the tools can generate acceptable results against the real data. The real data was also the daily traffic from 465 detectors. In this study, the available data during the construction was utilized for an in-depth analysis of the model theory of Cube Voyager, which is a typical tool implemented in travel demand model theory. This additional examination is to observe whether Cube Voyager can accurately predict the traffic diversion during full closure of TH-36.

Figure 7.5 shows the linear regression between real data and Cube Voyager data. Real data is the average daily traffic volume of 30 days during the full road closure construction, while the Cube Voyager data is the corresponding daily traffic volume from the traffic assignment. Similar to the results in the Base Case, the slope of the regression line is close to 1 and the correlation coefficient is 0.95. This figure shows that the traffic assignment for the During Case in Cube Voyager is a good estimation of the real data.

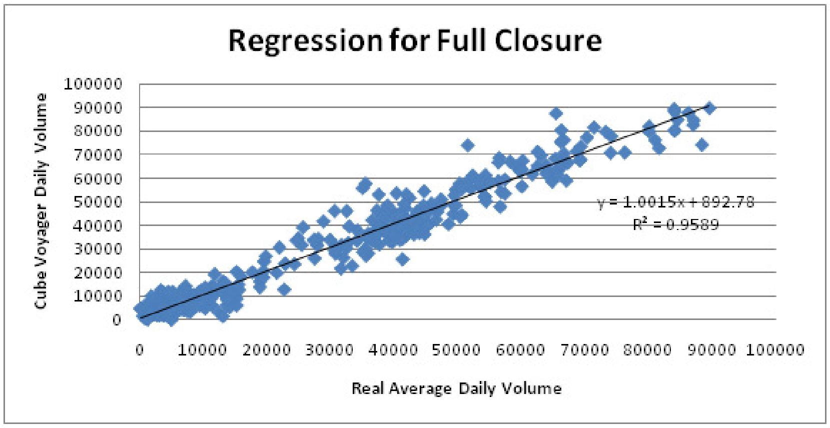

Figure 7.5: Linear regression for Full Closure in Cube Voyager

The good estimate from Cube Voyager can also be seen in Figure 7.6, which is a Bland-Altman plot. The average represents the average volumes of Cube Voyager and real data, while the difference was the volume difference between the two. Most of the data points were around the x-axis, which means the Cube Voyager data was close to the real data. In addition, the slope of the regression line is 0.04. The average of the difference of daily volume is approximately 930, which indicates that the Cube Voyager data can be generally higher than real data. In this case, the traffic assignment results from Cube Voyager for the Full Closure scenario were a good estimate of the real data.

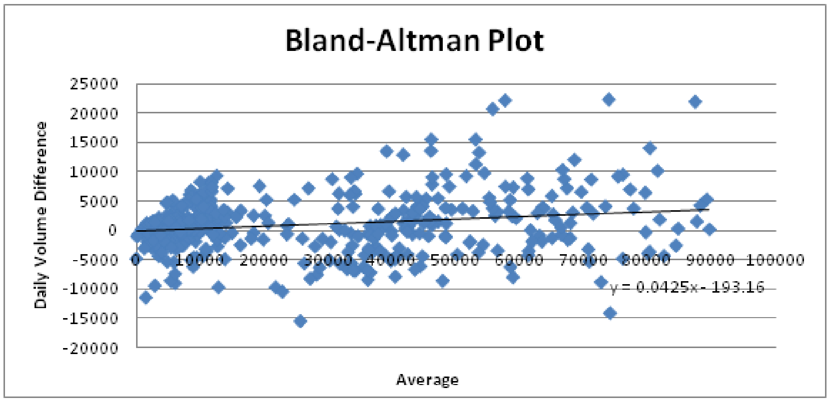

Figure 7.6: Bland-Altman Plot for Full Closure in Cube Voyager

7.3 AIMSUN

AIMSUN is a microscopic simulator that requires great effort to build, to prepare input data for, and to conduct calibration. Distinct from the Cube Voyager model, which is built by the particular organization and can be immediately used, the AIMSUN model requires more effort for model building and calibration. In the TH-36 project, plenty of input data was collected and great effort was spent building a valid AIMSUN model.

7.3.1 Model preparation

As mentioned in the Tool/Model Overview Chapter, three basic inputs are needed for AIMSUN models: network, traffic demand, and traffic control. The network contains the information about roadway geometry, layout of roadways and intersections, and locations of traffic equipment, such as loop detectors. The traffic demand can be either Traffic States or OD Matrices. The traffic control plans contain the signal phases and timing for signalized intersections and priority information for un-signalized intersections. In addition, other inputs such as route choice model parameters are needed as well.

Network Geometry

The impacted area was selected based on the traffic analysis described in the Site Description Chapter. Due to the size of the network, the AIMSUN network was imported from an ArcGIS shape file extracted from the 2010 Twin Cities Regional Planning Model, instead of being manually built by the analyst. The extent and complexity of the network can be seen in Figure 7.7. In addition, the connections of ramps and freeways had the greatest effect in the model operation and therefore required the most attention. Approximately two months were spent in the adjustment of the geometry.

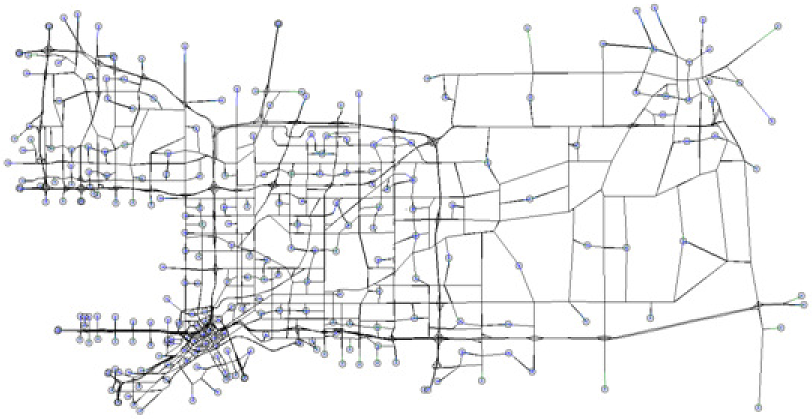

Figure 7.7: AIMSUN network

Traffic demand

The source for the traffic demands in this model was the Traffic States from loop detector data and Origin/Destination information extracted from the 2010 Twin Cities Regional Planning Model. The Traffic States were used for freeway calibration while the O/D matrices were used in network calibration. The O/D matrices used for this model was the traffic demand in the Base Case. There were three sets of matrices, indicating different vehicle types: HOV, SOV, and truck. HOV and SOV mean high occupancy vehicle demand and single occupancy vehicle demand, respectively, while truck represents the commercial vehicle demand. Apart from a few HOV bypass lanes on metered ramps, this network did not involve any real HOV facilities. In addition, each set of matrices also included 24 matrices representing 24 periods in a day. The time periods were based on the rate of change of traffic conditions, rather than being simply hourly. Since there are 259 centroids in the entire network, each matrix includes 259*258 pairs of origins and destinations.

Traffic control plans

Since this large network includes many arterials, traffic control plans are needed to manage traffic. However, not all traffic control plans on all intersections were available, nor would it have been efficient to seek out and implement all of them. The traffic control information on intersections closest to the construction site, such as White Bear Avenue and Central Avenue, were replicated exactly based on control plans acquired from Mn/DOT and Ramsey County.

For the remainder of the system, default control information for key intersections is implemented, to avoid severe unrealistic congestion affecting the results of the simulation. The artificial traffic control plans are implemented mainly for downtown St Paul and TH-36 east of I-694 to the eastern boundary of the network. For non-key intersections, only stop/yield sign control is utilized. In addition, since the network did not consider ramp metering strategies on the ramps, the traffic control plans for ramp metering were not implemented either from real data or artificial design. Some errors in simulation could have happened due to this limitation. However, for the network in such large scale, this drawback can be accepted in state of practice.

The procedure of signal timing design is as follow:

Step One. Collect the demand of intersections

The initial traffic demands of the intersections are collected by conducting static traffic assignment in the AIMSUN model. These traffic demands are important to develop phase plans and calculate critical lane volumes. However, traffic assignment results only show the section flows. The flow of each movement is not available from the aggregate data. Therefore, all intersections only have two default phases of pre-timed operation at the beginning. Whether a protected left turn signal is needed is mainly based on observation by utilizing animation in step three. In addition, the geometry information of the intersections is utilized as well. If the leg of the section has a left turn lane, the protected left turn signal might be implemented in reality.

Step Two. Parameters and assumptions

The yellow time, all-red clearance time, total lost time, and cycle length are calculated in this step. The Webster delay formula is implemented in this study:

$$C = \frac{1.5L + 5}{1 - Y} \tag{7.1}$$

Where C is cycle length, L is total lost time, and Y is the sum of critical phase flow ratios [41]. Equations of yellow time, all-red time, and so on can be found in Traffic Engineering, by R.P. [42].

The average approaching speed S of an intersection is defined as the speed limit of that intersection, since the speed acceptance in the network is 1.1, which allows vehicles to travel at a higher speed than the defined section speed which is the speed during off-peak. If different speed limits are found, the lowest one is selected. Saturation flow rate is defined as 1,800 tvu's per hour of green. The distance from stop line to far side of the most distant crosswalk in all intersections is defined as 40 ft, even though this value varies in different intersections. Standard vehicle length is defined as 15 ft, which is the length of SOV in vehicle characteristic dialog, although there are three types of vehicles in the network. Reaction time t is defined as 1.0 second and deceleration rate is 14 , which is the vehicle parameter calibrated in freeway calibration process.[42].

Step Three. Signal timing revising

The initial demands of the sections are from static traffic assignment, which only considers the travel time and link capacity. However, the dynamic traffic assignment in microscopic simulation models might be different, since traffic control plans are considered. Vehicles might not follow the same routes in dynamic traffic assignment; so, the demand of the sections might be changed. In this case, the animation simulation is implemented to observe the traffic conditions of intersections. If the default control plans designed in step two does not work well, revision is needed to reduce the delay in the intersections. In this step, the left turn movement is observed. Since in step two, all left turns are permitted instead of protected, the delay due to conflicting and yielding in the intersections might increase when the demand for left turns is high. The cycle length is recalculated, when the left turn phase is implemented. In addition, a side lane is built for left turn movement when the left turn phase is implemented.

By and large, the signal design follows the process presented in Traffic Engineering[42] but the cycle length calculation is from the Webster delay formula[41]. The implementation of signal control is to make sure that the system works well and maintain the traffic condition within the network in a reasonable level. The objective is not to obtain optimal control plans for all intersections, but only to maintain the system by avoiding significantly delay due to improper traffic control plans. In general, approximately 100 intersections use signal control plans and others are controlled by stop/yield signs. Real information of traffic control plans is implemented for the intersections near the TH-36 work zone area, which are mainly in White Bear, TH-61, and TH-120 (Central Avenue).

Measure of goodness of fit

When basic inputs for the model are prepared, the AIMSUN model needs to be calibrated. Measures of goodness-of-fit are used to evaluate the relationship between simulated and observed measurements. Since there are many goodness-of-fit measures, selecting a proper methodology is important before calibration. Two common methods are used for evaluation: correlation coefficient and root mean squared. The correlation coefficient is defined as:

$$r = \frac{1}{n-1} \sum_{i=1}^{n} \frac{(x_i - \bar{x}) - (y_i - \bar{y})}{\sigma_x \sigma_y} \tag{7.2}$$

Root mean squared is defined as:

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\frac{x_i - y_i}{y_i})^2} \tag{7.3}$$

Where x_i is the simulated measurement value at time period i; $y_i$is the observed measurement value at time period i; $\bar{x}$ is the mean of the simulated measurement values; $\bar{y}$ is the mean of the observed measurement values; $\sigma_x\sigma_y$ are the standard deviation; and n is the number of observed measurement values.

7.3.2 Model calibration process

The reliability of AIMSUN is based on its capability to generate results close to reality. In order to judge this reliability, calibration is needed, which is an iterative trial-and-error process for adjusting model parameters, and comparing the model to the system being simulated until the discrepancies between the model and actual system are accepted. Calibration of this AIMSUN model includes two parts: freeway calibration and network calibration. Freeway calibration was only used for freeway sections of the network. Each freeway direction was an individual system and there were no routing issues in this calibration process. All freeway sections share the same calibrated global parameters, while local parameters for each model vary. Network calibration involved route choice calibration, besides the same process for freeway calibration. O/D matrices estimation was also included in network calibration, to obtain better representation of the traffic demand.

Freeway calibration

For freeway calibration, only two types of input data are required: network and traffic demand. In contrast to the network geometry mentioned before, the geometry here has only freeway segments. The vehicles did not have routing issues, since the different freeways were not connected to each other, and each freeway direction was an individual system. The movement of vehicles was based on link flows and turning percentages instead of origin and destination information. Link flows and turning percentages were contained in Traffic States in the AIMSUN model. The objective of the freeway calibration was to obtain well-calibrated global parameters and proper local parameters for simulating traffic behavior of vehicles. Then these global parameters were used in the network calibration.

Traffic States

The traffic states contained the traffic demand information for freeway calibration, which included the input flows of all entrances in the system and the turning percentages for flow splits. The traffic states can be estimated from loop detector data. Input flow was the flow from all entrances, including all entrance ramps and the mainline boundary of the freeway. The turning percentages define the probability for each vehicle to either exit the freeway or stay in the mainline. With certain percentage, any vehicle is randomly assigned to next section.

