MOBILITY IMPROVEMENT BENEFIT ANALYSIS OF SIGNAL TIMING OPTIMIZATION FOR URBAN STREET NETWORK

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Submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering in the Graduate College of the Illinois Institute of Technology

Approved

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Chicago, Illinois
May 2015
I express my deepest gratitude for the constant inspiration, motivation, persuasion, guidance and support from all the people around me. First of all, I am so deeply grateful to my advisor Dr. Zongzhi Li for his insight, guidance and involvement, who continually and convincingly convert the spirit of exploration in regard to research and academia. Without his guidance and persistent help this thesis would not have been possible. I would also want to thank the other committee members, Professor Jamshid Mohammadi and Professor Lili Du, who all were very supportive in diverse ways.

In addition, I would like to thank my sinner, Dr. Arash M. Roshandeh, whose work demonstrated to me the details of his signal optimization method and its corresponding simulation. Thanks for your patience and the time you spent on thinking and answering every questions I asked, even if some of them are very simple.

I am also thankful to the faculty and staff of the Department of Civil, Architectural, and Environmental Engineering for serving and maintaining an open and conducive intellectual environment. I acknowledge the friendship and support of my fellow seniors and friends, Xi Lu, Yi Liu, Harshingar Patel, Paulin Hakizimana, Bharathi Perumal, Mohammad Neishapouri, Siyang Feng, and Lu Wang, to name a few.

I want to thank my parents for supporting me in all decisions I made. I would like to thank Mr. Yunkai Fu and Mr. Jinhao Tan for offering the most precious help to me and inspiring me when I encountered challenges in graduate study. I would also like to sincerely thank my family members who have always been there in time of need and supported me emotionally.
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<tr>
<td>UB</td>
<td>The user benefit to be computed</td>
</tr>
<tr>
<td>$U_0$</td>
<td>The user cost per unit of traffic before the improvement</td>
</tr>
<tr>
<td>$U_1$</td>
<td>The user cost per unit of traffic after the improvement</td>
</tr>
<tr>
<td>$V_0$</td>
<td>The level of traffic before the improvement</td>
</tr>
<tr>
<td>$V_1$</td>
<td>The level of traffic after the improvement, including any induced or diverted traffic</td>
</tr>
<tr>
<td>$t$</td>
<td>Time period ID</td>
</tr>
<tr>
<td>$l$</td>
<td>Segment ID</td>
</tr>
<tr>
<td>$UB_{l,t}$</td>
<td>The user benefit the users of segment $l$ during time period $t$</td>
</tr>
<tr>
<td>$TT_{l,t}^0$</td>
<td>The travel time of segment $l$ during the time period $t$ before the treatment</td>
</tr>
<tr>
<td>$TT_{l,t}^1$</td>
<td>The travel time of segment $l$ during the time period $t$ after the treatment</td>
</tr>
<tr>
<td>$V_{l,t}^0$</td>
<td>The total number of vehicles that pass over the midpoint of segment $l$ during the time period $t$ before the treatment</td>
</tr>
<tr>
<td>$V_{l,t}^1$</td>
<td>The total number of vehicles that pass over the midpoint of segment $l$ during the time period $t$ after the treatment</td>
</tr>
<tr>
<td>$i$</td>
<td>The intersection ID</td>
</tr>
<tr>
<td>$a$</td>
<td>The approach ID at intersection $i$</td>
</tr>
<tr>
<td>$m$</td>
<td>The movement ID of approach $a$ at intersection $i$</td>
</tr>
<tr>
<td>$UB_{i,a,m,t}$</td>
<td>The user benefit the users in movement $m$ of approach $a$ at intersection $i$ during time period $t$</td>
</tr>
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</table>
\[ D_{i,a,m,t}^0 \] The average delay of movement \( m \) of approach \( a \) at intersection \( i \) during time period \( t \) before the treatment

\[ D_{i,a,m,t}^1 \] The average delay of movement \( m \) of approach \( a \) at intersection \( i \) during time period \( t \) after the treatment

\[ V_{i,a,m,t}^0 \] The total number of vehicles in movement \( m \) of approach \( a \) at intersection \( i \) during time period \( t \) before the treatment

\[ V_{i,a,m,t}^1 \] The total number of vehicles in movement \( m \) of approach \( a \) at intersection \( i \) during time period \( t \) after the treatment

\[ UB_{i,t} \] The UB of intersection \( i \) during the time period \( t \)

\[ M_a^i \] The set of all movement IDs of approach \( a \) at intersection \( i \)

\[ A_i \] The set of all approach IDs at intersection \( i \)

\[ \#(M_a^i) \] Number of elements in set \( M_a^i \)

\[ D_{i,a,t}^0 \] The average delay per vehicle of approach \( a \) at intersection \( i \) during time period \( t \) before the treatment

\[ D_{i,a,t}^1 \] The average delay per vehicle of approach \( a \) at intersection \( i \) during time period \( t \) after the treatment

\[ V_{i,a,t}^0 \] The total number of vehicles passing the stop bar of approach \( a \) at intersection \( i \) during time period \( t \) before the treatment

\[ V_{i,a,t}^1 \] The total number of vehicles passing the stop bar of approach \( a \) at intersection \( i \) during time period \( t \) after the treatment

\[ UB_{i,a,t} \] The UB of the approach \( a \) at the intersection \( i \) during the time period \( t \)

\[ VTTTS_t \] The value of travel time savings in dollars per person-hour during time period \( t \) for local travel by surface modes

\[ P_t^P \] The proportion of personal trips among all trips during time period \( t \)

\[ P_t^B \] The proportion of business trips among all trips during time period \( t \)

\[ I_p \] The personal earning rates in dollars per household-hour
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tr>
<td>$I_B$</td>
<td>The business earning rates in dollars per household-hour</td>
</tr>
<tr>
<td>$R$</td>
<td>The daily MUB of the entire network</td>
</tr>
<tr>
<td>$C$</td>
<td>The average vehicle occupancy</td>
</tr>
<tr>
<td>$T$</td>
<td>The set of all analysis periods in a day</td>
</tr>
<tr>
<td>$L$</td>
<td>The set of all segments in the study area</td>
</tr>
<tr>
<td>$I$</td>
<td>The set of all intersections in the study area</td>
</tr>
<tr>
<td>$RY$</td>
<td>The network-wide MUB in the first year</td>
</tr>
<tr>
<td>$n$</td>
<td>The service life of the implemented project, also the analysis period in number of years</td>
</tr>
<tr>
<td>$R_0$</td>
<td>The typical daily MUB of the entire network in the first year</td>
</tr>
<tr>
<td>$RY_0$</td>
<td>The annual network-wide MUB for the first year</td>
</tr>
<tr>
<td>$PW$</td>
<td>The present worth of annual network-wide MUB</td>
</tr>
<tr>
<td>$PW_0$</td>
<td>The present worth of annual network-wide MUB for the first year</td>
</tr>
<tr>
<td>$TMUB$</td>
<td>The total network-wide MUB over the life-cycle in present worth</td>
</tr>
<tr>
<td>$EUAMUB$</td>
<td>The equivalent uniform annual MUB over the life-cycle in present worth</td>
</tr>
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# LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Term</th>
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<tr>
<td>AASHTO</td>
<td>American Association of State Highway and Transportation Officials</td>
</tr>
<tr>
<td>CBD</td>
<td>Central Business District</td>
</tr>
<tr>
<td>CMAP</td>
<td>Chicago Metropolitan Agency for Planning</td>
</tr>
<tr>
<td>DOT</td>
<td>Department of Transportation</td>
</tr>
<tr>
<td>FHWA</td>
<td>Federal Highway Administration</td>
</tr>
<tr>
<td>LCCA</td>
<td>Life-cycle Cost Analysis</td>
</tr>
<tr>
<td>MUB</td>
<td>Monetized User Benefit</td>
</tr>
<tr>
<td>TRANSIMS</td>
<td>Transportation Analysis and Simulation System</td>
</tr>
<tr>
<td>TTI</td>
<td>Texas A&amp;M Transportation Institute</td>
</tr>
<tr>
<td>TTR</td>
<td>Travel Time Reduction</td>
</tr>
<tr>
<td>UB</td>
<td>User Benefit</td>
</tr>
<tr>
<td>USDOT</td>
<td>United States Department of Transportation</td>
</tr>
<tr>
<td>VTTS</td>
<td>Value of Travel Time Savings</td>
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ABSTRACT

