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ABSTRACT

The primary objective of Transportation Systems Management and Operation (TSM&O) strategies, or Intelligent Transportation Systems (ITS) is to optimize the capacity of existing transportation infrastructure by reducing congestion. Over past decades, agencies and researchers investigated the use of various strategies such as deployment of adaptive traffic control systems (ATCS), ramp metering systems (RMS), surveillance through closed circuit TV (CCTV) cameras, and information sharing systems to achieve this objective. Life Cycle Agency Cost Agency Analysis (LCCA) of various alternative intelligent transportation strategies has received particular attention to identify the strategy with the lowest cost. However, increasing concerns over the impacts of transportation systems on nearby communities as well as the environment are urging decision makers to consider the environmental impacts of various TSM&O strategies in addition to user costs.

Sustainability refers to a long-term perspective of economic, social and environmental progress, which not only addresses the present conditions but also includes the needs of future generations. In United States, due to its vastness, transportation infrastructure can be considered as “major contributors of sustainability”. The triple bottom line of sustainability (TBL), if incorporated in TSM&O strategies decision-making, can address issues like climate change, environmental protection, funds optimization, and social equity.

The work for this dissertation focuses on developing a comprehensive Life Cycle Benefit/Cost (LCB/C) analysis framework to evaluate existing and anticipated intelligent ITS strategies, particularly, adaptive traffic control systems (ATCS) and ramp metering systems (RMS), in

terms of the triple bottom line (TBL) of sustainability. The B/C framework for each ITS category was divided into two main categories: Life Cycle Cost Analysis (LCCA) and Life Cycle Benefit Analysis (LCBA). The LCCA of ITS deployment includes initial infrastructure cost, periodical incremental cost, and O&M cost. A typical service life and interest rate are assumed for each ITS. For the benefits analysis, three main research areas are included. Conducted by the triple bottom line principal, the LCBA section is divided into analysis of benefits through travel time savings, reductions in energy consumption, and safety enhancements.

ITS are known to have several advantages such as increasing link capacity, accelerating traffic flow, reducing delay and congestion, decreasing safety concerns, and in turn minimizing environmental and socio-economic impacts associated with affected traffic zones. However, it comes with its own share of disadvantages, like higher initial infrastructure cost and periodical incremental cost, design complexity, and challenges lie in operation and maintenance. Meanwhile, it is hard to evaluate the benefit/cost performance of ITS implementation over the service life span. The purpose of this study is to prepare such comprehensive benefit/cost framework, as well as the corresponding decision support tool featuring data obtained from national averages. The tool is spreadsheet based and it is easily customizable. The tool also generates graphical outputs as visual summaries. The framework and tool, will help decision makers to assess the overall performance of ITS from perspectives of long term costs and triple bottom line benefits, then opt for the most suitable alternatives from the life cycle point of view.

A LIFE-CYCLE BENEFIT / COST ANALYSIS FRAMEWORK FOR ITS
DEPLOYMENTS

by

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B.E., Nanjing Tech University, 2009
M.S., Syracuse University, 2011

Dissertation

Submitted in partial fulfillment of the requirements for the degree of
Doctor of Philosophy in *Civil Engineering*.

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ABBREVIATIONS

ATCS	Adaptive Traffic Control System
ATT	Anticipated Travel Time
ATTR	Anticipated Travel Time Reliability
BCA	Benefits/Costs Ratio
BCR	Benefits/Costs Analysis
BCR	Benefits-to-Costs Ratio
BPR	Bureau of Public Roads
CO ₂ e	Carbon Dioxide Equivalent
ETT	Existing Travel Time
ETTR	Existing Travel Time Reliability
FFS	Free Flow Speed
GPS	Global Positioning System
ICM	Integrated Corridor Management
ITS	Intelligent Transportation System
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Analysis

O&M	Operation and Maintenance
PDO	Property Damage Only
PV	Present Value
RMS	Ramp Metering System
RR	Reliability Ratio
TBL	Triple Bottom Lines
TMS	Traffic Management System
TSM&O	Transportation Systems Management and Operation
TSP	Transit Signal Priority
V/C	Volume/Capacity
VHT	Vehicle Hours Traveled
VoR	Value of Reliability
VoT	Value of Time
VPH	Vehicle per Hour

Chapter 1. INTRODUCTION

1.1. BACKGROUND

As the name implies, an Adaptive Traffic Control System (ATCS) indicates an advanced traffic signal control system that updates traffic signal timing in some automated ways (Selinger & Schmidt, 2010) to stabilize and smoothen the traffic. The primary objective of ATCS is to optimize the capacity of existing transportation infrastructure under certain traffic demands.