In the calibration process, loop detector data from a typical day was selected. The selection of this typical day was important for freeway calibration. In order to select a typical day, plenty of candidate days should be selected. The data from these candidate days should be valid, which means that no weather issues, crash issues, and event issues happen on these days that cause a change in normal traffic patterns. In addition, the loop detectors should be valid. If system errors occur in some detectors on some days, those days cannot be candidates, either. In this case, DataPlot was implemented for the typical day selection. Eventually, the typical day was selected from those candidates by using GEH statistics[43]. If the GEH results of data from 80% of the detectors were less than five, the day can be defined as typical day. The average data is presented in the Site Description Chapter.

$$GEH = \sqrt{\frac{(V - V_a)^2}{V + V_a/2}} \tag{7.4}$$

In the TH-36 project, five typical days were selected for AIMSUN simulation. The details are shown in Table 7.1. The data from typical days was used for model calibration and model validation.

From the observations in DataPlot, the peak hours in westbound traffic were found to be approximately 6:30 to 8:30 in the morning. The peak hours in eastbound traffic were found to be approximately 4:00 to 6:00 in the afternoon. If only peak hours were evaluated, the congestion situation may not be fully observed during the time period, since the queue may not be clear before the end of the simulation. The exact beginning and ending times of the peak hours were unknown and varied in different detectors. If the upstream conditions were affected by downstream bottlenecks, the peak hours of upstream could be later than that of downstream, but the congestion duration could be less. In order to capture all operation issues, the duration of the evaluation was extended from 5:00 to 10:00 in the morning and 2:00 to 8:00 in the afternoon.

Table 7.1: Simulation Days

Scenarios	Date
Base Case	April 26th 2007(Thursday)
Full closure	June 20th 2007(Wednesday)
One lane open	September 19th 2007 (Wednesday)

The interval was 15 minutes. Although loop detectors record the traffic data every 30 seconds, it is unnecessary to use this short of an interval. Because the evaluation durations are about five hours in the morning and six hours in the afternoon, a 15-minute interval is a reasonable assumption.

The vehicle composition was also important for the simulation, since each vehicle type has different parameters to define different driver behaviors. By looking up data from the 2010 Twin Cities Regional Planning Model, the composition of cars was observed to be between 93% -97% for all types of vehicles. To simplify, 95% was chosen for cars, 3% for trucks, and 2% for semis.

Freeway calibration process

The freeway calibration contains two main steps: volume-based calibration and speed-based calibration. Usually, volume calibration is performed first and followed by speed calibration. However, this is an iterative process. In general, after volume-based calibration is preliminarily processed, the speed-based calibration follows to fine-tune the parameters, which could affect the results of volume calibration as well.

Volume-based calibration is mainly implemented in this case study. Global parameters are mainly concerned with volume-based calibration process. These global parameters (e.g., vehicle characteristics, Driver's reaction time, max desired speed, etc.) affect the driving behavior of all vehicles within the network. Additionally, the local parameters (e.g., speed limit of the section, distance zone 1 and 2, etc.) are also adjusted to calibrate the driving behavior models. All global parameters were initially obtained from another well-calibrated AIMSUN network. The model was proven to be valid.

There are many global parameters in an AIMSUN model, and different combinations of the parameters might obtain similar driving behavior for vehicles. In this case study, Driver's reaction time, Max desired speed, and Maximum acceleration and deceleration were adjusted. Driver's reaction time was adjusted from 0.6 s to 0.8 s, with increments of 0.05 s. Driver's reaction time is the time that a driver takes to react to speed changes in the preceding vehicle. Theoretically, since this value is related to the simulation step, a lower reaction time in the model will improve the traffic conditions in the system, but it will take a longer time to run the simulation. With a certain reaction time selected, the Max desired speed was adjusted from 70 mph to 90 mph with increments of 5 mph. The comparison of goodness-of-fit of simulated volumes was conducted each time, with parameter adjustment, to find the best combination of those parameters. The Max acceleration and deceleration were calibrated in a similar process, but the adjustment of the values was from a small scale.

Followed by preliminary volume-based calibration, speed-based calibration was conducted for obtaining simulated mainline speeds as close as possible to the detector measurements. The bottlenecks in the freeways were captured and simulated. Since in volume-based calibration global parameters are adjusted to a point where the discrepancies of simulated volumes and real volumes are accepted, the parameter adjustment in speed-based calibration is mostly local parameter fine-tuning. The initial section speed of each freeway section was defined as the average maximum speed that is observed from detector data. In addition, Distance Zone 1 and Distance Zone 2 were adjusted along with the section speeds, to simulate the bottleneck generated through weaving. For speed-based calibration, speed contour plots were implemented, to observe the bottlenecks in actual freeway systems and simulation models.

When parameters are changed, goodness-of-fit of simulated volumes (i.e., volume) are examined. For volume-based calibration, if the correlation coefficients were over 0.80 and RMS is lower 0.25, the simulated volumes of the detectors were acceptable.

Otherwise, more adjustment of local parameters are needed. For speed-based calibration, engineering judgment is implemented to evaluate the bottlenecks in the simulation models. The goodness-of-fit of simulated speed plays a less important role than speed contour plots since the object is to capture the bottlenecks, and the slight difference between simulated speed and real speed is acceptable. Adjustment of parameters can be stopped until the accuracy of the simulated data is judged.

Freeway calibration results

i.Parameter results

The initial values of global parameters are shown in Table 7.2. The final values of major global parameters are kept the same for network calibration later.

Table 7.2: Values of major global parameters

	Before calibration	After calibration
Reaction time	0.75 s	0.65 s
Reaction time at stop	1.35 s	1.15 s
Max Desired Speed of SOV	70 mph	85 mph
Max Acceleration of SOV	9.84 ft/s^2	14.40 ft/s^2
Normal Deceleration of SOV	16.40 ft/s^2	16.04 ft/s^2

ii. Volume-based calibration results

Table 7.3 show the goodness-of-fit results from volume-based calibration. All R-squares are between 0.85 and 0.99, which indicate that the linear dependent between simulated volumes and real volumes is strong. The RMS shows that the discrepancies of simulated volumes and real volumes can be accepted.

iii.Speed-based calibration results

Figure 7.8 and Figure 7.9 show one example of speed contours in final speed-based calibration. The color-map of two figures is from 10 mph to 80 mph. The y-axis is the detector Id and the x-axis is the time from 5 am to 10 am. The same color indicates the same speeds between them. The blue ones indicate the bottleneck in the freeway,

Table 7.3: Goodness of fit results of mainline stations after calibration

Freeways	Highest R^2	Lowest R2	Highest RMS	Lowest RMS
I-94WB	0.99	0.86	0.14	0.04
I-94EB	0.98	0.91	0.17	0.05
TH-36WB	0.99	0.93	0.10	0.04
TH-36EB	0.99	0.96	0.07	0.01
I-35ENB	0.98	0.90	0.21	0.05
I-35ESB	0.98	0.93	0.18	0.06
I-694EB	0.99	0.92	0.22	0.03
I-694WB	0.99	0.94	0.16	0.05

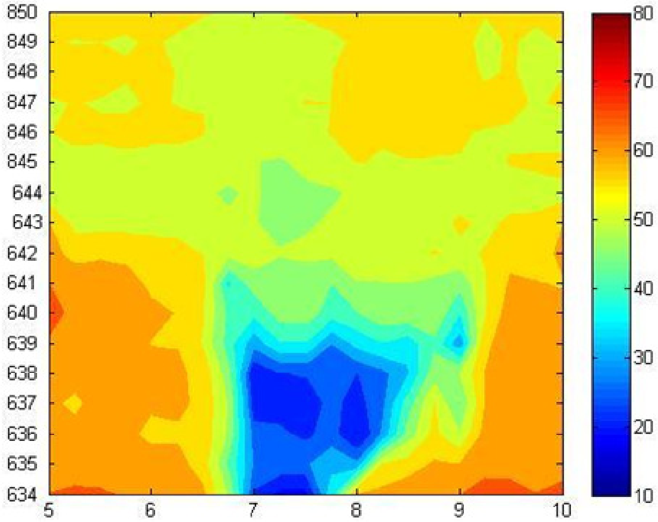

Figure 7.8: Contour for real speed in I-35E SB

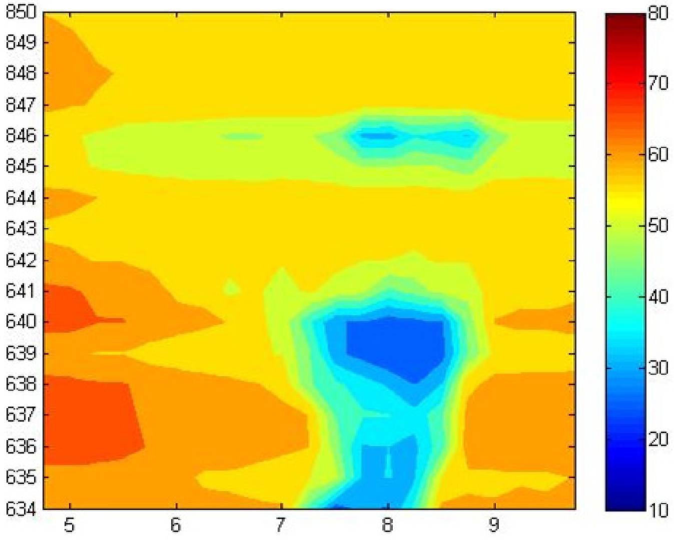

Figure 7.9: Contour for simulated speed in I-35E SB

which is in detector 634, starting from 7 am in reality. The congestion condition lasts until detector 639, and the congestion period lasts until 8 am. In Figure 7.9, the bottleneck occurs approximately at the same detector, and the congestion lasts for the same duration in the simulation model. In this case, although the numbers of the simulated speeds do not match the real speeds, the speed-based calibration for I-35E SB can also be finished from an engineering perspective.

Network calibration

Followed by freeway calibration, network calibration is conducted to calibrate route choice parameters (The flowchart of the calibration process was presented in the Methodology Chapter). In this calibration process, O/D matrices are adjusted to obtain a better representation of the traffic demand. Traffic control plans for intersections are revised to better manage the system. A similar volume-based validation is implemented to examine network calibration. The same goodness-of-fit measures are implemented in this calibration process.

As mentioned before, the basic inputs for the AIMSUN model are network, traffic demand, and traffic control plans. The network is shown in Figure 7.11. Differently from freeway calibration, the traffic demand for the entire network was in terms of 24 O/D matrices, which were obtained from the 2010 Regional Planning Model of the Twin Cities Metropolitan Area. The traffic control plans can be divided into two categories in this case study. One is the real data from Mn/DOT and Ramsey County; the other is a plan following the procedure mentioned above. After the basic input data was prepared, boundary condition verification was conducted.

Preparation for the calibration

Before the network calibration begins, two preliminary steps were conducted to obtain reasonable traffic conditions and better default values for model parameters. First, some of the traffic control plans were redesigned to obtain a higher level of service in the intersections. The procedure is presented above. Second, link costs parameters were adjusted, relying on a judgment of the discrepancies between simulated volumes and real volumes (e.g., detector data and AADT). Several runs of the simulation were conducted to compare the improvement of simulated data.

In this model, link capacity and speed were obtained from the 2010 Twin Cities Regional Planning Model, which has been calibrated in regards to link flows, capacities, free-flow speeds, link distances, and travel times. Such initial values might be a good start for calibrating link costs parameters in the calibration process. However, the link speed in the Regional Planning Model can be different from that of a microscopic simulation model. The speed in the previous model is estimated by the measured travel time, which takes the travel time in the links as well as the delays in the intersections into account. However, if those speeds are defined as the maximum average speed in AIMSUN, the delay in the intersections will be double counted. Therefore, the initial values of the speeds should be carefully considered, and those values may be adjusted during the O/D matrices estimation and route choice model calibration. After the levels of service of intersections were acceptable and link costs parameters are defined, the network calibration can start.

Origin/Destination matrices estimation

O/D matrices estimation was conducted to obtain time-dependent O/D demand for the microscopic simulation model, as well as to obtain better representation of the traffic demand for the simulation. In this case, although 24 O/D matrices were available from the 2010 Twin Cities Regional Planning Model, time dependent O/D with shorter intervals were needed to obtain better simulation. The time interval between those 24 O/D matrices is approximately an hour. The discrepancy between the demands of each period might influence the simulation results, since each matrix is discretely implemented. Time dependent matrices with 15-minute intervals were used to obtain a better representation of trip demand and to reduce the gap between two O/D matrices. Furthermore, the adjusted O/D matrices may achieve better representation of the traffic demand.

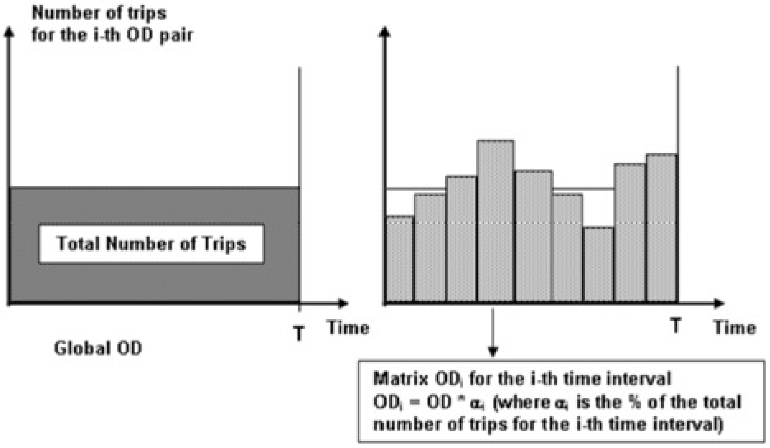

Figure 7.10: Time depend O/D matrices calculation[3]

O/D matrix adjustment is based on optimization algorithms and most of the current O/D adjustment methods depend on traffic counts[44]. The AIMSUN model utilizes heuristic approaches to split static O/D matrix into time dependent O/D matrices with shorter time intervals. First of all, according to real data, analysts define the time interval that the global matrix will be split into and the percentage of the sub-matrix to the seed matrix. AIMSUN will conduct static traffic assignment by using the sub-matrix, and adjust this sub-matrix with observed flows within that time interval. Eventually, the estimated OD matrix will be generated for that time interval, which can be used for dynamic simulation. The comparison of global OD and sub-matrix is shown in Figure 7.10.