The traffic congestion problem especially in urban areas is getting increasingly severe due to the ever-growing auto travel demand in the United States during the past few decades. In general, insufficient capacity can be solved by system expansion. However, expanding system is not feasible anymore because of the land scarcity in urban areas and its high cost. From this point of view, transportation operations that lead to the optimal system usage are more preferable thanks to their relatively low cost and remarkable consequences. Several performance indices were used in order to assess the effects of a given transportation operation. This study introduces a new method for evaluating the mobility performance of the transportation system before and after a transportation operation. And the mobility benefit is converted into monetary value. Further, a Life-Cycle Benefit Analysis is conducted to expand the evaluation process to the time dimension. An experimental study is performed to apply this method on the urban street network in Chicago downtown area that contains 917 intersections and 1675 roadway segments before and after a network-wide signal timing optimization treatment. Based on this application, the results indicate a few potential advantages and disadvantages of this system-wide signal timing optimization methodology.
CHAPTER 1
INTRODUCTION

1.1 Background

Cities are the concentration of human economic activities that are supported by transportation systems. Urban productivity highly depends on the efficiency of its transport system usage. Congestion is one of the prevalent issues in large and dense urban areas. According to the 2011 Urban Mobility Report (TTI, 2012), traffic congestion in 498 urban areas of the United States wasted 5.5 billion hours of extra time, that is equivalent to the time businesses and individuals spend a year filing their taxes; 2.9 million gallons of extra fuel and 121 billion dollars of delays and fuel costs. Additionally, the congestion released 56 billion pounds of additional carbon dioxide greenhouse gas into the atmosphere. Thus, urban congestion is a major issue that transportation agencies have to face.

Expanding transportation facilities might help reduce the severity of congestion problem. But this option is no longer feasible in urban areas due to the land scarcity and its high cost. Alternatively, how to increase the efficiency of the existing transportation network usage has been increasingly considered as an option. During the past twenty years, significant progress has been made to reduce vehicle delays and congestion in urban areas thanks to the development of transportation network modeling such like microscopic and macroscopic model, and the high fidelity, large scale network simulation accompanied with the advancement of high performance of computing capability.

Generally speaking, most vehicle delays in dense urban area is related to intersection. Thus, appropriate signal timing adjustment is considered to be the most direct
way to deal with the intersection related delays. Several signal timing optimization methods were proposed to mitigate overall vehicle delays and congestions from different perspectives. How to identify the most practical method among all candidates is the problem that transportation agencies have to face during the decision making process. The quintessential questions need to be answered in regard to the mobility improvement benefit, which arises the development of mobility performance evaluation for urban street network that will offer assistance to all transportation agencies for an improved urban street network mobility project selection and long term planning.

1.2 Problem Statement

In order to mitigate vehicle delays and congestions within a particular urban street network, one signal timing optimization method is adopted. Suppose the travel time for each segment within each time interval of 24 hours in a day before and after a certain signal timing optimization treatment can be obtained from simulation or field observation. The problem is how to quantify the mobility improvement benefit of this treatment within its life-cycle in a network level.

1.3 Study Objectives

A general objective of this study is to raise a specialized analysis method on mobility performance to help agencies identify the most profitable treatment dealing with urban signal timing optimization issues. The specific objectives are as follows: Developing a method for analyzing the mobility improvement benefit of signal timing optimization in a network level; Applying this method on a certain signal timing optimization treatment based on the simulated data; Discussing the results and the coordinated reasons.
1.4 Chapter Organization

The thesis is composed of five chapters. Chapter 1 discusses the traffic congestion problem in urban areas and indicates the specific objectives of this study. Chapter 2 briefly introduces previous researches pertaining to the life-cycle cost evaluation. Chapter 3 describes the proposed methodology in details. Chapter 4 focuses on the methodology application in a case study. This chapter also presents some additional observations and discussion of potential reasons of corresponding observations. Finally, Chapter 5 provides a study summary, and highlights future research directions.
CHAPTER 2
LITERATURE REVIEW

As the first step of the research, literature review was conducted on existing methodologies for urban signal timing optimization and the urban mobility performance evaluation methods.

2.1 Urban Signal Timing Optimization

A genetic algorithm approach was proposed to tackle the optimization of signal timings under stochastic user equilibrium circumstances with taking traffic assignment problem into consideration. The decision variables in this method were network cycle time, the green time for each signal stage, and the offsets between the junctions. And the objective function was defined as the weighted sum of delay and number of stops per unit time for all traffic flows, which was also the system performance index (Ceylan and Michael, 2004)

A reinforcement learning method was established to adjust the intersection signal control system by considering operating characteristic of intersection signal control system. Further, an optimization method for single intersection’s signal timing was proposed using SARSA (lambda) algorithm (Lu et al., 2008).

A simulated annealing-particle swarm optimization (Sa-PSO) algorithm was developed which bases on particle swarm optimization (PSO) and metropol rule. This study took the percentage reduction on average delay per vehicle and the average stop rate as the methodology performance indices (Dong et al., 2010)
The proposed Q-learning approach was proposed to deal with the traffic signal timing plan. Q-learning gains rewards from its past experiences including its future actions to learn from its experience and determine the best possible actions. The simulated results indicated that the proposed learning algorithm had a good valuable performance that able to improve the traffic signal timing plan for the dynamic traffic flows within a traffic network. The methodology performance index in this study is queue length (Chin et al., 2011).

Roshandeh et al. (2014) developed an intersection signal timing optimization for an urban street network aiming to minimize the weighted total of vehicular and pedestrian delays simultaneously by adjusting green splits in each cycle. Besides, one case study was conducted in Chicago CBD area simulated by the Chicago TRAMSIMS model. Additionally, a safety impact analysis was conducted based on the simulated results. In regard to the mobility impact, total vehicle-travel time before and after the signal timing plan adjustment is compared.

2.2 Valuation of Travel Time

The value of travel time savings (VTTS) is demonstrably the single most important factor in context of transportation economics. Travel time savings are usually a dominant component of user benefit. Although it is generally acknowledged that the VTTS is an important element of transportation decision making, there is numerous dispute about this value. Considerable theoretical and empirical researches were conducted to search for the best calculation methods in a wide range of situations. Admittedly, time value research is rapidly advancing in sophistication, the increasing number of issues were risen during the
past decades, and the level of reliability of the VTTS estimates cannot be guaranteed in some cases.

Two general techniques have most been used to estimate the VTTS. The first approach is derived by observing actual travelers to be willing to trade-off money expenditures for time savings when selecting routes and modes. Stopher used regression analysis to estimate VTTS from samples of London commuters (Stopher, 1968). The VTTS was computed by computing the ratio of the coefficients which are obtained from the regression model that the probability of choosing one mode was regressed against the time and cost differences between the two modes. Further, income level factor was taken into consideration. It turned out the estimated VTTS for relatively high income group was 42 percentage of the wage rate, while from 21 to 32 percentage of the average rate of the appropriate group. Similar approaches were employed by many researchers in other cities with divided mode categories. Specifically, for Chicago land, Lisco used multiple probit analysis to estimate the VTTS for car and rapid transit, and the resulting estimates of the VTTS ranged from 40 to 50 percent of wage rate (Lisco, 1968). Subsequently, Ergün and Gökmen utilized indifference analysis to infer the VTTS for parking cost and walking time. And the estimated value was implied to be 4.5 dollars per hour, which was approximately 50 percent or more of the wage rate for walking time (Ergün and Gökmen, 1971). Talvitie used logit, probit and discriminant analyses to estimate the VTTS for car and rapid transit modes with in-vehicle and out of vehicle time divided. It was indicated that the VTTS for in-vehicle time ranged from 12 to 14 percent of the wage rate, which is 7 times as high for out-of-vehicle time (Talvitie 1972).
The second approach indicated by empirical study is that the value of time for commute trips is related to the gross wage, varying widely by trip purpose. Typically, business travel has the highest value of time and discretionary leisure travel the least. Moreover, values rise with income or wage rate (Lave, 1969). The analyses of travel time savings during work hours generally based on the assumption that this value is related to the wage rate of the traveler. This approach is theoretically justified by the “marginal productivity theory of factor rewards”, which states that the wage rate can measure the marginal value of an additional hour’s work, assuming that travelers will spend the saved travel time on productive work (Harrison and Quarmby, 1969). At one time, the VTTS during nonwork hours was also measured by the wage rate even if the additional available time was spent at leisure because of the assumption that the labor markets are so competitive that every person has to dedicate their saved travel time on working or work related purpose (Moses and Williamson 1963; Wingo 1961). Later research revealed that the disutility or unpleasantness of travel time is of importance. Reductions in travel time allow people to add to their utility by reallocating the saved travel time to activities yielding greater utility. Therefore, the value of this type of travel time savings depends not only on the person whose travel time is reduced, but also on the particular type of travel time reduced and alternative uses of this saved time (Evans, 1972).