Similarly, a RMS is a traffic signal control system that regulates the flow of traffic entering freeways based on real-time traffic conditions. As the most direct and efficient way to improve the freeway capacity (Abouaïssa, Dryankova, & Jolly, 2013), the primary objectives of RMS are to 1) reduce congestion on freeways by restricting the total flow entering the freeway and 2) discourage short distance travelers from using the freeway.

Rapid development of technologies and regional disparities significantly influence the LCCA results for current and potential ATCS and RMS practices. Increasing concerns over the impacts of transportation systems on environmental and safety related issues, and the potential improvements through life cycle assessment (LCA) are urging decision makers to consider the environmental impacts of ATCS and RMS deployments from a more comprehensive perspective. Therefore, it is necessary to collect updated costs and benefits data for the entire life cycle of ATCS and RMS deployments to develop a new Benefit/Cost Analysis framework.

Currently, there is a lack of decision support systems that would allow decision makers to simultaneously compare environmental, social, and economic impacts of TSM&O strategies over their life cycle. The aim of the work in this dissertation is to address this gap in research.

On the traffic reliability side, according to data published by U.S.DOT, in 2011, the annual person-hours of highway traffic delay per auto commuter increases 153% comparing to the same data collected in the year 1982, based on 439 urban area average (Bureau of Transportation Statistics, 2013). It is worth noticing that the percentage is even higher in relatively small areas (238% for small area average, and 213% for medium area average). However, taking a short statistic analyzed period from 2006 to 2011 will lead to a negative 12% percentage, which represents the initiation and promotion of TSM&O strategies in United States. It is inevitable that the number of on-the-road vehicle will continually increase in the future, which will cause severer challenge to existing traffic infrastructural system. Meanwhile, the increasing value of time (VoT), the costs on traffic delay and traffic unreliability will also become a social-economic issue.

On the environment impacts side, there is a widespread awareness of the possible damage that high levels of Green House Gases (GHG) can cause to the planet. The Kyoto Protocol adopted in Kyoto, Japan in 1997 formally documented these risks and established certain ground rules in an effort to bring GHG emissions down to 1990 levels (United Nations Framework Convention on Climate Change (UNFCCC), 2008). Although United States signed the protocol, it did not push hard to ratify it. From 1990 to 2011, the total US GHG emissions have increased by 8.4% (USEPA, 2013). According to the data published by U.S. Department of Energy in 2008, the United States emitted 5.9 billion metric tons of CO₂, which is equivalent to 13% of the global CO₂ emissions taking the second spot after China, and approximately 1.104 billion metric tons of other GHG. CO₂ emissions coming from transportation activities have increased by 17% over the last decade amounting to 33% of the total national CO₂ emissions, of which 65% is due to gasoline consumption of personal

vehicles (USEPA, 2013). To better understand and quantify the overall environmental impacts caused human behaviors, Life Cycle Assessment (LCA) is becoming a keyword that has drawn more and more attention during the last decade. The introduction of LCA in transportation environmental study will expand the analyze area from on-the-road traffic emission to the entire life cycle chain, including raw material excavation, processing, manufacturing, and transportation to customers.

Lately, on the safety issue side, the crash rate increased dramatically due to the increasing of vehicle miles traveled, population, traffic density, and on-the-road uncertainties. According to the data published by U.S. DOT Fatality Analysis Reporting System (FARS) (U.S. Department of Transportation, 2013), the deaths per 100 million vehicle miles traveled in 2013 is 1.11. Among all the traffic crashes, fatal level crashes counted as 30,057, which caused 32,719 deaths. The deaths per 100,000 populations were 10.3.

1.2. ADAPTIVE TRAFFIC CONTROL SYSTEM

Conventional traffic control systems mainly adopt traffic signal systems that use pre-programmed and fixed signal-timing schedules. Lacking of the abilities of self-modification according to real-time traffic conditions, in some cases, conventional traffic control strategies not only lower the traffic control systems' efficacy, but also lead to traffic congestion and delay, increase the traffic unreliability, and exacerbate traffic safety issues. ATCS is a big step forward in responding to real-time traffic conditions with built-in algorithms, which control and adjust the signal-timing schedules. FHWA (FHWA, 2013) reported the benefits of ATCS over a conventional traffic control system as: 1) distribution of green light time equitably; 2) improvements to travel time reliability; 3) reductions in congestion; and 4) prolonged effectiveness.