Before O/D matrices were adjusted, link costs parameters were calibrated. In the AIMUSN-planner, the static traffic assignment is based on Volume Delay Functions (VDF). In this case study, the defaults VDF in AIMSUN were implemented, whose major parameters are link capacity and link length. Due to the size of the network, the link capacity was not estimated but imported from the Regional Planning Model, which should contain well-calibrated link capacities for the entire Twin-Cities metropolitan area. In this process, the major objective was to select suitable VDF for each link.

Different VDF were selected based on the type of roadway. Based on the selected VDF, a static traffic assignment was conducted to obtain link volumes. Such data was compared to two reference sets: real data and static traffic assignment results from Cube Voyager. Goodness-of-fit was implemented to judge the discrepancies between simulated link volumes and real link volumes (i.e., AADT), based on which VDF of the link might be re-selected. Due to the limitation of the data, link volumes from Cube Voyager were used as another reference, since that model was proven to be valid. Generally, VDF of the links was calibrated until the discrepancies between simulated link volumes and real link volumes were acceptable; then O/D matrix adjustment was conducted.

After the VDF was selected for all links, O/D adjustment was conducted by using the AIMSUN-planner. The estimation of time dependent matrices was as follow:

Step One. Estimate the percentage of each sub-matrix

There are 24 O/D matrices available in this study. Each matrix of those 24 O/D matrices can be seen as one global O/D matrix. Sub-matrices with 15-minute for each global O/D matrix are time dependent matrices during the particular time period. For example, a global O/D matrix was for 8:30 am to 9:30 am. There were four 15-minutes sub-matrices during this time period, which are from 8:30 am to 8:45 am; 8:45 am to

9:00 am; 9:00 am to 9:15 am; and 9:15 am to 9:30 am. The percentage of each sub-matrix should be defined in the AIMSUN model, and the sum of each percentage for a particular global O/D matrix can be 100% or less. Take this last example as well. The percentage could be 24%, 26%, 27%, and 23% for sub-matrices of different periods.

For the TH-36 project, the percentage of each sub-matrix was roughly estimated from loop detector data. First of all, some typical detectors were selected and the traffic volumes with 15-minute intervals were obtained for 24 hours. According to the time periods of those 24 global O/D matrices, the traffic volumes of an entire day, from loop detectors, were divided into 24 respective time periods. The percentage can be calculated by the following equation:

$$P = \frac{V_1}{V_{total}} \times 100\% \tag{7.5}$$

Where P is the percentage of the time dependent matrix, V_1 is the traffic volume during each 15-minute interval, and V_{total} is the traffic volume during the entire time period of the global matrix.

There were three types of vehicles defined in the AIMSUN network in this case study: SOV, HOV, and Truck. 24 global matrices were available for each type of vehicle. Since the flow proportion of HOV and Truck were unknown, it was assumed that SOV was 95% of total traffic volumes and the rest was HOV and Truck. In this case, only time dependent O/D matrices of SOV were estimated, and the traffic demand for HOV and Truck were still in global matrices. There were two reasons for this assumption. First of all, HOV and Truck demand were not generally distributed within the entire network. There can be some locations that have a high demand of HOV or Truck, and these locations were unknown in this case. If the global matrices of HOV and Truck were split into sub-matrices by using a uniform percentage, the demand in those locations might be decreased, while demand in other locations might be increased. In addition, the traffic demand of HOV and Truck were so small that the discrepancy between the global matrices of HOV or Truck does not influence the representation of the real traffic pattern. Therefore, only O/D matrices of SOV were split into sub-matrices with 15-minute intervals. Accordingly, the equation for calculating the matrix percentage was revised as follows:

$$P = \frac{V_1}{V_{total}} \times 95\% \tag{7.6}$$

Where 95% was the flow proportion of SOV of total traffic volume, and the others were the same as in last equation.

Step Two. Time dependent O/D matrix estimation

The sub-matrix from each global matrix was the target matrix used in the first iteration in the matrix estimation process. AIMSUN adjusted the matrix by using bi-level optimization methods to seek the fitted matrix. Static traffic assignment and least square methods were used against the observed data of link flows.

Step Three. Validation of adjusted matrices

The target of each O/D matrix adjustment was to obtain over a 90% coefficient correlation and less than 5% of a Relative Gap. The corresponding results of each converted sub-matrix are listed in Table 7.4. The results indicated that the adjusted matrices are capable of generating very good traffic patterns against the real link flows. All of the R-squares are higher than 93% and all Relative Gap are lower than 3.5%. From the table, it can be seen that all adjusted matrices reached the target.

Table 7.4: Results of O/D matrix adjustment

	R^2	Gap%
Minimum	0.931	0.261
Maximum	0.988	3.085

In addition, the static traffic assignment was implemented to compare the results of O/D matrix adjustment. The linear regression results are presented in Figure 7.11 and Figure 7.12. The data in the figures is the Average Daily Traffic (ADT).

The R-square before adjustment is 0.946, while after adjustment it is 0.98. The Standard Errors are reduced from 5398.2 to 3540.8. The regression statistics results indicate that the link flows with adjusted O/D matrices have better representations than initial O/D matrices. From these statistical results, new O/D matrices were accepted, and the calibration of link costs parameters (i.e. VDF) was not needed again. Such adjusted O/D matrices were implemented for rout choice model calibration in the next step:

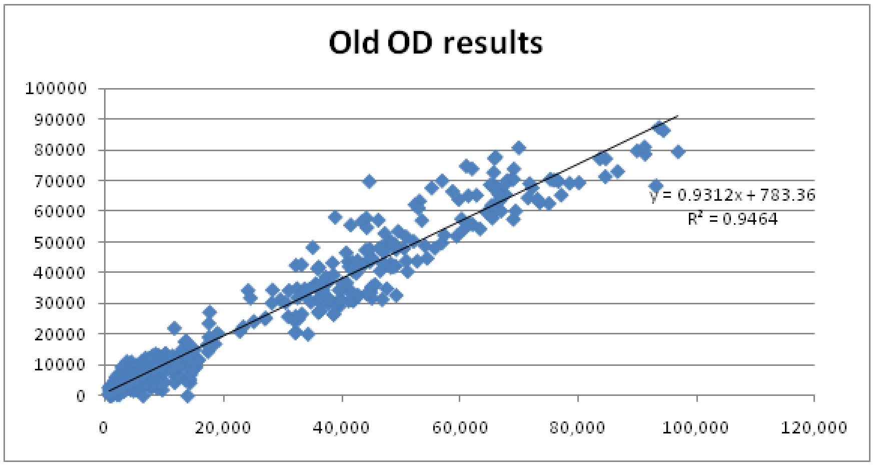

Figure 7.11: Linear regression results for old O/D

Route choice model calibration

Route choice model calibration can be conducted based on user defined paths, which can be aggregated data or individual data obtained by surveys[43]. However, in this case, the path information was not available for calibration. An alternative method is designed to calibrate the route choice for vehicles. In this process of calibration, the global parameters of route choice model were preliminarily calibrated first. The traffic conditions were improved and local parameters were calibrated based on those initial parameters.

In traffic assignment, the travelers' decision is made based on route choice models, which, in the AIMSUN simulator, are based on discrete choice theory. Route choice models describe the probability for travelers to select a path from all available alternatives. In the AIMSUN simulator, there are seven route choice models: Fixed Using

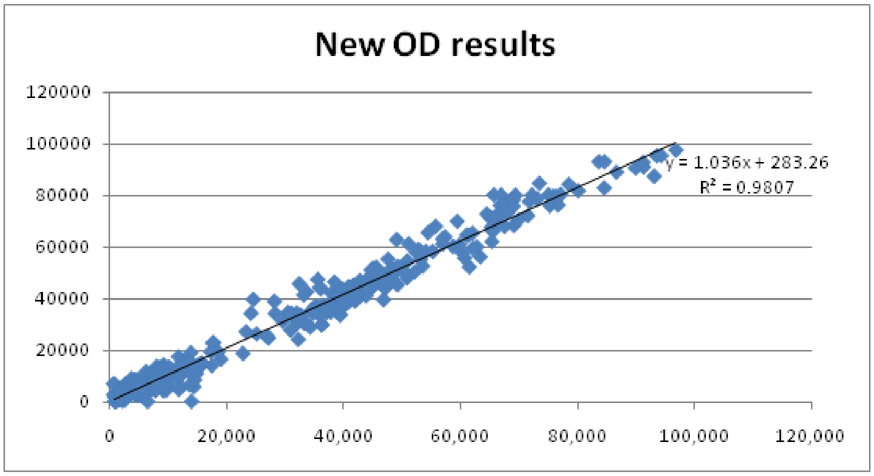

Figure 7.12: Linear regression results for new O/D

Travel Time in free flow condition, Fixed Using Travel Time in warm-up period, Binominal, Proportional, Multinomial Logit, C-Logit, and User-Defined Models. In this case study, the Multinomial Logit Model was selected, and the corresponding initial parameters were selected from a similar project.

The route choice model is used to define the probability of a path being selected from all possible alternative paths. In multinomial logit model, this probability is expressed as follow:

$$R_k^i = \frac{e^{-\theta^i_{tk}}}{\sum_l e^{-\theta^i_{tl}}} = \frac{1}{1 + \sum_{l \neq k} e^{-\theta(t_j^i - t_k^i)}} \tag{7.7}$$

This equation illustrates that the probability of a selected alternative is based on the difference between the measured utilities of that path and all other available paths. [3]. P_k^i is the probability of choosing path k amongst all alternative routes of O/D pair i. t_k^i is the expected travel time on path k of O/D pair i. θ is a shape or scale factor parameter, while t is the expected travel time on path k of OD pair i. $\theta < 1$ vehicles tend to use many alternative routes, while $\theta > 1$ will concentrate on selecting alternatives among a

Table 7.5: Regression Statistics for OD adjustment

Regression Statistics	Before Adjustment	After Adjustment
Multiple R	0.9728	0.9903
R^2	0.9464	0.9806
Adjusted R^2	0.9462	0.9806
Standard Error	5398.2	3540.8
Observations	465	465

few paths. In other words, when the θ becomes larger, the probability for selecting the shortest path will be higher. This scale factor parameter, θ, is the parameter defined by analysts.

In addition, traffic control plan should be adjusted as well. Vehicles can change their shortest paths when the travel time in the initial shortest paths are high (i.e., they encounter congestion). The traffic control plans in the intersections might be not sufficient or over-utilized due to the change of section flows. Those traffic control plans might generate unexpected congestion and increase the delay in the network, which affects the route choice of vehicles. After the global parameters were preliminarily calibrated, the traffic conditions within the network were observed to find the congestion in arterials. In freeway calibration, the bottlenecks in freeways can be identified by using speed contour plots. However, the data for arterials are limited, so the bottlenecks in the arterials cannot be identified. The objective is to obtain proper traffic control plans for major intersections and reduce the delay due to improper control plans.

Proper traffic control plans for the intersections are necessary to provide smooth movements for vehicles. This is an important step in route choice model calibration, since the facilities should provide a certain level of service. It would be ideal if the traffic control plans in the simulation network were the same as in reality. Vehicles can have the same preference. However, such information is not available in a large-scale simulation network. The alternative way is to obtain a healthy network that vehicles can move smoothly.

Furthermore, link costs parameters should be calibrated. Since the path information of travelers is not available, vehicles cannot exactly follow the paths in reality, which increases the difficulty of route choice model calibration. An alternative was thereby designed to conduct route choice calibration. It was observed that the simulated volumes are higher than observed volumes in the freeway sections, which is shown in Figure 7.13. The data is the Percentage Difference of ADT for all detectors, which is defined as:

$$PD = (V_s - V_o)/V_o \times 100\% \tag{7.8}$$

Where PD is Percentage difference, V_s is the simulated volume of 24 hours, and V_o is the observed volume of 24 hours.

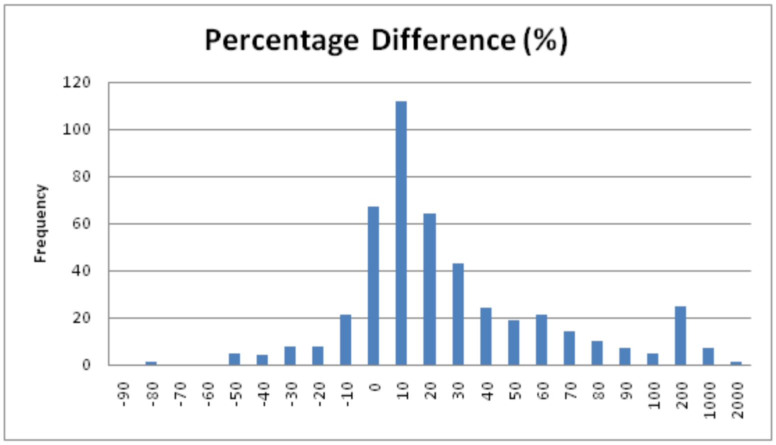

Figure 7.13: Percentage difference of ADT from all detectors before calibration

The mean of the Percentage Difference in Figure 7.13 is 29.6% and the standard deviation is 0.996. One sample t-test result shows that the P value is 0 in a confidence of 95%, which allows a rejection of the null hypothesis that the mean is zero. In addition, Percentages of the data from half of detectors are over 20%. By and large, the volumes in the freeway sections can be said to be higher than in reality. There might be two reasons for this. First, the traffic demand is generally higher than in reality. Second, freeways are more attractive in the AIMSUN model than in reality. Since O/D matrices adjustments have been conducted and obtained good results, the traffic demand is assumed to be at the same level as in reality.