Although the willingness to pay values of time is a good approach to infer VTTS, it is inappropriate to directly use the willingness to pay values for social appraisal of projects. Some form of social weighting scheme is also required (Mackie et al, 2001). It is apparent that we know a great deal about how people trade off time, reliability, and money.
Nonetheless, we still need to understand how these tradeoffs work in a complex decision-making process involving many choice dimensions (Small, 2012).

With regards to the application, the American Association of State Highway Officials (AASHTO) has made a remarkable contribution on the VTTS study. A 1952 report by a committee on planning and design policies of the AASHTO indicated that the dollar value of time saving may vary considerably and no precise method of evaluation yet has been founded. This report used a value of $1.35 per hour per car, which was computed by multiplying $0.75 per person per hour by 1.8 persons per car, as “representative of current opinion for a logical and practical value” (AASHTO, 1952). This value was updated in 1960 to $1.55 per hour per car, which was the product of $0.86 per person per hour and 1.8 persons per car (AASHTO, 1960). Later research conducted by AASHTO revealed that no significant variation in unit rate of travel time value as a function of the time or length of individual trips has yet been found. Furthermore, the value of commuter travel time savings was updated from approximate $2.80 per person hour in the late sixties to $2.40 person hour. Moreover, a travel time value of $3.00 per vehicle was generally used, which can be derived from a value of $2.40 per person hour and 1.25 person per vehicle (ASHTTO, 1977). No single value of VVTS for general use was recommended in a manual published by AASHTO in 2003. Instead, VTTS was estimated by multiplying a percentage value and the associated average wage rate, both of which were tabulated in the manual. Specifically, the percentage value varies with transportation modes and trip purposes. In practice, it is often the case that a complete and accurate tableau of time values is not available, or no sufficient resources to model the travel behavior at the necessary level of detail. In such cases, it is possible to use only a few values of time in the detailed
analysis, but then conduct sensitivity analysis to systematically explore how dependent the results are on the time value applied. Generally, if the feasibility of the project is irrespective of the time value selected, then the analyst can be more confident of the feasibility analysis (AASHTO, 2003).

Generally, two distinct purposes of travel are distinguished, 1) travel in the course of work, and 2) travel for all other purposes, including going to and from work. Working time is valued at its cost to the employer of the travelling employee, on the grounds that the value of the output produced in working time must be at least equal to the cost to the employer of hiring labor for that time. The value of non-working time is derived from studies of how people choose to travel when facing several choices with different price, travel time, route, degrees of comfort and so forth. Generally, without considering the some significant factors, such as personal preference and relative degree of comfort, if people choose to pay an extra amount of money to save a certain amount of time, the value of travel time saving in this case is the ratio of travel time saved to the money invested (Great Britain. Department for Transport, 2002). Similarly, USDOT classifies all trips into two categories, business and personal. The business trip here includes go-to-work trip which differs from the aforementioned definition. Further, all trips are classified into normal surface mode excluding high-speed rail and air mode. There are four combinations in total, and the value of travel time savings of each combination is the corresponding hourly earning rate multiplied by an associated percentage values, which turn out to be a hardly unchanged value since 1997 (USDOT, 2011).
2.3 Life-cycle Cost Analysis

Life-cycle cost analysis (LCCA) for physical highway assets is a process for evaluating the total economic worth of the capital cost and the discounted future costs of maintenance and rehabilitation associated with the assets. This concept has been widely used in highway pavement and bridge management.

The Federal Highway Administration (FHWA) has made a concerted effort for the application of LCCA in highway pavement management (FHWA). Further, a life-cycle cost component framework for rigid pavements was developed. Three cost components were introduced as 1) agency cost, which includes initial construction cost and subsequent costs of maintenance, rehabilitation, and overlays, 2) user cost, and 3) external costs. It was assumed that the periodic costs were calculated as per distress predicted by the end of each year and the initial costs as per design (Wilde et al., 1999). Additionally, alternative design strategies were established based on a comparison between conventional mixtures and the mixture containing asphalt rubber pavement materials. Construction costs, all administrative costs, and routine and preventive maintenance and rehabilitation costs that would be invested within the analysis period were counted in the agency costs estimation process. Salvage value was taken into consideration in order to compare the investments by the end of the analysis period, being a function of expected life of rehabilitation alternate, a portion of expected life consumed, and costs of rehabilitation strategies (Hicks and Epps, 1999). In regards to the LCCA application in pavement rehabilitation strategies, several key issues were risen including selection of appropriate analysis period with considering vehicle operating costs, predicted serviceability trends and user delay costs (Hall et al., 2003). An enhanced LCCA were developed through the development of cost
models applying Alberta roadway maintenance and rehabilitation analysis, which were tested to calculate maintenance costs that constitute LCCA and could be employed to analyze the rehabilitation alternatives based on the surface condition data along with the corresponding location data and maintenance work. Such type of application would provide help for monitoring and tracking investments (Fall and Tighe, 2003). A series of life-cycle presentative maintenance cost-effectiveness models for different pavement categories that were classified according to pavement type, traffic level, and service class. These models indicated that the cost-effectiveness of preventive maintenance was a function of preventive maintenance effort monetary values per lane-mile of the road. The model could be the basis of tradeoff analysis of different investment strategies over pavement service life (Labi and Sinha, 2005). Furthermore, the methodology based on analyzing pavement performance over a period of time to identify the optimal timing of treatment was proposed to achieve minimum life-cycle costs. The optimal timing was claimed to be that point of the largest benefit-to-cost ratio. Benefits were quantified by scaling influence on pavement performance measured by one or more condition indicators such as rutting. (Peshikin et al., 2005). An integrated life-cycle assessment and life cycle cost analysis model was developed to calculate the environmental impacts and costs of overlay systems resulting from the pavement overlay system, including material production and distribution, overlay construction and maintenance, construction-related traffic congestion, overlay usage, and end of life management (Zhang et al., 2008). This model was further developed to a life-cycle optimization model which integrated dynamic life-cycle assessment and life-cycle cost analysis model with an autoregressive pavement overlay deterioration model by using dynamic programming optimization techniques. This
optimization model was developed to determine an optimal preservation strategy for a pavement layout system and to minimize the total life-cycle environmental cost (Zhang et al., 2010). Results of life-cycle cost analysis approach highly relied on the many input factors such as discount rates, traffic increasing rates, and agency costs, which can hardly be explicitly determined and stay constant. Therefore, an uncertainty based life-cycle benefit/cost analysis at highway project level was established to handle uncertainty and risk (Li and Madanu, 2009).

The LCCA concept was also utilized in highway intersection hardware improvements at project-level, where safety index was used to assess intersection vehicle crash risks under the conditions of intersection safety hardware such as signs, signals, lighting, pavement markings, and guardrails. The annual potential for safety improvements were computed based on the safety indices before and after the implementation of the improvement project using the concept of consumer surplus. The annual potential safety improvements were further converted into dollar values and extrapolated to the overall intersection safety hardware service life cycle (Madanu et al., 2010). Similarly, a methodology for benefit-cost analysis of improving the conditions of highway segment safety hardware over its life cycle was developed cycle (Li et al., 2010).