In the United States, a sharp increase can be observed when the number of cases in which ATCS is deployed during the past 5 years (2009 to present) has been examined and this is pointed out in the HDR report. Before 2009, only 38 ATCS applications were known to be deployed, and half of these have either been abandoned or shut down (Selinger & Schmidt, 2010). With the increasing recognition of the short-term and long-term benefits of ATCS deployments, and the promising results of investment payback period analyses, there has been a renewed interest in the implementation of ATCS applications. Currently, several ATCS applications are available on the market. All of these ATCS applications can be categorized as either responsive adaptive systems or real-time adaptive systems. Listed below are some control systems that have been installed and operated in the United States:

1.2.1. INSYNC

InSync, developed by Rhythm Engineering, is one of the latest and most widely used real-time ATCS applications in the United States. HDR report ranked InSync as the number one ATCS application in several measures including affordability, up time, maintenance, and reductions in stops, delays, and travel time (Selinger & Schmidt, 2010).

1.2.2. ACS LITE

ACS Lite, an html browser-based ATCS developed by Siemens, is designed to adapt the splits and offsets of signal control plans in a closed loop system. In comparison to InSync system, ACS Lite was not widely used in the past 5 years.

1.2.3. LA ATCS

LA ATCS (Los Angeles ATCS) was developed around 14 years ago and was deployed in the surrounding areas of Los Angeles. Currently, there are only two jurisdictions that operate the LA ATCS system. The number of intersections per deployment for LA ATCS is comparatively

much larger than either ACS or InSync. In the summary of HDR report, 100 to 180 intersections per deployment were reported to feature LA ATCS.

1.2.4. QUICTRAC

QuicTrac Adaptive Control System, developed by McCain, is a component of QuicNet Central Software and it coordinates traffic signals along a corridor. QuicTrac has been deployed in the city of Temecula, the city of Marcos, and by CDOT as case studies.

1.2.5. SCATS

Sydney Coordinated Adaptive Traffic System (SCATS), developed in Sydney, Australia, is an intelligent system used all around the world since 1982. SCATS' case studies include Australia, New Zealand, Hong Kong, China, and the United States. As of 2012, about 35,000 intersections in over 150 cities in 25 countries used SCATS.

1.3. RAMP METERING SYSTEM

Conventional ramp control systems mainly adopt a basic traffic signal or red-green signal that uses pre-programmed and fixed signal-timing schedules. As in traditional ATCS deployments, lack of the abilities to quickly respond to real-time traffic conditions limits the efficacy of conventional ramp signal strategies. Currently, there are three main types of RMS installed and operated on the market (Miles, Quon, Ruano, & Razavi, 2010). They are 1) fixed time, 2) local responsive, and 3) system wide adaptive ramp metering.

Fixed RMS is operated on fixed metering rates for pre-set metering periods (Abouaïssa, Dryankova, & Jolly, 2013). As the simplest form of RMS, it controls the entering traffic flow on the ramp based on only a fixed schedule rather than based on real-time traffic conditions. Therefore, this type of RMS is suitable for locations where the daily traffic flow does not exhibit unexpected variations. A local responsive RMS includes an additional algorithm that

can override the fixed plan if some set points (e.g., high traffic demand) are triggered. In comparison to the fixed RMS, the local responsive RMS can quickly respond to real-time traffic conditions and therefore increase the operational efficiency. System wide adaptive ramp metering is a RMS for the entire study corridor. Unlike a single responsive ramp metering application that is limited to the control boundary, system wide adaptive ramp meters synchronize and communicate with each other to maximize the efficiency of the RMS. As of 2006, ramp management strategies have been adopted in 26 metropolitan areas across the United States (Jacobson, Stribiak, Nelson, & Sallman, 2006). Over 2,000 RMS were deployed as of 2002, and this number increased dramatically in the last 10 years.

1.4. MOTIVATION

1.4.1. PROBLEM STATEMENT

Increasing concerns regarding the above-mentioned impacts of congestion on the environment and the safety of commuters are urging decision makers to consider the environmental and social impacts of ITS deployments in addition to the agency costs. Currently, there is a lack of decision support system that would allow decision makers to simultaneous comparison of economic, environmental, and social impacts of ITS over their life cycle.

1.4.2. RESEARCH OBJECTIVES

The work for this dissertation focuses on:

- A. Developing a Life Cycle Benefit/Cost (B/C) Analysis-based framework that allows quantification of the impacts of TSM&O strategies from a triple bottom line perspective.