In order to reduce the attraction of freeway sections, an attempt was made to increase the costs of using freeways. In this case, User Defined Cost was implemented in ramps to increase the link costs of freeway paths. The vehicles in AIMSUN network follow the shortest paths in terms of lowest costs paths. The costs of a path are the aggregated costs of all links that belong to that path. Each link contains a section and a turning movement. The link costs are calculated by following equation[3]:

$$DynCost_j = ETT_j + ETT_j \times \varphi \times (1 - CL_J/Cl_{max}) + \tau \times UDC_s \tag{7.9}$$

Where $DynCost_j$ is the dynamic cost of link j, ETT_j is the estimated travel time of the link j, φ is a user-defined capacity weight parameters that control the importance of link capacity in link costs calculation, CL_j is the capacity of link j,CL_{max} is the theoretically estimated maximum link capacity, τ is the user-defined costs weight parameter that controls the importance of user defined costs in link costs calculation, and UCD_s is the user defined cost of the section s which belongs to link j.

According to this equation, if UCD_s is increased, the shortest paths for vehicles will change, due to the increased dynamic costs of link j. If the access of freeways has higher costs, the freeway will be less attractive; thus, the flows in freeways might be reduced.

UDC is also implemented to prevent a flip-flop of traffic flows; therefore, both entrance and exit ramps have UDC. Since vehicles can change their routes when they encounter congestion, once freeways have significant congestion, vehicles might divert to parallel arterials and come back to freeway sections to avoid the congested sections. However, in reality, most vehicles choose to stay on the freeway and wait in the queue, even though the congestion in the freeway is significant. In this case, the route choice model in AIMSUN network is too flexible for drivers to change routes. In order to emulate this situation in reality, such diversion should be prevented. If both exit and entrance ramp have UDC, the total costs of diversion can be higher than the costs of waiting in freeways, and the vehicles might choose to stay in the freeways. The objective is to figure out the balance between the costs of congestion and the UDC of exit as well as entrance ramps.

Based on this idea, User Defined Costs (UDC) of all ramps are calibrated in two steps:

Step One. Define initial uniform UDC

Since simulated flows in freeways are generally higher than observed data and information about UDC is not available, an initial uniform UDC is defined first to examine whether this idea works. In order to calibrate UDC, statistical results of simulated link flows are also utilized. Similarly to the process of adjusting global parameters in freeway calibration, UDC is designed as zero and increased with an interval of five. Eventually, a value of 60 is defined as the uniform UDC for all ramps.

Step Two. Calibrate local UDC

Through examining each plot of simulated verses observed link flow, as well as goodness-of-fit-such as correlation coefficient, RMS, and Percentage difference-the UDC of each ramp is adjusted to calibrate suitable costs of the shortest paths.

Although the data in arterials are limited, the calibration of route choice model can be based on Annual Average Daily Traffic (AADT) of arterials. In this case study, the AADT of the entire network is available from Mn/DOT[38]. If arterials are underutilized in AIMSUN network, the attraction of these arterials is increased; while if they are over-utilized, the attraction is decreased. Such attraction is in terms of speed, capacity, and UDC. As mentioned before, the speed and capacity of all arterial sections are from 2010 Regional Planning Model. They might not be suitable in a dynamic traffic assignment model in the AIMSUN simulator. It is assumed that the Average Daily Traffic (ADT) in AIMSUN is comparable to AADT in reality. If ADT in the AIMSUN network is 15% different from AADT of real data, the parameters are adjusted to increase or decrease the attraction. However, not all arterials sections are calibrated. In this case study, sections in TH-61, White Bear Ave, McKnight Ave, and TH-120 are calibrated.

7.3.3 Calibration results and model validation

Statistical analysis for Base Case

First of all, a correlation coefficient is implemented to evaluate the traffic volume of each 15-minute interval (There are 96 time intervals for 24 hours). The simulated data for each time interval is the traffic volumes of all detectors (i.e., 465 detectors) during the time period (i.e., 15 minutes). The real data is traffic volumes of corresponding detectors during the same time. Figure 7.14 shows that all correlation coefficients of 96 intervals are higher than 0.93 and most of them are close to 0.99, which indicates that the correlation between the simulated data and real data is strong. In addition, the percentage difference shows the discrepancies between them. As shown in Figure 7.15, most of the percentage difference are between -10% and 10%, which is acceptable in this study.

Linear regression and a Bland-Altman plot are also used. As shown in Figure 7.16, the slope of the regression line is 1.04 and the intercept is 353.9. From the regression results, the p values of the intercepts are 0.11 and the 95% confidence interval for the intercepts is between -90 and 800. The Bland-Altman plot (Figure 7.17) shows that the data points are around the x-axis, which means the AIMSUN data obtained a good estimation of the real data. The slope of the regression is 0.05. However, the t test results show that the p value is 0, which indicates that the hypothesis that the value is zero can be rejected. Additionally, in Figure 7.18, the average of percentage difference of all detectors after the calibration is 13% and the t test shows a rejection of the null hypothesis. Although after calibration the volumes in freeways are reduced significantly (the percentage difference was reduced from 0.29 to 0.13), the volumes in AIMSUN are still higher than the real data. However, in general, AIMSUN has better results in statistical analysis.

Statistical analysis for Full Closure

Similar to the Cube Voyager model validation, real data during the full closure of TH-36 was also used for examining the model validation for AIMSUN. Figure 7.19 shows the linear regression of real ADT of the detectors and simulated ADT in AIMSUN. The slope of the regression line is close to 1 and the correlation coefficient is 0.98. Similar to the Base Case, the Bland-Altman plot (Figure 7.20) also shows that the simulation data is higher than the real data. The slope of the regression line is 0.07, and the t test shows a rejection of null hypothesis as well.

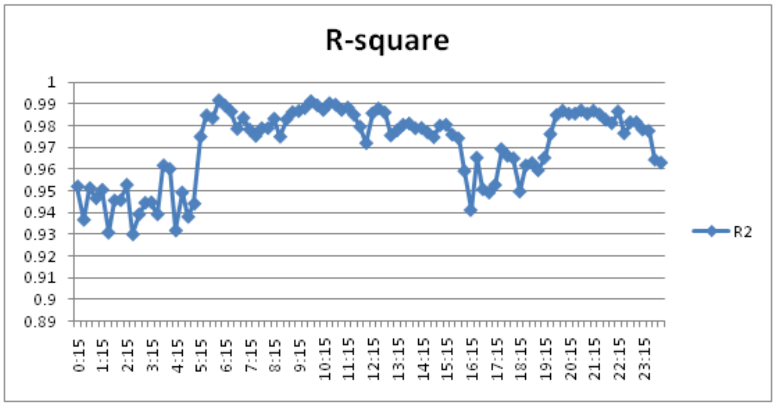

Figure 7.14: R-square of very time interval

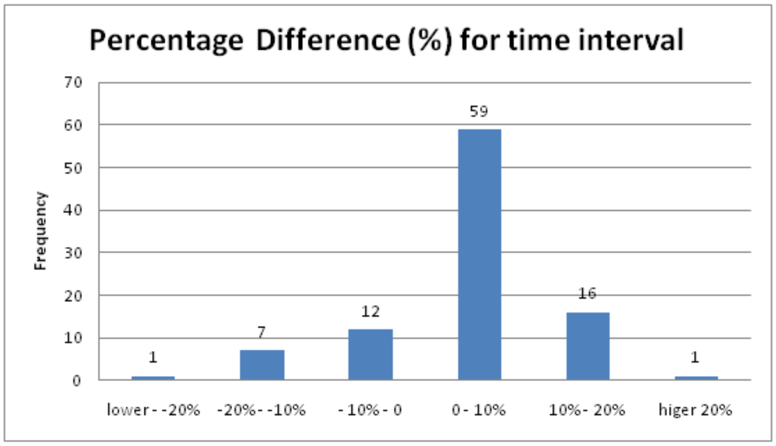

Figure 7.15: Percentage difference for time interval (15-min)

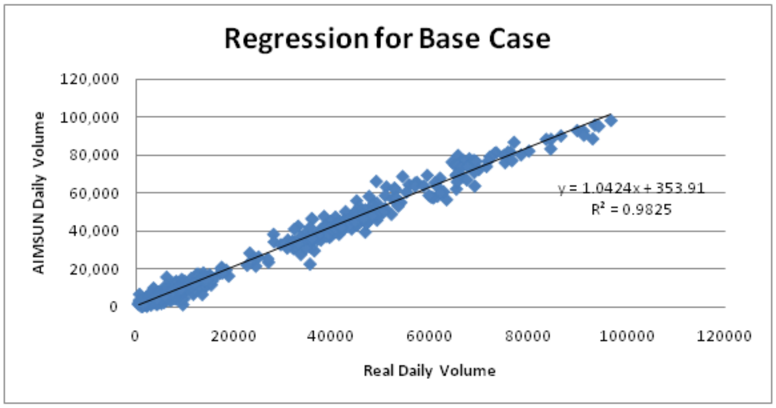

Figure 7.16: Regression for Base Case in AIMUSN

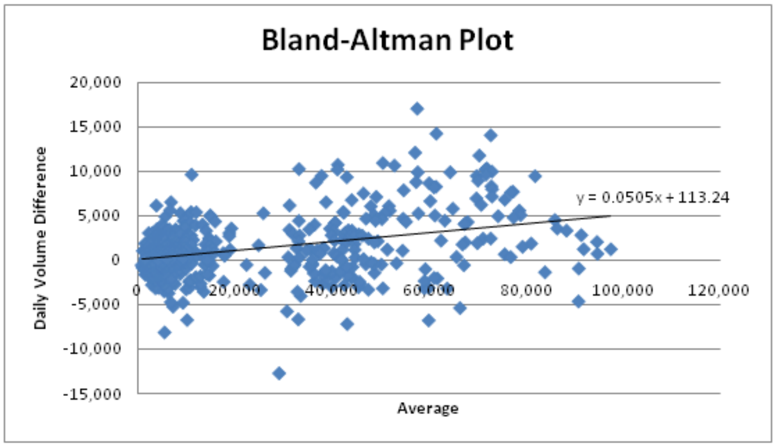

Figure 7.17: Bland-Altman Plot for Base Case in AIMSUN

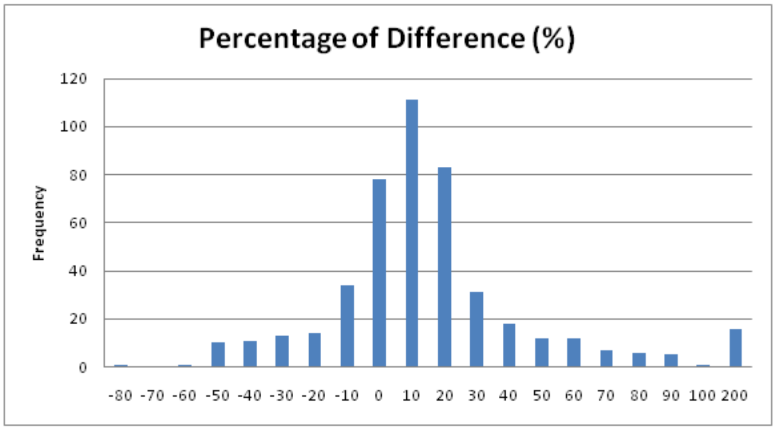

Figure 7.18: Percentage difference in Base Case after calibration

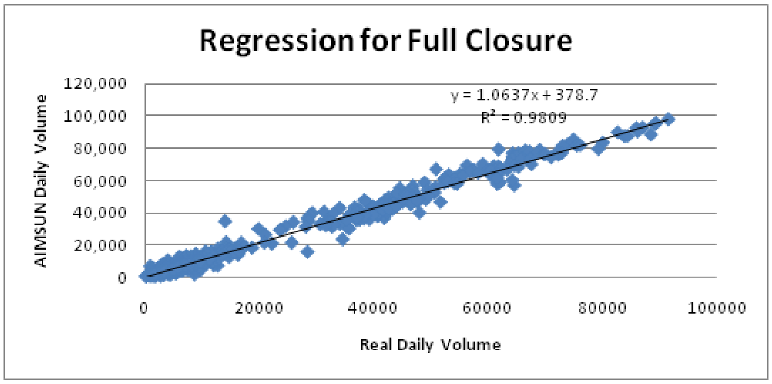

Figure 7.19: Regression for Full Closure in AIMSUN

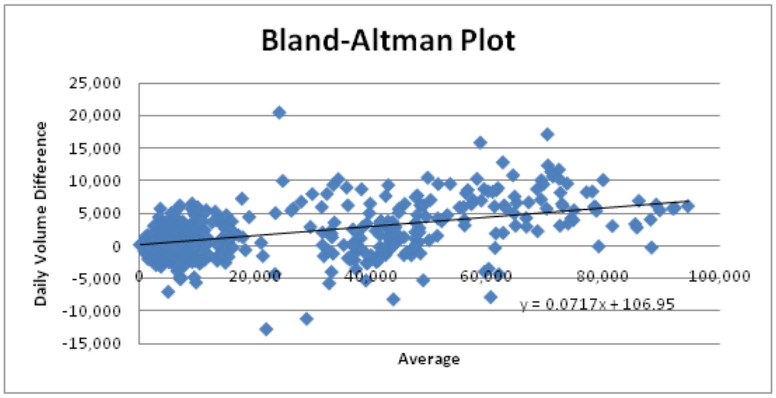

Figure 7.20: Bland-Altman Plot for Full Closure in AIMSUN

Chapter 8

Results

In the case study, three tools-QuickZone, Cube Voyager, and AIMSUN-were utilized to calculate RUC for the Full Closure and Partial Closure alternatives in the TH-36 project. These outputs are compared in this chapter, and several scenarios are designed for a preliminary sensitivity analysis of RUC.