LCCA has been widely used in bridge management as well. Life-cycle cost analysis of protection and rehabilitation of concrete bridges in related to corrosion reinforcement was conducted in 1994, where agency costs included deck and structural treatment costs. Computer method of LCCA was also covered to determine the optimal activity time to minimize the user and agency cost over the entire life-cycle (Purvis et al., 1994). A lifetime optimization methodology to determine the inspection and repair strategies for structures
that deteriorate over time is developed. The optimization is based on minimizing the expected total life-cycle cost while maintaining an allowable lifetime reliability for the structure (Frangopol et al., 1997). A comparison between two highway suspension bridges using LCCA were made for conventional steel and advanced all-composite of carbon fiber both. The capital construction and subsequent maintenance costs were counted in the analysis (Meiarashi et al., 2002). Further, overall costs were categorized into three distinct categories: 1) agency costs, which included routine maintenance costs, bridge element rehabilitation costs, bridge element replacement costs, and bridge replacement costs; 2) user costs, which included detour costs and crash costs; and 3) vulnerability costs that contained both agency and user costs, consisted of condition-related reduction in load capacity, life or both, seismic vulnerability, bridge scour, and overloads (Hawk, 2003). In 2004, a life-cycle cost model to assess the sustainability of bridge decks was developed with considering agency cost and social costs simultaneously. The social costs included emission pollution from agency activities, congestion, delays, crashes, and vehicle operating costs through all stages of bridge service life-cycle. Along with the study, one comparison of two types of bridge decks was made, one of which is equipped with conventional concrete joints and another with engineered cement composite link-slabs. It was found that fluctuations on annual average daily traffic highly affected bridge life-cycle costs while detours did not (Chandler, 2004).

Up to now, no LCCA concept utilization in signal timing improvement of a large scale urban street network has yet been found.
CHAPTER 3
PROPOSED METHODOLOGY

The benefits of user mobility improvements are hereby defined as the saving in travel time value that the users of improved signal timing plan will enjoy. Improvements that reduce users’ perceived travel time costs will often induce or divert additional traffic patronage over and above what would have been the level in the absence of the improvement. The measure of benefits presented in Equation 3-1 below, when applied to each link or section of the affected network and summed over all analysis sections, properly accounts for the benefits to both induced and diverted traffic as well as to continuing traffic.

\[
UB = (U_0 - U_1) \frac{(V_0 + V_1)}{2}
\]  

(3-1)

Where:

*UB* = the user benefit to be computed

*U₀* = the user cost per unit of traffic before the improvement

*U₁* = the user cost per unit of traffic after the improvement

*V₀* = the level of traffic before the improvement

*V₁* = the level of traffic after the improvement, including any induced or diverted traffic

This computed UB above is consistent with the theory of consumers’ surplus, as illustrated in Figure 3.1. This figure refers to a single time period and a single study object, which may be a segment or an intersection. In Figure 4, the consumer’s surplus at a particular price is the total area above that price enclosed by the demand curve up to the point its intersection with the price axis. But in comparing two prices such as *U₀* and *U₁*, it
is convenient to refer to differences in consumers’ surplus as the net benefit obtained from the price change.

Figure 3.1. Consumers’ surplus for a single time period and segment or intersection

The concept of consumers’ surplus is going to be further discussed in both segment and intersection scenarios in the following sessions.

3.1 Benefit of Urban Street Mobility Improvements

The travel time of a single vehicle running in an urban street network always consist of the travel time in segments and the intersection delays. We hereby define the segment travel time of one particular segment as the average time a vehicle spends on traversing this segment. Specifically, the time starts once the vehicle enters the upstream intersection and ends with 1) this vehicle stops to queue up, waiting for the signal, or 2) this vehicle crosses the stop bar directly without queuing up. If the vehicle stops caused by a crash or any other events, this part of waiting time is still included in the segment travel time.

The definition of segment in this study differs from that in HCM 2010. Segment hereby is defined as the directed-link connecting two ends of a link in a network. For example, segment from node A to node B is different from that from B to A. Figure 3.2
illustrates the segment analysis boundaries. The shaded area is where the queue up takes place. Since the queue length is dynamic, the corresponding boundary is dynamic as well.

![Segment analysis boundaries](image)

**Figure 3.2. Segment analysis boundaries**

As Figure 3.3 illustrated, the traffic stream on one segment normally has three sources: right-turn movement from origin 1, through movement from 2, and left-turn movement from 3. The UB computation process is supposed to execute for each origin using its own unit cost rate $U$ and traffic level $V$. To simplify the computation and save data collection cost, these three types of traffic are viewed as one stream. Therefore, we will take the average unit cost rate and the total traffic level when using Equation 3-1.

![Segment traffic configuration](image)

**Figure 3.3. Segment traffic configuration**

Generally speaking, the aforementioned level of traffic $V_1$ and $V_0$ should be in VMT (Vehicle Mile Travel) during segment UB computation. Here we use volume as the input level of traffic, since the length of each segment stay constant before and after the signal timing plan change. Denote $V_{l,t}^1$ and $V_{l,t}^0$ to be the total number of vehicles that pass
over the midpoint of segment $l$ during the time period $t$ after and before the signal timing optimization respectively, which is approximately the number of users of segment $l$ during the time period $t$.

This average segment travel time is the unit cost rate $U_1$ or $U_0$ in the Equation (3-1). Apparently, the segment travel time varies in different locations and time periods in a day. Such segment travel time is symbolized by $TT_{l,t}^1$ and $TT_{l,t}^0$, denoting the travel time of segment $l$ during the time period $t$ after and before the signal timing optimization respectively.

Apply the Equation 3-1 by replacing the parameters with the corresponding symbols discussed above, we have:

$$UB_{l,t} = \frac{1}{2} (TT_{l,t}^0 - TT_{l,t}^1)(V_{l,t}^0 + V_{l,t}^1)$$  \hspace{1cm} (3-2)

Where:

$t =$ time period ID

$l =$ segment ID

$UB_{l,t} =$ the user benefit the users of segment $l$ during time period $t$

$TT_{l,t}^0 =$ the travel time of segment $l$ during the time period $t$ before the treatment

$TT_{l,t}^1 =$ the travel time of segment $l$ during the time period $t$ after the treatment

$V_{l,t}^0 =$ the total number of vehicles that pass over the midpoint of segment $l$ during the time period $t$ before the treatment

$V_{l,t}^1 =$ the total number of vehicles that pass over the midpoint of segment $l$ during the time period $t$ after the treatment

Base on the Equation 3-2, the spatial and temporal distribution of segment UB can be easily computed.
3.2 Benefits of Intersection Mobility Improvements

Intersection delay costs consist of additional waiting time and running time due to decelerating to and accelerating from a stop caused by a traffic signal. The travel time saving at intersections are mainly from the intersection delay reduction. In this study, we count the additional running time spent on deceleration and acceleration in segment travel time in order to simplify the calculation.

The intersection analysis boundaries are not defined at a fixed distance for all intersection. The boundaries extend backward from the stop bar a sufficient distance to include the queues caused by the traffic signal on each intersection leg. The shaded area in Figure 3.4 indicates the intersection analysis area.

![Figure 3.4 Intersection analysis boundaries](image)

Take a normal four-leg intersection as an example, each leg of this intersection has three vehicular movements: through movement, left-turn and right turn. For each movement of an approach, UB is calculated by using Equation 3-3.

\[
UB_{i,a,m,t} = \frac{1}{2}(D_{i,a,m,t}^0 - D_{i,a,m,t}^1)(V_{i,a,m,t}^0 + V_{i,a,m,t}^1)
\]

(3-3)

Where:

\[i = \text{the intersection ID}\]
\( a \) = the approach ID at intersection \( i \)

\( m \) = the movement ID of approach \( a \) at intersection \( i \)

\( UB_{i,a,m,t} \) = the user benefit the users in movement \( m \) of approach \( a \) at intersection \( i \) during time period \( t \).