- B. Building a customizable tool that incorporates local measured data and/or national averages based on the Life Cycle B/C framework.
- a. To assess the travel time saving benefits (which include recurring and nonrecurring travel time saving) of ATCS and RMS deployment from a life cycle point of view.
 - b. To assess the energy consumption reduction benefits (which include fuel reduction benefits and Life Cycle Assessment of the reduced amount of gasoline) of ATCS and RMS deployment from a life cycle point of view.
 - c. To assess the safety enhancement benefits of ATCS and RMS deployment from a life cycle point of view.
- C. Interpreting the outputs of the generated tool with regards to whether the proposed ITS should be deployed and quantify long-term impacts.

1.4.3. CONTRIBUTIONS

The work for this dissertation conducts a high-level benefit/cost analysis in consideration of the factors that fall under the triple bottom line of sustainability. Develop methodologies that combine social and environmental impacts with economic impacts. Provide a generalizable framework that can be used to evaluate the anticipated monetary impacts and benefits of ITS deployments under various scenarios.

1.5. PUBLICATIONS

So far, the following publication / presentation resulted from this project:

- Chen, X., Salem, O. and Salman, B., 2016. Life-Cycle Benefit–Cost Analysis Framework for Ramp-Metering Deployments. *Transportation Research Record: Journal of the Transportation Research Board*, (2554), pp.69-76.

- Chen, Xifan, Ossama Salem, and Baris Salman. "A Life-Cycle Benefit/Cost Analysis Framework for Ramp Metering Deployments." *Transportation Research Board 95th Annual Meeting*. No. 16-1477. 2016.
- Salem, Ossama Sam, Jeff Xifan Chen, and Baris Salman. *Enhancing TSM&O Strategies through Life Cycle Benefit/Cost Analysis: Life Cycle Benefit/Cost Analysis & Life Cycle Assessment of Adaptive Traffic Control Systems and Ramp Metering Systems*. No. N15-03. 2015.

1.6. OUTLINE

Chapter II lists all the Literature and Databases that have been reviewed for the work of this dissertation. This chapter including Benefits and costs related report, research, and paper for current ATCS and RMS practices around United States, and other countries. Meanwhile, as an important component of this dissertation, all existing LCA approaches are reviewed in this chapter. Chapter III describes methodologies that used to conduct the work of this dissertation. This chapter is categorized according to four main research areas, which are Literature Review, Life Cycle Agency Cost Quantification, Travel Time Saving Benefit Evaluation, Energy Consumption Reduction Benefit Evaluation, followed by the LCA Of Reduced Energy, and Safety Benefit Evaluation. A demonstration of research framework is introduced and build up in Chapter IV. The chapter presents the analysis part of the research in the order of Life Cycle Cost Analysis, Analysis of Benefits Achieved Through Travel Time Savings, Analysis of Benefits Achieved Through Reductions in Energy Consumption, and Analysis of Benefits Achieved Through Reductions in Number of Accidents. Chapter V assembles research outputs and give interpretations on how existing on-the-road condition could be optimized after ATCS deployment under different traffic demands. The final outputs

are evaluated by cash flow, payback period, and benefits/cost ratio. Sensitivity studies are also concluded in this chapter. Chapter VI lists several recommendations for future works, while Chapter VII concludes the entire work of this dissertation.

Chapter 2. LITERATURE REVIEW

2.1. ATCS AND RMS COSTS/BENEFITS REVIEW

2.2. INTRODUCTION

Several LCCA and B/C analysis based case studies have been conducted for ATCS and RMS deployments in the recent decades. This chapter provides a review of the life cycle benefits and life cycle costs of existing ATCS and RMS case studies, which will be further expanded while preparing a BCA framework to assist transportation professionals in selecting economically and environmentally sustainable TSM&O strategies.

2.3. COST REVIEW

2.3.1. ATCS

In 2009, HDR Engineering, Inc. collected survey data to demonstrate costs for different ATCSs. It could be noticed from the results that the costs varied significantly depending on the different technologies used, number of intersections, and location of deployments. The cost per intersection ranged from \$49,000 to \$60,000 (Selinger & Schmidt, 2009). In 2010, NCHRP Synthesis 403 reported that the installation cost of ATCS per intersection varied dramatically according to ATCS users, ranging from \$20,000 to more than \$70,000 per intersection (Stevanovic A. , 2010). The same report indicated that, on average, the cost of a typical ATCS installation was approximately \$65,000 per intersection. The cost indicated by the report includes both the cost of ATCS components, and all the other additional cost items, such as upgrade and replacement of the local hardware, software, and installation of new communication infrastructure. In the same year, an LCCA of ATCS was provided for the SCATS system deployed in Oakland County, Michigan. The initial cost for implementing SCATS system on 7 intersections along the corridor was reported as \$120,000 in total (\$17,140 per

intersection). Total annual maintenance cost on this ATCS deployment was assumed as \$9,000, with a 4% fixed discount rate and 15 years of service life. The total present value (PV) was calculated as \$220,062 (\$31,437 per intersection) (Dutta, McAvoy, Lynch, & Vandeputte, 2010).