8.1 Results comparison

8.1.1 Traffic diversion analysis

The three tools used in this case study were implemented for area-wide RUC calculation. One important area-wide impact is traffic diversion due to the construction. QuickZone did not predict the traffic diversion, while Cube Voyager and AIMSUN can both be used for traffic diversion analysis. Agencies can use this analysis to develop several effective options for a Transportation Management Plan, to mitigate disruptions due to the construction[45].

The traffic diversions in Cube Voyager and AIMSUN were analyzed by comparing the link volumes discrepancies between Base Case and During Cases, which include Full Closure and Partial Closure. An AM period (i.e., 5 am-10 am) and a PM period (i.e., 2 pm - 8 pm) were selected, since traffic diversion can be more obvious during peak hours. The traffic diversion analysis was described in the Site Description Chapter, and the analysis was designed to compare the traffic diversions in reality and in simulation models for Full Closure. In addition, traffic diversions in Partial Closure are also analyzed in order to compare the impact due to different alternatives. The objective of this traffic diversion analysis for Cube Voyager and AIMSUN is to examine whether these two tools can predict the same routing due to the disruption of the TH-36 construction.

Full Closure

The traffic diversions are analyzed in terms of percentage difference of volume during the period defined in the Implementation Chapter. The actual diversion is briefly mentioned here, while the details can be found in the Site Description Chapter. The results from Cube Voyager and AIMSUN are compared with the actual diversion.

AM period

The traffic diversions during Full Closure in the AM period are shown in Figure 8.1 (real data), Figure 8.2 (Cube Voyager), and Figure 8.3 (AIMSUN). The traffic volumes used for Figure 8.1 were average data from loop detectors and volume measurements in 13 locations near TH-36. From this figure, we can see that the volumes in TH-36 have a significant decrease and the parallel roadways (e.g., County Rd C and County Rd B) have a significant increase. East-west-oriented I-694 (from the interchange of TH-36 to the interchange of TH-61) has increased volumes as well. Vehicles originally traveling on TH-36 WB might take this freeway as a detour instead of following the official detour route, which includes I-694 SB, I-94WB, and I-35NB. Since data is limited, the diversion of these vehicles cannot be captured beyond the interchange of TH-61 and I-694. In addition, there is an increase in I-94 WB in the AM period. It is possible that the travelers who used to travel on TH-36 took I-94 instead. However, due to the limitations of the data, the traffic diversions in reality cannot be fully captured; however, it is still a good reference for examining the performance of the traffic analysis tools.

Figure 8.2 shows the traffic diversions in Cube Voyager. Compared to Figure 8.1, the parallel roadways to TH-36 also have a significant increase in volume during this period. The percentage differences are on the same scale as in Figure 8.1. There is a slight increase in I-694 and in TH-61, which indicates that the WB travelers use I-694 and TH-61 to come back to TH-36. These two facts shown in Figure 8.2 agree with the

Figure 8.1: Traffic diversions of Full Closure in AM (real data)

Figure 8.2: Traffic diversions of Full Closure in AM (Cube Voyager)

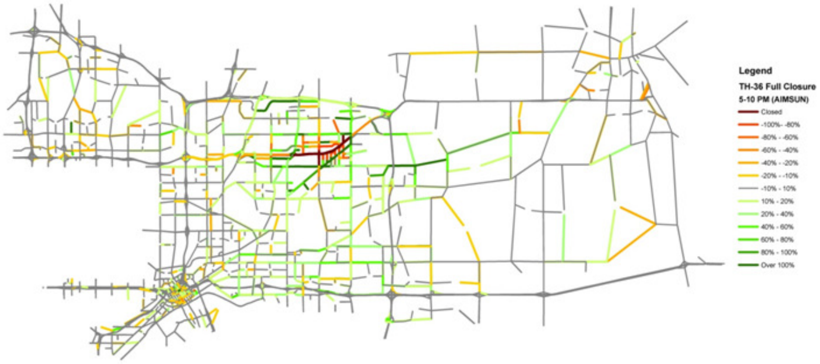

Figure 8.3: Traffic diversions of Full Closure in AM (AIMSUN)

real facts in Figure 8.1. However, the decrease in volume in the sections between the interchange of I-35E and the interchange of TH-61 was not captured. In addition, it also shows that there is a decrease of volumes on McKnight St., due to the closure. In Figure 8.1, we only have data for four links, while the impacts on the other links can be seen in Cube Voyager. The influence on McKnight St. is significant, since almost the entirety of McKnight from I-694 to I-94 is affected.

However, the increase in volume on I-94 was not captured by Cube Voyager. The traffic assignment was conducted for the entire Twin-Cities network, including some areas in Wisconsin. The model should have captured such a diversion if the demand was accurate for the model. However, this might indicate that a large number of work-based trips in the east area are not included in the model.

Figure 8.3 shows the traffic diversion in AIMSUN. The impacted area in this tool is wider than Cube Voyager. Similarly, the increases in volumes on parallel roadways to TH-36 are emulated, and the values of percentage difference are on the same scale as in reality. There is an increase, which is between 10% -20% in east-west oriented

I-694 sections (this agrees with the conditions in Figure 8.1). In addition, the volumes in TH-61 in both AIMSUN and Cube Voyager are increased, while the volumes in the common area of I-35E and I-694 do not show a significant change. Since the models for AIMSUN and Cube Voyager were proven to be valid through statistical analysis, it is safe to conclude that most of the long-trip travelers use the route that is consisted of TH-61 and I-694 links as their detour during the TH-36 full closure construction. AIMSUN also shows that McKnight is significantly influenced, due to the closure.

However, AIMSUN does not capture the diversion in I-94 as well. There may be two reasons causing this discrepancy. First, the traffic demand may not include the large number of work-based trips that we identifying missing from the regional planning network. Second, trips that enter the network from the centroids in Stillwater or east-end of I-94 cannot select the best entrance, due to the limitation of the connection between the entrance in Stillwater and the entrance in I-94. In reality, travelers from Wisconsin can select the best entrance for them from the two bridges in the boundary. However, the selected network in AIMSUN has a limitation in considering such route diversion. It is reasonable that the volume does not increase in I-94, since those travelers cannot make the diversion "outside" the network.

PM period

The traffic diversions during Full Closure in the PM period are shown in Figure 8.4 (real data), Figure 8.5 (Cube Voyager), and Figure 8.6 (AIMSUN). These figures have the same legend as the figures in the AM period. Similar conclusions can be made based on these three figures. In general, both Cube Voyager and AIMSUN capture the diverted traffic in parallel local roadways as well as the TH-61 and I-694 route.

Partial Closure

A Partial Closure Alternative is another construction alternative for TH-36, although it was not implemented in reality. In order to comprehensively compare these two models, traffic diversions generated by Cube Voyager and AIMSUN are also analyzed, but the real data was not available in this case. Since the traffic diversion analysis shown in last section indicates that these two tools predict a similar conclusion to reality, their

Figure 8.4: Traffic diversions of Full Closure in PM (real data)

Figure 8.5: Traffic diversions of Full Closure in PM (Cube Voyager)

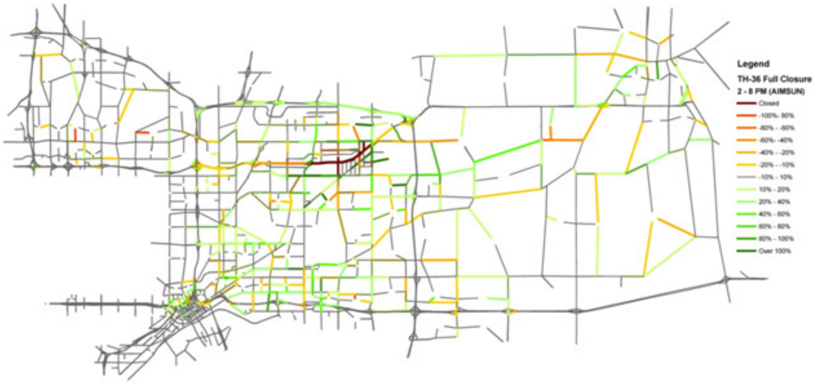

Figure 8.6: Traffic diversions of Full Closure in PM (AIMSUN)

prediction of the Partial Closure may be trustworthy enough to understand the difference between the two construction alternatives. For Partial Closure, the analyses for the AM period and the PM period are separated as well.

AM period

The traffic diversions in Partial Closure during the AM period are shown in Figure 8.7 (Cube Voyager) and Figure 8.8 (AIMSUN). From Figure 8.7, we can see that the impacted area is smaller than in Full Closure. The volumes in freeways do not show a significant change, while the volume increases in parallel roadways to TH-36 in Cube Voyager are slight. In contrast to Cube Voyager, AIMSUN shows a wider impacted area. As mentioned in the Implementation chapter, the volumes in freeways system are higher than reality in an AIMSUN network. This might indicate that the arterials do not have enough demand when compared to reality. However, only AADT is available for arterial analysis in this case, so the validation of simulated volumes during the AM or PM periods is unknown. If the travel volumes in arterial links are low, the percentage

Figure 8.7: Traffic diversions of Partial Closure in AM (Cube Voyager)

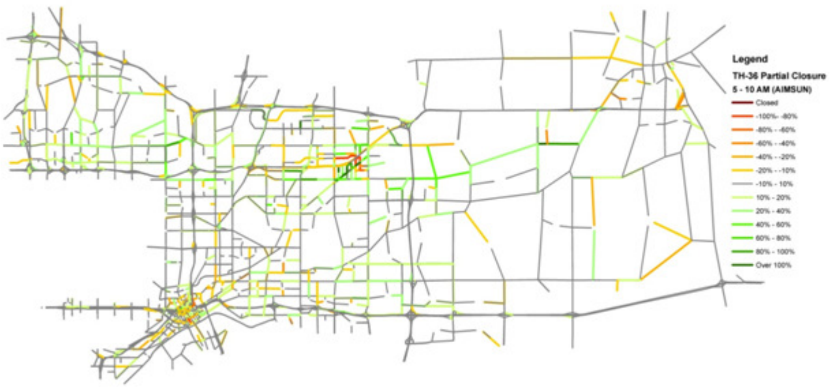

Figure 8.8: Traffic diversions of Partial Closure in AM (AIMSUN)

difference might show bias, since the absolute discrepancies of link volumes between Base Case and During Case are low.

Similarly, the volume changes of the links around TH-36 are in the same scale as Cube Voyager. In addition, HW 5 in both cases gets influences, which indicate the impacts due to the Partial Closure reach only the local area around the work zone but also the roadways far away.

PM period

The traffic diversions in Partial Closure during the PM period are shown in Figure 8.9 (Cube Voyager) and Figure 8.10 (AIMSUN).From these two figures, the impacts of partial closure in PM period are similar to those in AM period.

Figure 8.9: Traffic diversions of Partial Closure in PM (Cube Voyager)

Summary

From the figures shown above, one can conclude that the Cube Voyager and AIMSUN models can predict traffic diversion in most cases. Both tools show that the local

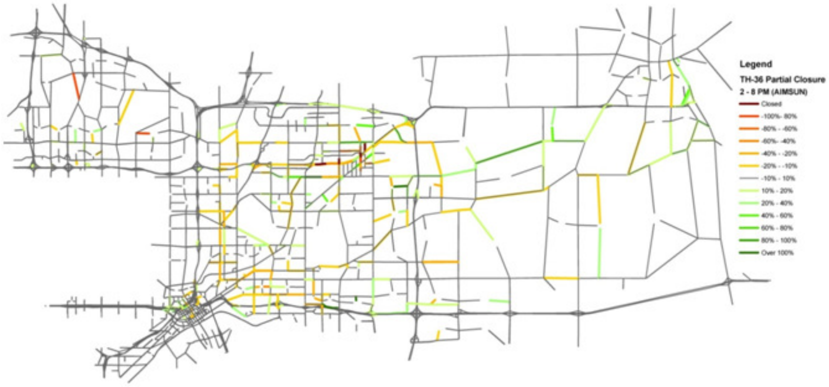

Figure 8.10: Traffic diversions of Partial Closure in PM (AIMSUN)

roadways around the work zone get significant diversion, and their results agree with the real data that most of the travelers use TH-61 and east-west oriented I-694 as a freeway detour during TH-36 full closure. In addition, the Full Closure impact area is wider than the impact area of Partial Closure, and the influences for Partial Closure are not only in local areas near the work zone, but in other areas as well.