\( D_{i,a,m,t}^0 \) = the average delay of movement \( m \) of approach \( a \) at intersection \( i \) during time period \( t \) before the treatment

\( D_{i,a,m,t}^1 \) = the average delay of movement \( m \) of approach \( a \) at intersection \( i \) during time period \( t \) after the treatment

\( V_{i,a,m,t}^0 \) = the total number of vehicles in movement \( m \) of approach \( a \) at intersection \( i \) during time period \( t \) before the treatment

\( V_{i,a,m,t}^1 \) = the total number of vehicles in movement \( m \) of approach \( a \) at intersection \( i \) during time period \( t \) after the treatment

The total UB of one intersection during a certain time period is computed by summing over all movements’ UB at this intersection, which is presented in Equation 3-4 below.

\[
UB_{i,t} = \sum_{a \in A_i} \sum_{m \in M_a^i} UB_{i,a,m,t} \tag{3-4}
\]

Where:

\( UB_{i,t} \) = the UB of intersection \( i \) during the time period \( t \)

\( M_a^i \) = the set of all movement IDs of approach \( a \) at intersection \( i \)

\( A_i \) = the set of all approach IDs at intersection \( i \)

Same simplification strategy that applied during the segment UB computation can also be utilized in the intersection UB computation. We may take the average delay of all movements at one approach as the approach delay, and use the total volume of this
approach as the input traffic volume while computing the approach UB. Equation 3-5 to 3-10 summarize the simplified process.

\[
\overline{D}_{i,a,t}^0 = \frac{\sum_{m \in M^i_a} D_{i,a,m,t}^0}{\#(M^i_a)}
\]

(3-5)

\[
\overline{D}_{i,a,t}^1 = \frac{\sum_{m \in M^i_a} D_{i,a,m,t}^1}{\#(M^i_a)}
\]

(3-6)

\[
V_{i,a,t}^0 = \sum_{m \in M^i_a} V_{i,a,m,t}^0
\]

(3-7)

\[
V_{i,a,t}^1 = \sum_{m \in M^i_a} V_{i,a,m,t}^1
\]

(3-8)

\[
UB_{i,a,t} = \frac{1}{2} (\overline{D}_{i,a,t}^0 - \overline{D}_{i,a,t}^1) (V_{i,a,t}^0 + V_{i,a,t}^1)
\]

(3-9)

\[
UB_{i,t} = \sum_{a \in A_i} UB_{i,a,t}
\]

(3-10)

Where:

\#(M^i_a) = \text{number of elements in set } M^i_a

\[
\overline{D}_{i,a,t} = \text{the average delay per vehicle of approach } a \text{ at intersection } i \text{ during time period } t \text{ before the treatment}
\]

\[
\overline{D}_{i,a,t}^1 = \text{the average delay per vehicle of approach } a \text{ at intersection } i \text{ during time period } t \text{ after the treatment}
\]

\[
V_{i,a,t}^0 = \text{the total number of vehicles passing the stop bar of approach } a \text{ at intersection } i \text{ during time period } t \text{ before the treatment}
\]

\[
V_{i,a,t}^1 = \text{the total number of vehicles passing the stop bar of approach } a \text{ at intersection } i \text{ during time period } t \text{ after the treatment}
\]

\[
UB_{i,a,t} = \text{the UB of the approach } a \text{ at the intersection } i \text{ during the time period } t
\]

The advantage of this simplification is that the quantity of the data set needed is much less than the non-simplified method, especially for the volume data, which can
remarkably reduce the data collection cost. The disadvantage is the loss of computation accuracy due to the simplification. In regard to how to quantify the accuracy lost, it’s beyond the coverage of this study.

3.3 The Value of Travel Time Savings

The previous two sections describe the way to calculate the spatial and temporal distribution of segment UB and intersection UB respectively. This session ought to be about how to evaluate the travel time saving into monetary value, based on which MUB (monetized user benefit) is computed.

The value of travel time savings (VTTS) is an important factor in evaluating benefits of transportation improvement projects. A value is usually placed on travel time saving by selecting a unit value or values of time, which is expressed in dollars per traveler or vehicle hour. Then, the monetary travel time saving can be computed by multiplying the unit value of time by the amount of travel time saved in corresponding unit. Unit values can be selected according to the type of traveler, trip purpose, mode, and so forth.

In this study, we recommend the simplified valuation of travel time saving for DOT application proposed by USDOT. The simplified method classifies all local trips into two broad categories, and recommends a ratio of VTTS to hourly income for each trip category. Table 3.1 presents the recommended ratios, and the corresponding plausible ranges, expressed as percentages.

<table>
<thead>
<tr>
<th>Category</th>
<th>VTTS (per person-hour as a percentage of total earnings)</th>
<th>Plausible Ranges for VTTS (per person-hour as a percentage of total earnings)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Personal</td>
<td>50%</td>
<td>35%-60%</td>
</tr>
<tr>
<td>Business</td>
<td>100%</td>
<td>80%-120%</td>
</tr>
</tbody>
</table>
Some remarks on Table 3.1:

1. These recommended ratios only apply to local travel;
2. These recommended ratios only apply to surface modes except high-speed rail, including all combinations of in-vehicle and other time;
3. The principal distinction between these two categories of trip purpose is that between “on-the-clock” travel time, for which a market wage is paid, and personal time allocated according to the traveler’s preference.

The VTTS can be calculated by using Equation 3-11.

\[ VTTS_t = P_t^P (50\% I_P) + P_t^B (100\% I_B) \]  

Where:

\( VTTS_t = \) the value of travel time savings in dollars per person-hour during time period \( t \) for local travel by surface modes

\( P_t^P = \) the proportion of personal trips among all trips during time period \( t \)

\( P_t^B = \) the proportion of business trips among all trips during time period \( t \)

\( I_P = \) the personal earning rates in dollars per household-hour

\( I_B = \) the business earning rates in dollars per person-hour

\( I_B \) is defined as a median gross wage, the sum of the median hourly wage and an estimate of hourly benefits. The simplified valuation method recommends a nationwide \( I_B \) in 2009, which is estimated to be $22.90 per person-hour.

\( I_P \) is the hourly median household income. The simplified valuation also method recommend the nationwide value. The nationwide media annual household income, $49,777 in 2009, is divided by 2,080 to yield an income of $23.90 per hour.
$P_t^P$ and $P_t^B$ are the proportion of personal and business trips among all trips during time period $t$ respectively. Apparently, both of them vary over time. The simplified valuation method also presents the recommended value for each of them which are derived from 2001 National Household Travel Survey. The distributions so derived are: 95.4% personal, 4.6% business.

Some of the aforementioned factors may vary widely from cities to cities over time. Therefore, this study recommends to use the latest local related data unless they are unavailable to ensure the accuracy.

Having computed the VTTS, the monetized UB can be computed by using Equation 3-12 as follow.

$$R = \sum_{t \in T} (\sum_{l \in L} UB_{l,t} + \sum_{i \in I} UB_{i,t}) \times C \times VTTS_t$$  

Where,

$R =$the daily MUB of the entire network

$C =$the average vehicle occupancy

$T =$the set of all analysis periods in a day

$L =$the set of all segments in the study area

$I =$the set of all intersections in the study area

Monetized yearly user benefits can be calculate based on the daily value by simply multiplying the daily value by 365, as presented by Equation 3-13.

$$RY = 365 \times R$$  

Where,

$RY =$ the network-wide MUB in the first year
If possible, separating the daily MUB computation of weekdays’ and weekends’ is highly recommended to achieve high accuracy since the traffic pattern and configuration is very distinct.

### 3.4 Life-cycle User Benefit Analysis

This session focuses on expanding the monetized UB analysis in the time dimension. Life-cycle user benefit analysis for transportation improvement projects such as signal timing optimization projects is a process that evaluate the total economic worth of the discounted future user benefit obtained from the implemented improvement projects.

For a certain transportation problem, there are typically several alternative solutions, each with its unique set of benefits and costs. During the decision making process, several performance measures of each alternatives need to be computed and referred to. Economic efficiency is one of the most crucial performance measures when selecting one action or several actions among all options. The combined monetized costs and benefits, including life-cycle benefit, constitute the basis of economic efficiency, which highly influences the attractiveness of each alternative.