In 2012, Colorado Department of Transportation (CDOT) implemented InSync and QuicTrac, two ATCSs in two separate regions to meet the goals of the “Every Day Counts” initiative that was designed by FHWA. The costs for deploying these two ATCS applications were \$82,300 and \$22,000 per intersection, respectively. However, these costs include updates to existing infrastructure, which may not be necessary for other ATCS practices. The “net” installation cost for both systems were reported as \$34,000 and \$20,300 per intersection, respectively (Sprague, 2012). When compared to the results of HDR 2009 study (Selinger & Schmidt, 2009), the results of this survey indicated the apparent cost reduction was due to the rapid technology development in signal control systems.

The most recent survey report (published in 2013) indicated a variation in pricing of different ATCS implementations. The prices of the most popular ATCS applications were compared in this survey and it was found that the average cost of ATCS installation per intersection was highest when the system featured video detection technology and lowest when the system was using the magnetometer detection method. Among all the commonly deployed ATCS applications, SCATS was the most expensive one with a cost of \$61,161 per intersection. InSync and ACS Lite had the same price around \$30,000 per intersection. As a result, the average cost to implement ATCS, without all the additional cost items, was \$28,725 per

intersection for current practices (Lodes & Benekohal, 2013). Figure 1 below represents the change of ATCS deployment cost during the last 5 years.

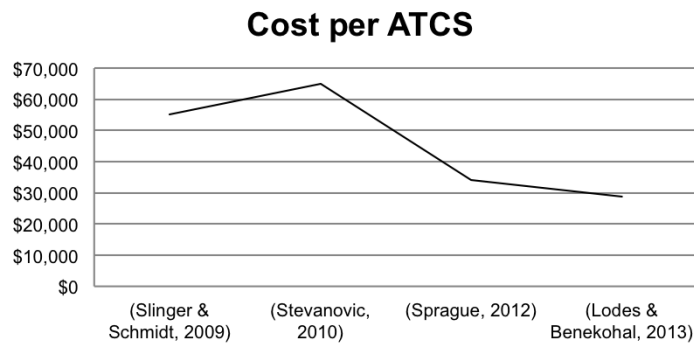


Figure 1: The change of ATCS deployment cost from 2009 to 2013.

2.3.2. RMS

On the other side, cost of RMS varies widely according to the location and year of deployment, as well as the sophistication of the algorithm used for timing, and the number of ramps included in the system. Cost values obtained by examining the actual projects can be used to estimate the national average cost for RMS deployments. In the year 2006, based on a case study on I-70 (Bhargava, Oware, Labi, & Sinha, 2006), the capital cost and annual O&M cost per ramp was calculated as \$185,000 and \$18,000, respectively. Similarly, CALTRANS 2007 Traffic Management System (TMS) Inventory presented the capital cost and annual O&M cost per unit as \$169,800 and \$37,800, respectively. On the other hand, according to a recent study that focused on an adaptive RMS deployment in Kansas City, Missouri (McDOT & KDOT, 2011) the cost of deployment was approximately \$30,000 per ramp. A similar value (\$40,000 per ramp) is estimated by San Francisco, California (USDOT, 2008), with an annual O&M cost of \$2,000. Due to rapid technological developments in Intelligent Transportation System (ITS), an analysis that focuses on a long time horizon may result in an increased level of uncertainty and inaccuracy. Considering the useful life of ramp metering components,

including loop detectors, meters, etc., and application recommendations from TIGER Grant, an analysis period of 20 to 25 years would be more appropriate for an LCCA study.

2.4. BENEFITS REVIEW

2.4.1. ATCS

The largest scale survey that aimed to determine benefits of existing ATCS practices was conducted in 2006. This voluntary self-assessment survey was completed by 417 agencies in the US and Canada. National Transportation Operations Coalition (NTOC) published the results of this survey in 2007. It was reported that at least 10% reduction in delays, 23% reduction in the number of stops, and 3.5% reduction in fuel consumption could be achieved as a result of signal system upgrades and re-timings (Institute of Transportation Engineers, 2007).