8.1.2 RUC results comparison

The RUC results from all three tools are compared in order to better understand the capability of each tool. In order to calculate the RUC for Project Alternatives, information about the Base Case and the During Case should be known. For the Full Closure alternative, the During Case includes a Full Closure scenario in which TH-36 is completely closed in both directions, and a One Lane Open scenario in which one lane of TH-36 (in both directions) is opened for traffic. In the Project Alternative design, the construction stage of Full Closure takes five months, while the next stage of construction in Full Closure Alternative – One Lane Open– takes three months. Accordingly, the total RUC in this alternative includes the RUC during Full Closure and the RUC during One Lane Open. For the Partial Closure Alternative, the During Case includes only one construction stage: One Lane Closure, in which one lane of TH-36 (in both directions) is closed for traffic for 20 months to finish the construction of TH-36.

In the QuickZone calculation, the network consists of four roadways: TH-36, I-694 (which is assumed as a freeway detour), County Rd B, and County Rd C (which are assumed as arterial detours). The daily RUC is the user costs differences of these four roadways between the Base Case and the During Case.

In the Cube Voyager calculation, the impacted area is selected based on a traffic assignment model. The daily RUC is the user costs differences of all links within the impacted area. In AIMSUN, the impacted area is the same as Cube Voyager, and the daily RUC is also the user costs differences of all links within the impacted area. The final RUC is presented in Table 8.1.

Table 8.1: results of three tools

	Full Closure		Partial Closure	
Tools	Daily RUC	Total RUC	Daily RUC	Total RUC
Empirical	69,000	11,160,000	9,000	5,307,000
QuickZone	69,600	12,114,000	18,600	10,969,000
Cube Voyager	79,500	13,680,000	19,500	11,492,000
AIMSUN	83,000	14,781,000	25,900	15,273,600

In Table 8.1, the daily RUC is obtained from the tools, while the total RUC is calculated by multiplying the daily RUC with the number of days during the corresponding construction period. It is assumed that the daily RUC does not change during construction. The daily RUC in the Full Closure alternative only includes the daily RUC for the Full Closure scenario. The daily RUC in the One Lane Open scenario in the Full Closure alternative is the same as in the One Lane Closure scenario in the Partial Closure alternative. It is assumed that daily traffic conditions of these two scenarios are the same. Both scenarios have the same network geometry, demand, and assumptions for calculation; therefore, the daily RUC can be seen as the same for both scenarios. The total RUC in the Full Closure alternative in Table 8.1 is the sum of the total RUC in the Full Closure scenario and the One Lane Open scenario.

As shown in Table 8.1, the daily RUC in the Full Closure alternative is higher than the Partial Closure alternative for all four tools, and the daily RUC grows with the sophistication of the tools. However, total RUC in the Full Closure alternative from AIMSUN is lower than the Partial Closure alternative, while the results from the other three tools show that total RUC in the Full Closure alternative is higher.

The total RUC depends on the number of days in the construction period, which is decided in the Project Alternative design. Due to unpredictable situations, the estimated construction duration, which relies on risk factors, can be longer than the actual implementation. The estimated construction period is an important issue, since it will affect the final results of the BCA. For example, if the construction period during Full Closure is four months instead of five months, the total RUC in the Full Closure alternative from all three tools would be less than the Partial Closure alternative. If the construction period is six months, the total RUC in the Full Closure alternative is higher. Therefore, even though daily RUC from the tools can be accurate, the estimated construction period is also important when obtaining reliable RUC and reliable BCA results.

On the other hand, since the daily RUC in the Full Closure is much higher than the in Partial Closure, Full Closure has a high variation of benefits and costs. If the actual work in the field takes a longer time than the design, the Full Closure might lose more money than Partial Closure.

By and large, these tools all show that daily RUC in the Full Closure alternative is higher than the Partial Closure alternative, while the total RUC does not have the same trend. It is not necessarily the case that higher daily RUC causes higher total RUC. However, the total RUC in Full Closure has higher variation than Partial Closure. If the construction is delayed, the Full Closure can lose more benefits.

8.1.3 The BCA results comparison

The objective in this study is to examine whether Benefit Costs Analysis (BCA) results can be different with and without considering RUC. According to the improved procedure of BCA calculation in the Methodology Chapter, a Benefit Costs Analysis was conducted for Full Closure and Partial Closure. Due to the limitations of the data, several assumptions were made in this analysis. The costs in the analysis were in terms of Time Cost and Vehicle Operating Costs, and the benefits are the cost savings between different alternatives. A 5% discount rate was selected, as recommended by the US office of Management and Budget[46]. The annual increase of Vehicle Hour Travel and Vehicle Mile Travel was defined as 1%. The total number of the days in one year was defined as 350. The final results are presented in Table 8.2. To simplify the process, the maintenance costs for both alternatives were the same, and only construction costs were considered as costs.

Table 8.2: Benefit Costs Analysis Results with RUC

	Cube Voyager		AIMSUN	
	Full Closure	Partial Closure	Full Closure	Partial Closure
PV of Benefit(20years)	-112,911,860	-106,559,241	-192,400,998	-177,946,128
Construction Cost	27,562,000	32,097,000	27,562,000	32,097,000
Net PV	-85,349,860	-74,462,241	-164,838,998	-145,849,128
B/C Ratio	4.10	3.32	6.98	5.54

Table 8.3: Benefit Costs Analysis Results without RUC

	Cube Voyager		AIMSUN	
	Full Closure	Partial Closure	Full Closure	Partial Closure
PV of Benefit(20years)	-126,592,441	-118,051,687	-207,215,459	-193,235,349
Construction Cost	27,562,000	32,097,000	27,562,000	32,097,000
Net PV	-99,030,441	-85,954,687	-179,653,459	-161,138,349
B/C Ratio	4.59	3.68	7.52	6.02

From the results of Net Present Value in Table 8.2, we can see that in both models Full Closure (in the long run) will save more money for society. Although the monetary numbers are not the same, they agree with each other that Full Closure is more economically feasible than Partial Closure in this case. Table 8.3 shows the BCA results based on a traditional process. In this case, Full Closure has more economical feasibility as well. However, in Table 8.2, even though the construction costs of Full Closure have a 30% increase, this alternative still has higher economical feasibility. Therefore, considering RUC into the BCA process can make significantly different decision.

8.2 Tool comparison

8.2.1 Output accuracy

Among these three tools, the output accuracy is difficult to conclude, since there are many factors affecting the final RUC. From the QuickZone model, the results might be underestimated, since QuickZone does not consider reduced speed in the work zone; the capacity estimation for network links might be so high that the final results are underestimated: the traffic assignment in QuickZone might be too subjective to indicate the diversion. Also, the reliability of the QuickZone results is based on proper assumptions and accurate input data.

Cube Voyager is more sophisticated, and able to evaluate traffic diversion. The results from this tool might be more reliable than those of QuickZone, since the goodness-of-fit of the results in the model validation is at an acceptable level. Also, the static traffic assignment in Cube Voyager generates more reliable Vehicle Hour Travel (VHT) and Vehicle Distance Travel (VDT) than QuickZone.

The AIMSUN simulator generates the highest results among the three tools, since it takes many more factors into consideration, such as the traffic control delay, the reduced speed due to the capacity reduction in the work zone, and the speed change due to the diversion. The model validation of the AIMSUN simulator shows that the results from AIMSUN have better goodness-of-fit than the Cube Voyager results. However, since the values of VDT and VHT are high, RUC has a high variance in different replications of simulation, although the VDT and VHT generated by different replications shows slight differences.

8.2.2 Effort requirement

The requirement for data and effort also increases with the sophistication of the tools. The effort for utilizing the tools and their output accuracy are presented in Table 8.4.

Table 8.4: Model comparison

Tools	Expected Output accuracy	Time spent for analysis
Time spent for analysis	minimum	couple of days
Cube Voyager	medium	several days
AIMSUN R^2	maximum	seven months

If analysts are familiar with the tool, only one or two days are needed to conduct the analysis by QuickZone. Basically, the time spent on QuickZone is for making assumptions, as well as for input data collection. The assumptions are needed for network selection and traffic assignment, both of which are mostly dependent on engineering judgment. In order to obtain proper assumptions, analysts need to conduct the traffic analysis before using QuickZone. The analysis could include traffic condition analysis for a particular area, based on which analysts can make proper assumptions to select the impacted area for QuickZone.

In addition, input data collection requires effort, too. Link capacities and link demand are two important inputs for a QuickZone network. Link capacity is often available by estimates based on Highway Capacity Manuals, other similar projects, and historical records and so on. Besides these recourses, link demand can also be available from previous measurements. However, the data might not be immediately available when analysts need to conduct the analysis by using QuickZone. Additionally, the time for making assumptions and data collection can vary due to different kinds of projects. In the case study of TH-36 project, two or three days were spent preparing data and proper assumptions. Ultimately, the calculation time for QuickZone is very short after these things are prepared.

For the travel demand model, only a traffic assignment model is utilized for RUC calculation. The input data is traffic demand and network information, including link geometry, link capacity, link travel time, and so on. In this case study, the Regional

Planning Model of the Twin Cities Metropolitan Area was available for analysis in Cube Voyager. The Regional Planning Model includes the traffic demand and network information, which are used in the Cube Voyager traffic assignment model. Effort was spent conducting a traffic assignment model to obtain VHT and VDT for the entire network, and to obtain an impact area due to different Project Alternatives in the TH-36 construction. In this particular case, since all the input data was available, little effort was spent by analysts in generating the results from Cube Voyager. The traffic assignment for the Base Case and the During Case of the two project alternatives took several hours, but the final Daily RUC was obtained with less effort. If the Regional Planning Model is not available for analysis, analysts need to decide whether the travel demand model is still a good option, since when conducting Four Step models, it takes a long time to build the model for a particular area.

A microscopic simulation model for a particular area is usually built by analysts. Great effort is needed for building network geometry, collecting input data, and calibration. In this case study, a large network was selected for AIMSUN simulation; this network included over 3,500 links and 300 intersections. Building the network geometry and collecting the input data took approximately two months for such large network (shown in Figure 7.7). Calibration of the network took approximately five months, to obtain the best goodness-of-fit. Freeway calibration in this case study took two months, in order to obtain the calibrated parameters for driving behavior models. Network calibration took another three months to obtain better OD matrices and the route choice model.

In contrast to QuickZone and Voyager, obtaining the simulation results in AIMSUN takes a long time. Each replication of the simulation needs approximately two hours, and several replications should be run for different scenarios. The daily RUC is calculated in terms of the difference between the Base and During cases. However, due to stochastic features in the Microscopic Simulation model, more than one replication for one case is needed to obtain the average results. It is recommended that thirty replications are enough for microscopic simulation[31]. Dozens of hours are spent in obtaining the final results. Additionally, the computer requirements of AIMSUN are much greater than QuickZone and Cube Voyager. Compared to Cube Voyager, the AIMSUN simulator requires significantly greater effort, but the accuracy of the results does not show a significant improvement.

8.3 Preliminary sensitivity analysis of the RUC

Implementing these three tools found that the RUC results are sensitive in many cases. For QuickZone, the RUC results are sensitive to the link capacities, link demand, and traffic assignment results. For Cube Voyager, the RUC in the Partial Closure alternative is sensitive to the travel time in the work zone. For the AIMSUN simulator, due to stochastic features in the model, the RUC changes significantly for different replications of the simulation. It should be noted that the sensitivity test presented here is not a formal sensitivity analysis but only a preliminary analysis for better understanding the relationship between RUC and the models.

In this section, several test scenarios are designed for each tool to examine the sensitivity of RUC to the model. One test scenario is designed for QuickZone, to examine the effectiveness of link capacity. Three test scenarios are designed for Cube Voyager, to examine the effectiveness of link capacity and link speed for the work zone. One scenario is designed for Cube Voyager, which also refers to the scenario in QuickZone. For the AIMSUN simulator, no additional scenario is designed, but the results from nine replications of the simulation are compared to examine the sensitivity of RUC to the stochastic features in the microscopic simulation model.

8.3.1 QuickZone

The initial demand of each link is AADT measured in 2006 from the Mn/Dot website[38]. The link capacities are roughly estimated based on the Highway Capacity Manual[39] and from the Regional Planning Model. However, since the Regional Planning Model of the Twin Cities Metropolitan Area contains information about link capacities, it is interesting to know the difference in results between the current network and the network with the link capacities from the Regional Planning Model. Therefore, one scenario is designed to examine such a difference.

The only difference between the current network and the designed scenario is the link capacities, while other input data-such as network geometry, link demand, project information, and traffic assignment results-remain the same. The objective is to examine whether RUC results are significantly different between these two networks. The link capacities of two networks are shown in Table 8.5, and the RUC results are shown in Table 8.6. "Initial Design" indicates the initial design for QuickZone, and "Test Scenario" indicates the test scenario for RUC sensitivity.

Table 8.5: Link Capacities of two networks

Capacity*	Initial Design	Test Scenario
TH-36	1100	1100
I-694	2200	1750
TH-61	1500	1300
WhiteBear Ave	1000	1000
County Rd B	800	800
County Rd C	800	800

*The unit of the capacity is vehicle/hour/lane

Table 8.6: Link Capacities of two networks

	Full Closure Alternative	Partial Closure Alternative
	Daily RUC*	Daily RUC
Initial Design	$\$70,000$	$\$18,500$
Test Scenario	$\$1,010,000$	$\$920,000$

Table 8.6 shows that the daily RUC in the Test Scenario is greater than the Initial Design. Since traffic assignment results are the same for both scenarios, the link capacities in the Test Scenario might be too low to carry the assigned demand. From Table 8.5, the capacities in I-694 andTH-61 are different, which are two roadways of the freeway detour. However, the sharp increase of RUC in Test Scenaro indicates that link capacities affect the RUC results significantly.