Before establishing the formulation, a few of assumptions need to be made.

1. The improvement project is complete at the beginning of first year.
2. After the improvement project is complete, for each segment and intersection, the traffic volumes before and after the treatment, including any induced or diverted traffic in the study area, grow at a constant rate of $r$.
3. The compounding annual interest rate $i$ is constant during the analysis period.
4. The unit cost rate before and after the treatment (U₀ and U₁ in Equation 3-1) remain constant for both segment and intersection cases. This assumption is reasonable because the traffic volume grows slowly at a small rate r.

5. The average yearly income level of the local area increases at a yearly compounding rate g. This assumption makes the VTTS increases with g.

6. r, i, g are end-of-period compounding rates expressed as a percentage per year.

7. The vehicle occupancy factor C remain the constant.

8. All the benefits take place at the end of the year.

Based on the assumptions above, the lift-cycle benefit analysis can be conducted. Table 3.2 presents the whole details of the process. Figure 3.5 illustrates the corresponding user benefit profile according to assumption 8.

![Figure 3.5. Life-cycle User Benefit Profile](image)
Table 3.2. Details of the life-cycle benefit analysis

<table>
<thead>
<tr>
<th>Item</th>
<th>1st year</th>
<th>2nd year</th>
<th>nth year</th>
<th>Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>(V_0)</td>
<td>(V_0)</td>
<td>(V_0(1+r))</td>
<td>(V_0(1+r)^n)</td>
<td>1,6</td>
</tr>
<tr>
<td>(V_1)</td>
<td>(V_1)</td>
<td>(V_1(1+r))</td>
<td>(V_1(1+r)^{n-1})</td>
<td>1,6</td>
</tr>
<tr>
<td>(U_0)</td>
<td>(U_0)</td>
<td>(U_0)</td>
<td>(U_0)</td>
<td>4</td>
</tr>
<tr>
<td>(U_1)</td>
<td>(U_1)</td>
<td>(U_1)</td>
<td>(U_1)</td>
<td>4</td>
</tr>
<tr>
<td>UB</td>
<td>UB = 0.5(U_0 - U_1) (V_0 + V_1)</td>
<td>UB(1+r)</td>
<td>UB(1+r)^{n-1}</td>
<td>3-1</td>
</tr>
</tbody>
</table>

VTTS | VTTS \(^{(1+g)}\) | VTTS \(0(1+g)^{n-1}\) | 5,6 |

MUB | MUB \(_0 = VTTS \(_0 \times C \times UB \(_0 \) \) (1+g) | MUB \(_0(1+r)\) | MUB \(_0[(1+r)(1+g)]^{n-1}\) | 7,3-12 |

R | R = \(\sum_{site} \sum_{time} MUB \(_0\) | R0(1+r)(1+g) | R0[(1+r)(1+g)] \(n-1\) | 3-12 |

Annual network-wide MUB in future worth

RY | RY \(_0 = 365 \times R \(_0\) | RY \(_0(1+r)(1+g)\) | RY \(_0[(1+r)(1+g)]^{n-1}\) | 3-13 |

Annual network-wide MUB in present worth

PW | PW \(_0 = RY \(_0(1+i)\)^{-1}\) | RY \(_0(1+r)(1+g)\) | RY \(_0[(1+r)(1+g)]^{n-1}\) | 3,6 |

Where,

Basis column indicates which equations and assumptions is based on in each step.

\[n\] = the service life of the implemented project, also the analysis period in number of years

\[R_0\] = the typical daily MUB of the entire network in the first year,

\[RY_0\] = the annual network-wide MUB for the first year

\[PW\] = the present worth of annual network-wide MUB

\[PW_0\] = the present worth of annual network-wide MUB for the first year

The total network-wide MUB, and the equivalent annual MUB over the life-cycle of the implemented project is computed by using Equation 3-14 and 3-15 respectively.

\[
TMUB = \sum_{j=1}^{n} RY_0 \frac{[(1+r)(1+g)]^{j-1}}{(1+i)^j} = RY_0 \frac{1-(1+r)(1+g)(1+i)^n}{(1+i) - (1+r)(1+g)(1+i)}
\]

\[
EUAMUB = TMUB \frac{(1+i)^n}{(1+i)^{n-1}}
\]
Where,

\( TMUB \) = the total network-wide MUB over the life-cycle in present worth

\( EUAMUB \) = the equivalent uniform annual MUB over the life-cycle in present worth

The life-cycle user benefit analysis is complete up to this step is complete.

In sum, the Figure 3.6 briefly illustrates the flow chart of the entire methodology.
Data Collection
- Collect the related traffic data

**Segment UB Computation**
- Compute the travel time saving for each segment during each time period in a day. (in vehicle hours)

**Intersection UB Computation**
- Compute the intersection delay reduction for each intersection during each time period in a day. (in vehicle hours)

**Network-wide UB Computation**
- Compute the network-wide travel time savings for each time period by summing over the UB of segments and intersections in each time period. (in vehicle hour)

**Network-wide MUB Computation**
- Convert the network-wide travel time savings into dollar term. The results of this step are the network-wide MUB in each time period in a day. (in dollars)

**Daily Network-wide MUB Computation**
- Compute the daily network-wide MUB by summing over the MUB in all time period in a day. (in dollars)

**Network-wide UB Computation in the first year**
- Compute the annual network-wide MUB based on the daily MUB. (in dollars)

**Annual growth rate of local traffic. (in percentage)**

Discount rate, annual growth rate of average household income (in percentage)

**Life-cycle User Benefit Computation**
- Compute the total life-cycle user benefit and the equivalent uniform annual user benefit by applying economic principles and the existing results and information. (in dollars)

**Collect the local social economic data**

- Compute the VTTS for both business and personal trips. (in dollars/person hour)

**Average vehicle occupancy (in persons/vehicle), and distribution of trip purpose over time. (in percentage)**

Figure 3.6. Overall Framework of the Proposed Methodology
Dr. Arash M. Roshandeh (2014) developed a signal timing optimization method which can minimize the vehicle and pedestrian delay simultaneously. This method was applied in the dense CBD of Chicago simulated within the agent-based Chicago TRANSIMS model, which is capable of conducting large-scale, high fidelity simulation. The related data before and after the signal timing optimization was exported, which is the basis of the application.

4.1 Data Collection, Processing, and Integration

The Chicago model was calibrated and validated based on the field observation of traffic volumes, speeds, and travel times collected from over eight hundred continuous traffic counting stations and twelve hundred urban street mid-block counting locations in Chicago metropolitan area. The travel demand information were obtained from Chicago Metropolitan Agency for Planning (CMAP) including 28.5 million trips over 24 hours in a typical day.

Downtown Chicago is select as the study area in this application. Specifically, as Figure 4.1 illustrated, the study area is bordered by the North Ave in the north, the Ashland Ave in the west, the Roosevelt Rd in the south, and the Michigan Lake in the east. The study area contains 917 intersections and 1675 roadway links in record.
Because the raw data contains some noises result from the reliability issue of the simulator, these noise records need to be ironed out from the study to ensure the accuracy. After eliminating these noise records, the study area contains 866 intersections and 1358 links.

**Travel time, and traffic volume.** The simulator exported the average travel time, average travel speed, and traffic volume for each simulated hour and segment before and after the signal timing optimization, which constitute the basis of the data to be analyzed. However, the simulator did not differentiate the segment travel time and the intersection delay. Figure 4.2 illustrates a typical vehicular trajectory between two intersections. The reported travel time from node A to node B is the summation of the travel time of segment AB and the delay of intersection B. In order to separate segment travel time and intersection delay, this study assumes that segment travel before and after the signal timing plan change time remains the same, which is the travel time under the speed limit, calculated by dividing the segment length by the corresponding speed limit. This assumption makes sense because
the signal timing optimization method applied aims at minimizing the intersection delay. Admittedly, this assumption is not realistic because well-coordinated signal timing plans are capable to help reduce the occurrence of slowing down, queuing up and speeding up, and the time for deceleration and acceleration are parts of segment travel time. This assumption might be the best option under the lack of related information.

![Diagram of vehicular trajectory]

Figure 4.2. A Typical Vehicular Trajectory

**Distribution of trip purpose over time.** This study define the go-to-work as the only business trip, and other trips belong to personal trip. Figure 4.3 illustrates the trip purpose distribution over a weekday in metropolitan Chicago reported by CMAP. This study assumes the percentage of business travel stays constant since the year of 2007 so that this data set can be used in the study for current year.
Value of travel time savings. The median household income in metropolitan Chicago was $60,564 in 2013 reported by the United States Census Bureau. Equivalently, the hourly earning rate per household was $29.11/household hour. However, the current local median gross wage is hardly to estimate, especially for the hourly benefits. Therefore, the hourly benefits are neglected. According to the U.S. Bureau of Labor statistic, workers in the Chicago metropolitan area had an average hourly wage of $23.95 in May 2013, which is going to be taken as our business hourly earning rate. Table 4.1 presents the average percentage of business trips and personal trips, along with the corresponding VTTS in each time period according to the trip purpose distribution and the associated hourly earning rate.
Table 4.1. Average Percentage of Business Trips and Personal Trips

<table>
<thead>
<tr>
<th>Time period</th>
<th>0:00-1:00</th>
<th>1:00-2:00</th>
<th>2:00-3:00</th>
<th>3:00-4:00</th>
<th>4:00-5:00</th>
<th>5:00-6:00</th>
<th>6:00-7:00</th>
<th>7:00-8:00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Business</td>
<td>1.5%</td>
<td>0.9%</td>
<td>0.3%</td>
<td>24.1%</td>
<td>42.4%</td>
<td>68.5%</td>
<td>60.2%</td>
<td>43.5%</td>
</tr>
<tr>
<td>Personal</td>
<td>98.5%</td>
<td>99.1%</td>
<td>99.7%</td>
<td>75.9%</td>
<td>57.6%</td>
<td>31.5%</td>
<td>39.8%</td>
<td>56.5%</td>
</tr>
<tr>
<td>VTTS</td>
<td>14.70</td>
<td>14.64</td>
<td>14.58</td>
<td>16.82</td>
<td>16.54</td>
<td>20.99</td>
<td>20.21</td>
<td>18.64</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time period</th>
<th>8:00-9:00</th>
<th>9:00-10:00</th>
<th>10:00-11:00</th>
<th>11:00-12:00</th>
<th>12:00-13:00</th>
<th>13:00-14:00</th>
<th>14:00-15:00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Business</td>
<td>35.0%</td>
<td>23.0%</td>
<td>11.1%</td>
<td>8.4%</td>
<td>8.0%</td>
<td>7.7%</td>
<td>6.0%</td>
</tr>
<tr>
<td>Personal</td>
<td>65.0%</td>
<td>77.0%</td>
<td>88.9%</td>
<td>91.6%</td>
<td>92.0%</td>
<td>92.3%</td>
<td>94.0%</td>
</tr>
<tr>
<td>VTTS</td>
<td>17.84</td>
<td>16.72</td>
<td>15.60</td>
<td>15.34</td>
<td>15.31</td>
<td>15.28</td>
<td>15.12</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time period</th>
<th>16:00-17:00</th>
<th>17:00-18:00</th>
<th>18:00-19:00</th>
<th>19:00-20:00</th>
<th>20:00-21:00</th>
<th>21:00-22:00</th>
<th>22:00-23:00</th>
<th>23:00-00:00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Business</td>
<td>1.9%</td>
<td>1.2%</td>
<td>2.2%</td>
<td>4.2%</td>
<td>5.3%</td>
<td>6.1%</td>
<td>6.1%</td>
<td>3.8%</td>
</tr>
<tr>
<td>Personal</td>
<td>98.1%</td>
<td>98.8%</td>
<td>97.8%</td>
<td>95.8%</td>
<td>94.7%</td>
<td>93.9%</td>
<td>93.9%</td>
<td>96.2%</td>
</tr>
<tr>
<td>VTTS</td>
<td>14.73</td>
<td>14.67</td>
<td>14.76</td>
<td>14.95</td>
<td>15.05</td>
<td>15.13</td>
<td>15.13</td>
<td>14.91</td>
</tr>
</tbody>
</table>

**Other information and assumptions.** Suppose the signal timing optimization project is finished at the beginning of 2013 with 5 years' service life and the 2013 is selected to be the reference year. Assume the vehicular occupancy factor is 1.5 travelers/vehicle. Moreover, the annual income growth rate is approximately 0.74% computed by the data of 2013 and 2012. It is reported that the federal discount rate is 0.75% reported by The Federal Reserve Bank.

### 4.2 Data Analysis

In terms of the segment UB computation. Because the segment travel time is assumed to be fixed before and after the treatment, segment travel time saving is zero. In other words, there no segment mobility benefit, and the UB of the entire network comes from the intersection UB.

As regards the intersection UB computation. The approach delay at one intersection before and after the treatment is computed for each approach in each time period. The intersection delay is computed by summing over the corresponding approach delays.
Following the proposed process, several performance measures can be computed as discussed as follows.

1. The total UB (travel time reduction) of the entire network in a day is 2113.328 vehicle hours.
2. The total percentage travel time reduction, computed by dividing the UB (in vehicle hour) by the total vehicle travel time after the treatment (in vehicle hour), is 2.23%.
3. The total MUB of the entire network in a day is 55,420.75 dollars.
4. The total MUB of the entire network in the first year (2013) is 20.23 million dollars in future worth.
5. The total network-wide MUB in the entire service life-cycle is 103.09 million dollars in present worth.
6. The equivalent uniform annual user benefit over the life-cycle is 20.98 million dollars in present worth.

4.3 More Discussions of results

The results presented in the previous session offer a brief overview of the performance methodology. This session aims at pointing out more detailed performance measures and the associated reasons to see the goodness of applying this signal timing optimization method in downtown Chicago.

1. Figure 4.4 illustrates how the network-wide percentage travel time reduction change over time. As is shown in the Figure 4.4, the signal timing after the optimization performs remarkable during the night time (from 9:00 p.m. to 6:00 a.m.), the reason is that both the vehicle flow and pedestrian flow during this
time is very low, which results in the low v/c ratio. Therefore, the optimization method has large amount of time resource to assign to achieve the optimal system-usage.

Moreover, the adjusted signal timing plan still works during the peak hours (from 6:00 a.m. to 10:00 p.m. and from 3:00 p.m. to 8:00 p.m.), but the effectiveness is not as higher as that in the night. The reason is the ever increasing vehicle volume and pedestrian volume along with the increasing v/c ratio consequently. That makes the time resource get limited gradually, which make the time assignment more difficult. Further, the adjusted signal timing plan turns out to be deficient during the adjacent-peak hour (from 10 a.m. to 3:00 p.m.). Although the vehicle volume goes down in this time interval, the pedestrian volume goes up because most of the stores’ work hours start at 10:00 a.m. or 11:00 a.m., which may attract more shoppers among which are doing window shopping, leading the increase of the pedestrian volume partially. In addition, workers working in this area may walk out and find a restaurant

Figure 4.4. Network-wide Percentage Travel Time Reduction versus Time
nearby for lunch during that time period, especially from 11:00 a.m. to 2:00 p.m. That results in increasing the pedestrian volume as well. The signal timing optimization method considers the pedestrian delay and the vehicular delay simultaneously. Both the increasing pedestrian volume and the decreasing vehicle volume make the system have to assign more time to pedestrian flows on the cost of increasing the waiting time of vehicle flows to achieve the most effect system usage and the minimum system delay.

2. Figure 4.5 illustrates the contour of the percentage intersection delay reduction. The darker the area is, the worse the new signal timing plan performs in this area. Three areas displaying negative benefit are the North Rush Avenue and the Water Tower in the northeast, the Greektown in the middle, and the Noble Square in the Northwest. By the same logic discussed above, high volume of pedestrian flows triggers the higher vehicular delay in the northeast and northeast part. In regard to the Greektown, the dense on-ramp and off-ramp in the area make the signal timing plans nearby hard to coordinate mutually. Once one intersection cannot satisfy the demand, the queue cannot discharge completely in every cycle, the cumulated queue will expand backward rapidly and mess up the traffic flows on the upstream intersections. Therefore, the system delay is very sensitive to every single intersection’s performance. Appendix A gives the time and spatial distribution of the percentage delay reduction of each intersection. The analysis above is based on the data set in the Appendix A.
3. Figure 4.6 shows histograms of percentage reductions in intersection delays for both one-way and two-way streets. The x-axis represents the percentage travel time reduction expressed in percentage and the y-axis is the frequency rate.