From the results of the Test Scenario, we can see that the link capacity significantly affects the RUC results. If the link capacity is not accurately estimated, the results from QuickZone might not be reliable. There are many resources to obtain link capacity, such as estimation based on the Highway Capacity Manual[39], historical data from other similar projects, a regional planning model, and so on. However, the data from all resources might not agree with each other. Engineering judgment is needed to select the most suitable data for a particular project.

8.3.2 Cube Voyager

The initial design of scenarios for Cube Voyager is presented in the Implementation chapter. There are no assumptions for Full Closure alternatives, while an assumption is made in Partial Closure about the link capacities in the work zone. The reductions of link capacities in the work zone are unknown for the Partial Closure alternative. Since there is plenty of literature about the estimation of capacity in a work zone, accurately estimating the capacity of the work zone is out of scope for this study. It is assumed that the capacity is half of the capacity before closure, in which case the capacity is reduced from 2200 veh/hr to 1100 veh/hr. Since the capacity of the work zone is not estimated by using sophisticated methods, a different capacity is assumed in the test scenario, to examine whether different capacity in the work zone affects the final RUC in the Partial Closure alternative. Furthermore, in the initial network, only link capacity is reduced, while the speed reduction due to the work zone is not considered. The travel time might be increased, due to the reduced speed, which might affect the results of the traffic assignment. In this case, another two scenarios are designed to examine whether increased travel time affects the final RUC.

Test Scenarios for the work zone capacity and speed

There are three test scenarios to examine the effectiveness of link capacity and free-flow travel time in traffic assignment for the Partial Closure alternative. The first test scenario is to examine the effectiveness of different work zone capacities. The link capacity of the work zone before construction is 2200 veh/hr in the Regional Planning Model, while it is assumed that the work zone capacity is reduced to 1100 veh/hr in the initial design. In this test scenario, it is assumed that the capacity is reduced to 1500 veh/hr. Other conditions remain the same as in the initial design. The final RUC of the test scenario is 18,800 dollars, while the daily RUC is 19,500 dollars in the initial design scenario.

The second and third test scenarios are to examine the effectiveness of reduced speed due to the work zone. In the initial design for Cube Voyager, the speed in the work zone is 40 mph, which is the same as in the Base Case. In the second test scenario, the speed is reduced to 30 mph, while the speed is reduced to 25 mph in the third test scenario. The initial travel time of the work zone links is recalculated by using the reduced free-flow speed. Other conditions remain the same as in the initial design. In Cube Voyager, the static traffic assignment is based on the link costs function. It is assumed that vehicles select the shortest path in terms of lowest path costs. In the case study, the link costs function is designed and calibrated by MPO, which contains three variables: initial travel time of the link, assigned link volume, and link capacity. The initial travel time of the link is calculated by dividing the link length by the speed, which is measured in the field. In order to consider the reduced speed in the work zone in the Partial Closure alternative, two speeds in the work zone are defined.

Results comparison

The scenarios' designs as well as the corresponding daily RUC are presented in Table 8.7.

Table 8.7: Comparison of Initial Design and Test Scenarios

	Speed in the Work Zone (mph)	Daily RUC (dollars)	Work Zone Capacity (veh/hr/ln)	Percentage Change
Initial Network	40	19,500	1100	0%
Test Scenario 1	40	18,800	1500	−4%
Test Scenario 2	30	22,400	1100	15%
Test Scenario 3	25	34,600	1100	77%

In Table 8.7, the Percentage change is calculated by following equation:

$$P = (RUC_T - RUC_I)/RUC_I \times 100\% \tag{8.1}$$

Where P is the Percentage change, RUC_T and RUC_I are the Daily RUC of the Test Scenario and Initial Design.

From Table 8.7, we can see that the change in the capacity of the work zone only causes a 4% difference in RUC. It is possible that the work zone in the Partial Closure alternative is not significantly congested and that the diversion is not severe when the speed is 40 mph. The increase of the work zone capacity does not help to reduce the delay in the work zone. However, the speed of the work zone affects the traffic assignment results significantly. Test Scenario Two has a 15% increase of Daily RUC while Test Scenario Three has 77%. It turns out that initial travel time of the link is more important than capacity, from the results of these Test Scenarios. The reduction of capacity in the work zone reduces the speed in the work zone and causes traffic diversion. Therefore, it would be better to consider this effect before traffic assignment is conducted. Compared to the results in Table 8.1, the Daily RUC in Test Scenario Two here is much closer to the Daily RUC of the AIMSUN simulator in the Partial Closure alternative.

8.3.3 AIMUSN simulator

AIMSUN is a comprehensive tool for traffic simulation. Fewer assumptions are needed to build the simulation model. However, due to the stochastic features of Microscopic Simulation models, the AIMSUN simulator generates different VHT and VDT for daily RUC calculation. However, the sensitivity of the daily RUC to the change in VDT and VHT is unknown. If the change of VHT and VDT does not cause a significant change in RUC, a few replications might be enough. On the other hand, if the RUC is sensitive to the change in VHT and VDT, the number of replications should be carefully considered. In this sensitivity analysis, the objective is to examine whether a slight change in VHT and VDT causes a difference in daily RUC.

The daily RUC is calculated in terms of the difference in VHT and VDT between the Base Case and the During Case, the details of which can be seen in the equations in the Methodology chapter. However, each replication is independent, and there is no correspondence between the replications for the Base Case and the During Case. In order to examine the sensitivity of daily RUC for the AIMSUN simulator, nine replications are run for, respectively, the Base Case, the Full Closure During Case, and the Partial Closure During Case. Different combinations of replications for the Base Case and the During Case generate different RUC. In total, 81 daily RUC in Full Closure and 81 daily RUC in Partial Closure can be generated by those simulation replications. In this sensitivity analysis, only the results of several replications are shown to illustrate the idea. The Daily RUC of nine replications is shown in Figure 8.11 and the percentage change is shown in Figure 8.12.

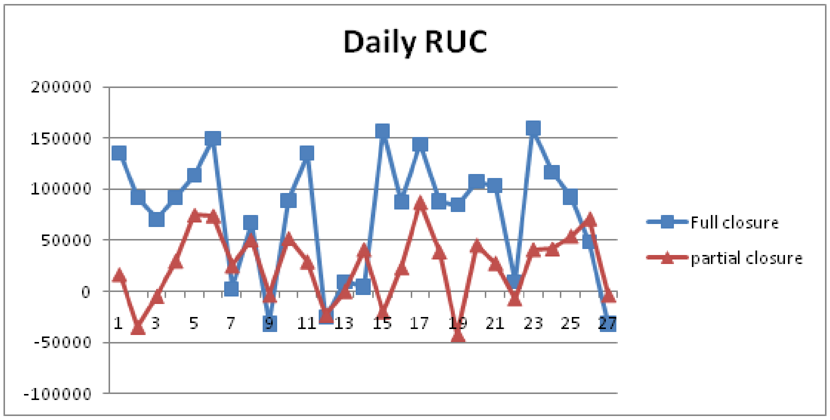

Figure 8.11: Daily RUC of 9 replications

Figure 8.11 and Figure 8.12 show that the daily RUC for Full Closure or Partial Closure is significantly fluctuating. The means of daily RUC are shown in Table 8.1, which are defined as the final daily RUC for AIMSUN. In Figure 8.12, the standard deviation of the percentage change for the Full Closure is 76%, while the standard deviation for the Partial Closure is 136%. However, the percentage change of VDT and VHT is not significant (shown in Figure 8.13 and Figure 8.14). The maximum percentage change of VDT for three cases is 0.2% and the minimum is -0.25%, while the maximum percentage change of VHT is 1.5% and the minimum is -2%. One reason for such a small change could be the large base number for VDT and VHT. The average VDT is approximately 188,000,000 vehicle-miles and the average VHT is approximately 280,000 vehicle-hours. A slight difference of VDT or VHT will cause

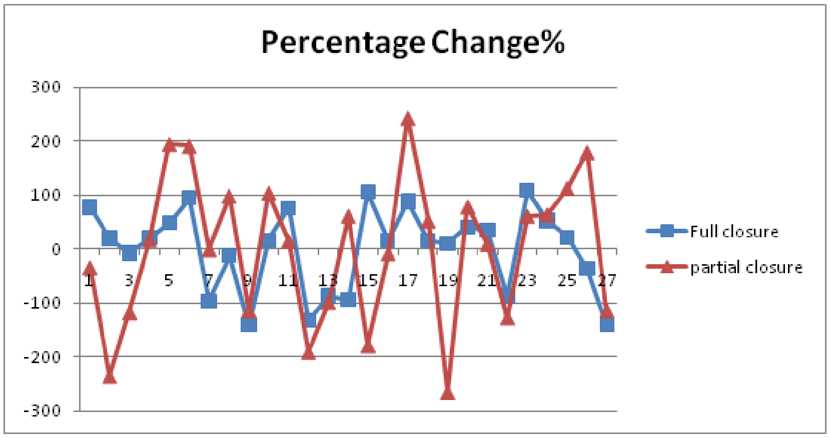

Figure 8.12: Percentage change of Daily RUC

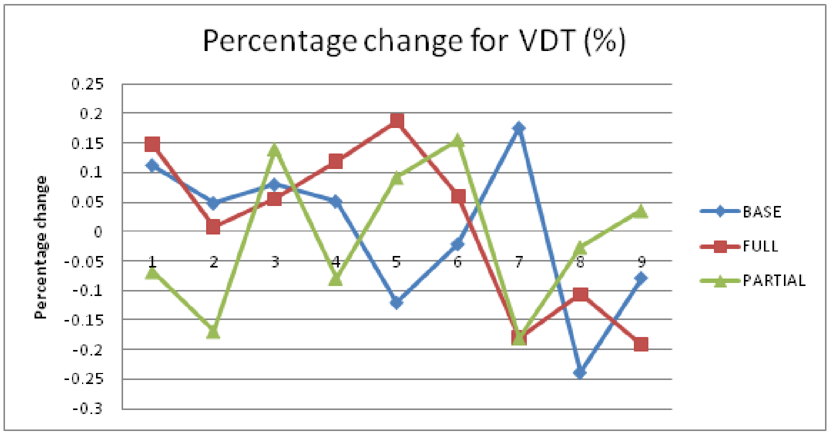

Figure 8.13: Percentage change of VDT

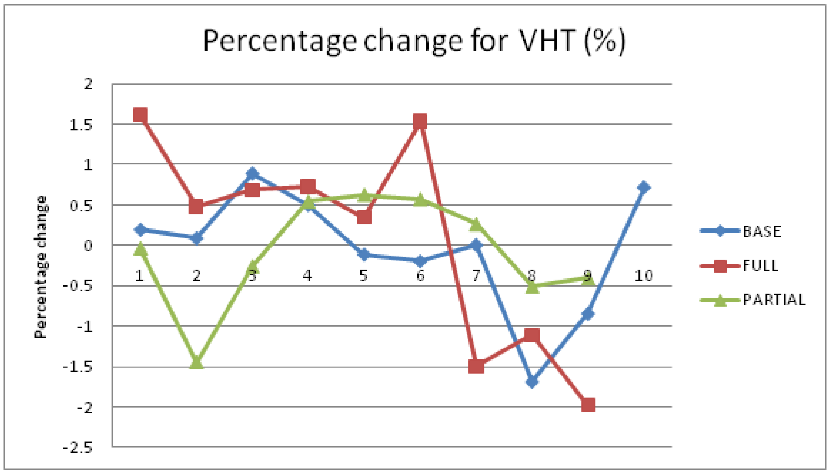

Figure 8.14: Percentage change of VHT

significant difference for RUC in such a case.

8.3.4 Hypothetical scenarios for BCA

In this work, the preliminary objective was to utilize a real project in the investigation of the importance of Road User Cost in construction operations. However, when a real project is used for research, there is always the danger that the results will not clearly illustrate the examined hypothesis. Unfortunately, such was the case in this project. The advantages of Full Closure in terms of shorter construction duration and lower costs are so obvious that make the Full Closure a better choice irrelevant of the inclusion of RUC in the BCA or not. In an effort to expand the investigation but still utilize as much as possible the parameters set by the case study, four hypothetical scenarios based on the TH-36 reconstruction project are designed to better illustrate the importance of RUC. By changing construction costs, duration of full closure, and including the effect of a half year construction period as is the norm in Minnesota , the changes on B/C ratios are illustrated along with the possibility of a decision switch on the selection of full closure as the construction alternative . B/C ratios generated with and without RUC are used to illustrate the weight RUC has in the decision.

Cost Variation Scenario

The Cost Variation Scenario is designed to illustrate how RUC affects the B/C ratios as the construction cost of Full Closure changes. In this scenario, based on the initial bid costs of Full Closure (i.e. 27.6 million), the construction costs in each step are increased or decreased by 100 thousand dollars. The net present values of benefit in Full Closure remain the same. The B/C Ratio in each step is calculated and listed in Figure 8.15.

In Figure 8.15, the y axis is the B/C Ratio while the x axis is the construction costs of Full Closure. The two horizontal lines are the constant B/C Ratios of Partial Closure as estimated with and without RUC. Point A is the intersect point of the lines of Full Closure and Partial Closure in the case with RUC while Point B is the intersect point in the case without RUC. From this figure, we observe that the corresponding construction cost of Point A (34 million) is less than that in Point B (34.5 million). This indicates that RUC affects the value of the difference in bid costs between the alternatives but only by less than 1.5%. This is not a surprising result since the RUC is affected only by the difference in durations between alternatives and its daily values. In this case the difference between total RUCs is approximately 1.5%.