Only based on the observation of probability histogram shown above, the mean and variance of the performance measure for both one-way and two-way case
are almost even. But this observation still need to be test via hypothesis test, which is beyond the scope of this study.

4. Table 4.2 shows the daily percentage travel time reduction on each of the main corridors. It is true for both East-west and North-South corridors that negative benefits take place in some locations evenly. But the variance of the percentage travel time reduction for North-South corridors are higher than East-West corridors. The reason might be the difference between the configurations of the traffic on both types of corridors. For most of the travelers traveling on the East-West corridors, their origin or destination is in the downtown area, while for the travelers heading north or south, roughly half of them have destinations out of downtown area. They just pass by downtown area. This observation needs to be validated by some tests such like analysis of variance.
Table 4.2. The Daily Percentage Travel Time Reductions of Main Corridors

<table>
<thead>
<tr>
<th>Name</th>
<th>TTR</th>
<th>Name</th>
<th>TTR</th>
</tr>
</thead>
<tbody>
<tr>
<td>NORTH AVIL-64</td>
<td>8.73%</td>
<td>LAKE SHORE DR</td>
<td>6.52%</td>
</tr>
<tr>
<td>(US-41)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DIVISION AV</td>
<td>-8.39%</td>
<td>COLUMBUS AV</td>
<td>35.59%</td>
</tr>
<tr>
<td>DIVISION ST</td>
<td>12.90%</td>
<td>S COLUMBUS DR</td>
<td>-26.19%</td>
</tr>
<tr>
<td>CHICAGO AV</td>
<td>14.26%</td>
<td>MICHIGAN AV</td>
<td>17.10%</td>
</tr>
<tr>
<td>GRAND AV</td>
<td>-4.41%</td>
<td>STATE ST</td>
<td>25.99%</td>
</tr>
<tr>
<td>RANDOLPH ST</td>
<td>8.45%</td>
<td>STATE AV</td>
<td>12.03%</td>
</tr>
<tr>
<td>MADISON ST</td>
<td>8.01%</td>
<td>HALSTED AV</td>
<td>11.41%</td>
</tr>
<tr>
<td>HARRISON ST</td>
<td>13.04%</td>
<td>HALSTED ST</td>
<td>-17.57%</td>
</tr>
<tr>
<td>ROOSEVELT RD</td>
<td>-9.54%</td>
<td>ASHLAND AV</td>
<td>-1.56%</td>
</tr>
</tbody>
</table>

Where, TTR means the Travel Time Reductions expressed in percentage.

Based on the discussion above, one can see the v/c ratio and the pedestrian flows affect the vehicular mobility performance after the signal timing optimization significantly, both from the space and time perspectives referring to the Appendix A. Also from the systematic perspective, pedestrian flows play an important role in urban transportation treatments such like signal timing optimization. Therefore, pedestrian mobility improvement is expected to be taken into consideration when doing a systematic mobility evaluation in the future research.
5.1 Study Summary

Time is a scarce resource. The signal timing optimization essentially is attempting to assign this resource to system users properly to achieve the maximum system gain. Whether and where to apply a certain signal timing optimization method require an evaluation in a holistic way. This study developed an analytical framework utilizing the economic principles for assessing the benefits of mobility improvements as a result of intersection signal timing optimization for an urban street network in the intersection service life-cycle expressed in dollar values. After explaining the proposed methodology, one case study was conducted based on the dataset exported from the Chicago TRANSIMS model running an urban signal timing optimization method proposed in 2013 in addition to some reports from CMAP and USDOT. Besides computing monetized user benefit over the service life of the treatment, a few more observations and discussions were made to conclude some properties of the urban signal timing optimization methodology and seek more room to improve and refine the proposed evaluation methodology.

5.2 Conclusion Remarks

According to the calculated results and the discussions above, we may find that the network-wide vehicular user benefits reach the maximum after adjusting the signal timing during the night time when the low volume of both vehicle and pedestrian flows take place. During the rush hours, the adjusted signal timing plan is still functional but not as effective as that in the night time because of the high demand of auto and pedestrian travels. The
deficiency of the signal timing adjustment takes place during the time period between the morning peak and afternoon peak hours, at which time the ratio of pedestrian volume to vehicle volume reach the maximum. Hence, the effectiveness of the vehicular delay reduction are highly related to the volume of pedestrian flows. Consequently, the pedestrian flow is a critical component of the traffic in dense urban areas and needs to be taken in to consideration when conducting urban mobility analysis.

Analyzing how user benefits distribute is not only useful for transportation practice, but it provides fundamental clues to find penitential reasons leading to the deficiency at some locations to refine the signal timing optimization method further. The two extra observations of the applied signal timing optimization method in the case study are that this method works equivalently for both one-way streets and two-way streets and the effectiveness is independent with the direction of the street.

5.3 Future Research Directions

One major limitation of this study is the data collection cost. The proposed methodology needs a large amount of traffic data which requires lots of data collection work or a large-scale, high-fidelity simulation system. This methodology is not practical in the case with insufficient data set. Additional, this study only focused on the vehicular mobility assessment. As discussed above, pedestrian flow is a crucial component in urban traffic. Researches on developing a comprehensive urban mobility evaluation method considering pedestrian mobility would be a great future research topic. Furthermore, the life-cycle analysis is based on some economic factors such as discount rate, which is fixed in the methodology session. In reality, these factors are influenced by numerous factors, and hence the values of the user benefit computed by the model. To ensure more accurate
future mobility analysis, it is necessary that the uncertainty and risks within the analysis be taken into consideration and the pedestrian flows be accounted in the analysis so as to capture the holistic picture.
APPENDIX A

THE SPATIAL AND TEMPORAL DISTRIBUTION OF DAILY PERCENTAGE DELAY REDUCTIONS
The values is adjusted in the range from -300% to 300%. Any value beyond the upper bound (less than the lower bound) will be set to be the upper bound (or the lower bound).

Figure A.1. Percentage Delay Reduction for 0:00-1:00
Figure A.2. Percentage Delay Reduction for 1:00-2:00

Figure A.3. Percentage Delay Reduction for 2:00-3:00
Figure A.4. Percentage Delay Reduction for 3:00-4:00

Figure A.5. Percentage Delay Reduction for 4:00-5:00
Figure A.6. Percentage Delay Reduction for 5:00-6:00

Figure A.7. Percentage Delay Reduction for 6:00-7:00
Figure A.8. Percentage Delay Reduction for 7:00-8:00

Figure A.9. Percentage Delay Reduction for 8:00-9:00
Figure A.10. Percentage Delay Reduction for 9:00-10:00

Figure A.11. Percentage Delay Reduction for 10:00-11:00
Figure A.12. Percentage Delay Reduction for 11:00-12:00

Figure A.13. Percentage Delay Reduction for 12:00-13:00
Figure A.14. Percentage Delay Reduction for 13:00-14:00

Figure A.15. Percentage Delay Reduction for 14:00-15:00
Figure A.16. Percentage Delay Reduction for 15:00-16:00

Figure A.17. Percentage Delay Reduction for 16:00-17:00
Figure A.18. Percentage Delay Reduction for 17:00-18:00

Figure A.19. Percentage Delay Reduction for 18:00-19:00
Figure A.20. Percentage Delay Reduction for 19:00-20:00

Figure A.20. Percentage Delay Reduction for 20:00-21:00
Figure A.23. Percentage Delay Reduction for 22:00-23:00

Figure A.24. Percentage Delay Reduction for 23:00-24:00


Wilde, William James, Steve Waalkes, and Rob Harrison. *Life cycle cost analysis of Portland cement concrete pavements*. Center for Transportation Research, Bureau of Engineering Research, the University of Texas at Austin, 1999.