Duration Variation Scenario

The second scenario is designed to observe how RUC affect the B/C ratios when the construction duration of the Full Closure is varied. The longer the duration, the higher the total RUC of the Full Closure will be. In this scenario, starting from the initial construction duration (5 months), the duration of Full Closure is increased or decreased by one month (3 months to 8 months). The upper limit of 8 months was established due to the fact that it is highly unrealistic to extend a full closure during the winter months in Minnesota. The construction cost of both Full and Partial Closures remain the same as well as the duration f the Partial Closure. The B/C Ratio is calculated for each combination and plotted in Figure 8.16.

The y axis in Figure 8.16 is the B/C ratio while the x axis is the duration of the Full Closure. From this figure we observe that with the inclusion of RUC the impact of the FC duration is considerably greater (slope). This is indicative of the risk level involved

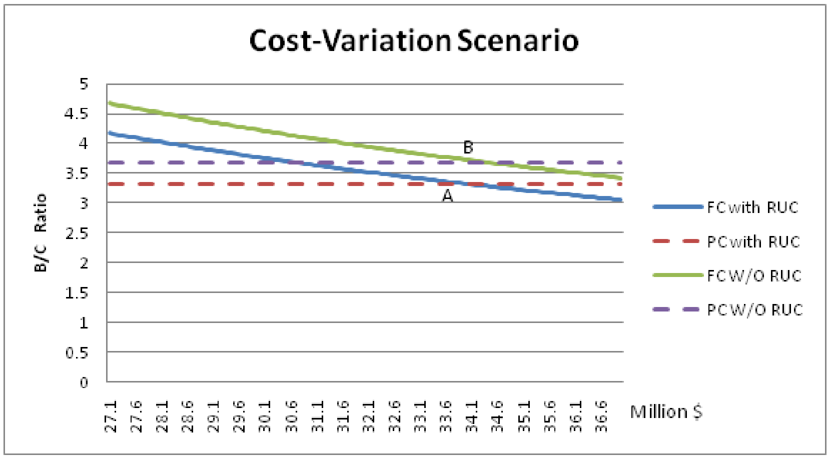

Figure 8.15: B/C Ratio of Cost-Variation Scenario

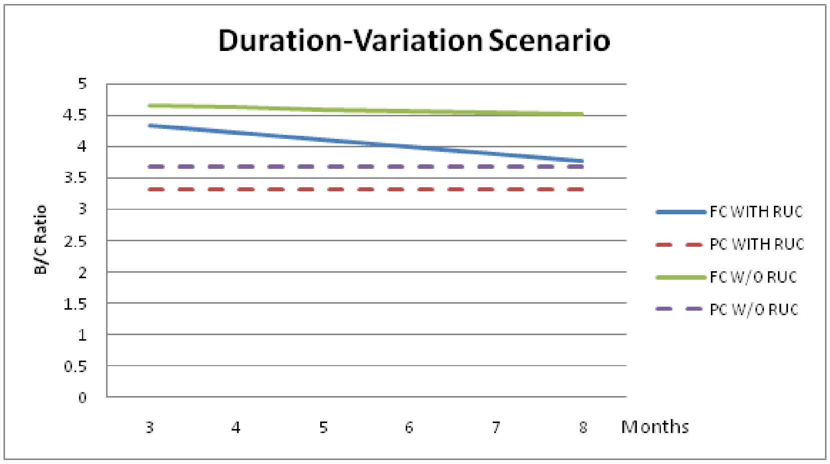

Figure 8.16: B/C Ratio of Cost-Variation Scenario

in Full Closure operations can be greatly underestimated if RUC is not considered in the BCA. Taking under consideration the other project parameters, it is clear that the value of time is greater in the Full Closure alternative and if the danger for delays is large, Partial Closure could be a safer choice.

Combined Time and Cost Variation Scenario

It is realistic to assume that the longer the time of construction the higher the costs. Although this is not applicable in fixed bid contract cases it is illustrative of the project size difference between alternatives. This scenario is designed to vary the construct duration and cost. For simplicity, the monthly cost of Full Closure is the initial amount of 27.6 million divided by the initial duration of 5 months. The construction cost of each combination is calculated by multiplying the monthly cost with the duration. Since the total RUC is calculated by multiplying the daily RUC with construction duration, they are increased or decrease along with the increase or decrease of the duration.

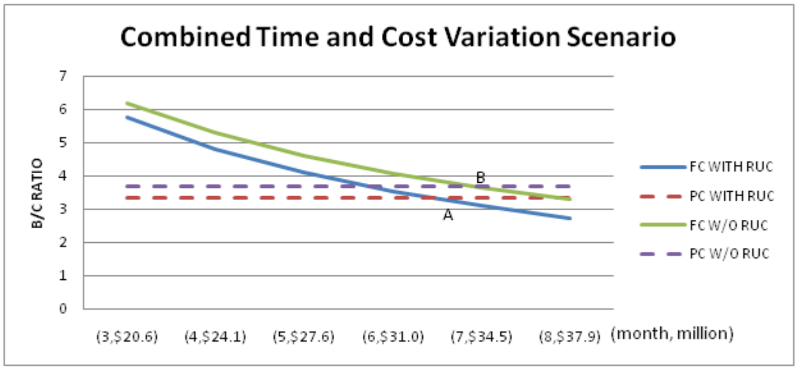

Figure 8.17: B/C ratios of Combined Scenario

The x axis tracks the different combinations of duration and costs for example the first point refers to the case where the FC lasts 3 months and costs $20.6M. It is obvious that inclusion of RUC in BCA can affect the decision. The risk level of the construction alternative increases as the difference of cost between alternatives reduces. If the construction duration between Full Closure and Partial Closure is short, the Partial Closure can be a safer and better choice when RUC is considered.

Minnesota Winter Scenario

Second scenario considered the importance of the RUC in terms of change of the FC duration. In the explored variation a year round construction season is assumed allowing the PC stage of the FC alternative to follow as soon as the FC stage is completed. Similarly, the 8 month long FC ending in December is assumed a viable combination. It will be more realistic to take into account the half year construction season experienced in Minnesota. In this scenario it is assumed that work cannot progress between the months of December and March. The project will remain in the stage reached by the end of November till April 1st. The same duration variation is implemented as in second scenario but with the aforementioned constraint. Figure 8.18 illustrates the change in B/C ratios with the variation of FC duration.

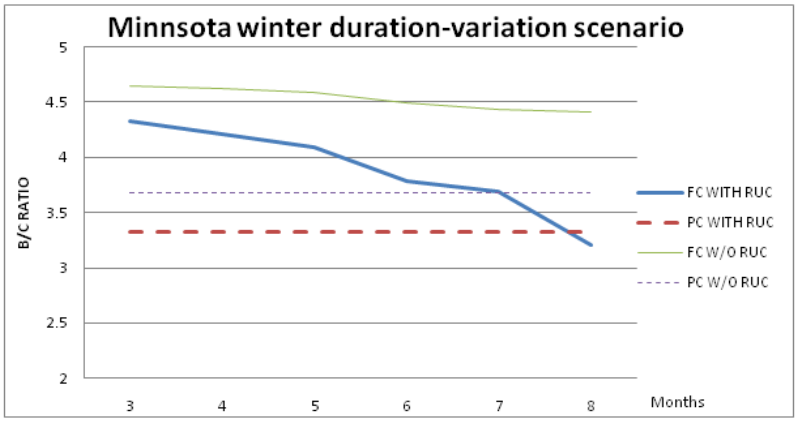

Figure 8.18: B/C ratios of Winter Scenario

As illustrated in figure 8.18, if we take into account the work pause during the winter months the inclusion of RUC results in considerably different B/C ratios as compared to the case where RUC is ignored. Even if the FC does not extend over the winter the extension of the next construction date from 90 to 180 days eliminates almost all benefit from the reduced cost FC alternative. According to this scenario it was very fortunate that the actual TH-36 FC was concluded one month ahead of time allowing the following PC to finish before December. If the FC was instead delayed by a month the benefit difference between alternatives would have been reduced by 50%. The slope change in the case where RUC is ignored is only due to the change of time where the benefits from the new road start to accrue.

The hypothetical scenarios presented in this section do not reveal something that was not evident from the original results but clearly illustrate the importance of RUC under different project circumstances and point out the fact that time is a lot more valuable in the case of a FC increasing the risk of any delay. Such risk can be greatly underestimated if RUC is not taken into account during the Benefit Cost Analysis.

8.4 Summary

This chapter presents the results from three models that are implemented for RUC calculation. The results include the traffic diversion analysis, the RUC results, and the results of Benefit Costs Analysis. It was found that the three tools agree with each other about the daily RUC for two different project alternatives, and the results of BCA showed that considering RUC could make a difference in the selection of project alternatives. Furthermore, a preliminary sensitivity analysis of RUC was conducted to investigate the RUC sensitivity to the model parameters. This analysis showed that the impact area for traffic analysis should be carefully selected, since a larger network generates a larger value of VDT and VHT, and therefore RUC will be more sensitive to the parameters.

Four hypothetical scenarios for exploring the RUC in clearer terms are presented, which illustrate the importance of RUC for the decision making process. It is found out that time is important for Full Closure and the risk of such construction operation alternative can be properly estimated, if RUC is considered during the BCA.

Chapter 9

Conclusion

In this research study, an improved Benefit Costs Analysis (BCA) process was proposed, in which area-wide Road User Costs (RUC) were considered as an important element of BCA. This study examined whether an improved BCA process, taking into account area-wide RUC, makes a difference in final decisions during Project Alternatives selection. Procedures for calculating area-wide RUC by three different tools with different traffic analysis capabilities was also proposed and implemented in a case study involving a real project, the TH-36 reconstruction in North St Paul, Minnesota. Two different Project Alternatives (i.e., Full Closure and Partial Closure) were proposed, developed, and compared. In this case study, QuickZone, Cube Voyager, and AIMSUN were selected as being representative of sketch-planning tools, travel demand models, and microscopic simulation models, respectively.

The RUC of the two Closure alternatives were calculated, and the improved BCA process was implemented. Issues related to implementation in the case study were encountered and discussed. It was found that the improved BCA process with area-wide RUC considered is more comprehensive; area-wide RUC can influence the decisions in Project Alternative selection.

For the TH-36 project, all tools were in agreement that daily RUC during Full Closure was greater than during Partial Closure. In this particular case study, results indicate that the magnitude of daily RUC increased along with the sophistication of the tool used to calculate it. This is not a particular encouraging outcome, since it may lead to two contradictory statements. On the one hand, the tools with higher resolution are more sensitive to causes of delays. For example, the negative effects of weaving and shockwave propagation of congestion are more evident in microscopic simulation. On the other hand, the benefits of arterial control, ramp metering, and the ability of vehicles to dynamically reroute in order to minimize path travel time should also be more evident.

Regardless of the actual result in terms of daily RUC, the large difference in duration among project alternatives most of the time levels the field and brings all tools into agreement. In this project, the construction duration of the Full Closure was predicted to last five months. If it was four months or six months, these three tools can agree that Full Closure costs are less or more than Partial Closure. This brings up an issue that the alternative with higher daily RUC gets more variance in cost savings and losses during the construction. The higher daily RUC in an alternative, the higher risk the alternative carries.

The results from implementing the improved BCA process show that Full Closure results in more benefits than Partial Closure in the long run, since Full Closure has a significantly shorter construction duration; thus, society can receive the benefits from the project earlier. Although the estimated total RUC of Full Closure can be higher (e.g., in Cube Voyager) or lower (e.g., in AIMSUN), the final results of BCA show that Full Closure has higher economic feasibility than Partial Closure. Compared to the results based on traditional BCA process, considering RUC in BCA process is more comprehensive and can result in different decisions in Project Alternatives selection.

Some issues of RUC calculation were investigated in this research. First, RUC is sensitive in all three tools. In QuickZone, a slight difference in estimating the link capacities can lead a significant change in RUC. In Cube Voyager, a slight difference in initial travel time in the work zone also leads to a wide variance in RUC. In AIMSUN, due to the stochastic features of the microscopic simulation model, RUC can vary significantly in different replications of a simulation. For Cube Voyager and AIMSUN, a slight difference of VDT and VHT can lead a significant change in RUC, if the values are large. It was observed that the wider the area being analyzed, the higher the values of VHT and VDT will be. Therefore, RUC can be sensitive to the parameters that affect the final results of VDT and VHT, and the larger the analysis network is, the higher the sensitivity of RUC. Engineering judgment should be allowed to evaluate the final results of RUC.

Additionally, since the details of the outputs and the input requirements increases along with the sophistication of the tools, analysts need to carefully select the proper traffic analysis tools in different stages of planning. In the case of TH-36, QuickZone can only produce the RUC, while Cube Voyager and AIMSUN can be used for traffic diversion analysis. AIMSUN can also be used to evaluate the traffic control plans around the work zone or even inside the entire impacted area, while Cube Voyager cannot. However, for simply calculating RUC, the microscopic simulation model may not be a good choice, since simulating a large network requires a much greater effort, and the results are highly sensitive. The calibration of the model may also be limited, due to commonly insufficient data in arterials. If calibration is not adequate, the results of the models can be less accurate than travel demand models.

In this study, RUC only includes delay and vehicle operating costs. Accident and environmental factors are not considered, due to limitations in the data. The impact on businesses might also affect RUC as well. In the practice of RUC estimation, such factors can be considered in order to obtain a more comprehensive analysis of user costs and Benefit Costs Analysis, if the data is available. In addition, the impacted area due to construction should be carefully selected based on traffic analysis tools as well as engineering judgment, as RUC could be more sensitive when the analysis network becomes larger. The possibility that RUC could be cancelled out in the links not affected needs more in-depth investigation in future research to examine different sizes of network for the same project.

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