In 2010, as part of an NCHRP study, a survey of agencies that installed and operated ATCS applications was published. Various agencies including city agencies, over 16 state DOTs, and some International agencies (China, Canada, Australia, etc.) responded to this survey. It was determined that over 60% of the agencies observed a reduction in travel times when the system was deployed, and over 70% of the agencies believed that ATCS outperformed their previous system (Stevanovic A. , 2010). During the same year, a study was undertaken to examine the safety effectiveness of SCATS on a 6-mile segment in the northern metropolitan area of Detroit, Michigan. The study was based on a comparison between the SCATS controlled segment and a similar segment that featured a conventional traffic control system that used a preset timing signal control. It was found that, by reducing the number of vehicle stops on the corridor, total crashes per mile per year were decreased by 28.84% between 1999-2001 and 2003-2008. Between these two periods, permanent injury, temporary injury,

and slight bruises-level crash severity decreased around 49%, 51% and 36%, respectively (Dutta, McAvoy, Lynch, & Vandeputte, 2010). Other than safety issues, in the same year (2010), the Atlanta Smart Corridor project evaluated the implementation of SCATS and Transit Signal Priority (TSP) as an integrated system designed to improve mobility, reduce emissions, and decrease the costs of delay and fuel consumption on an 8.2-mile segment between the City of Marietta and Atlanta, Georgia. As a result, fuel consumption was reduced up to 40% during peak hours, and by an average of 34%. Travel time was decreased by 22% and total vehicle delay was decreased by 40% across all peak periods. The estimated benefit/cost ratio achieved was approximately 25:1 (Atlanta Smart Corridor, 2010).

On a higher level, the Integrated Corridor Management (ICM) aims at maximizing the benefits of integrating ITS technologies. USDOT sponsored the “ICM Tools, Strategies and Deployment Support” project to demonstrate the benefits of ICM. In 2010, a project report was published by Cambridge Systematics, Inc. to present the benefits of a well-operated ICM. The analysis assessed traffic travel time savings, incident travel time savings, emissions, and fuel consumption. The results pointed out that the estimated average Benefit-to-Cost Ratio (BCR) over the 10-year life cycle of the project was 20.4:1. While the benefits varied widely due to differing traffic demands, it is worth noting that low demand conditions earned the largest annual benefits, which could be mainly attributable to reductions in the on-the-road fuel consumption from improved signal timing during incident conditions (Cambridge Systematics, Inc., 2010). A similar analysis was published in 2009 indicating BCRs for ICM range from 7:1 to 25:1 for San Francisco areas (Alexiadis, Cronin, Mortensen, & Thompson, 2009).

In 2012, Colorado Department of Transportation (CDOT) implemented two ATCS applications in two separate regions, InSync and QuicTrac, to meet the goals of the FHWA's "Every Day Counts" initiative. As a result, 6% to 9% weekday travel time improvements were achieved, followed by an increase in average speed by 7% to 11%. Fuel consumption was reduced by 2% to 7%; and emissions were reduced by up to 17%. Meanwhile, a BCR range of 1.58:1 to 6.10:1 was calculated for these ATCS implementations (Sprague, 2012). Similarly, in 2010, an evaluation of InSync systems installed at 12 intersections on a 2.5-mile section of route-291 in Lee's Summit, Missouri was published by Missouri Department of Transportation. The evaluation is based on the travel time before and after the ATCS implementation. As a result, an average improvement of 39% was estimated for the travel time (Hutton, Bokenkroger, & Meyer, 2010).

One of the most recent innovations in ATCS came from the Robotics Institute at Carnegie Mellon University (CMU), aiming at controlling traffic on urban road networks. The innovative ATCS developed in 2012 was named "SURTRAC" (Scalable URban TRAffic Control). Unlike the commonly used centralized ATCSs, each signal in SURTRAC system works independently and uses neighboring signals' data to determine its own schedule. The SURTRAC system was later implemented on nine intersections among the East Liberty area of Pittsburgh for performance evaluation. During evaluation, travel time, energy consumption, and pollution reduction were monitored and reported. As a result of the evaluation, it was found that overall travel time was reduced by 25%, and vehicle speeds increased by 34%. Fuel consumption was improved by 21%. Meanwhile, a BCR of 20:1 was expected for an operation time of five years (J. Barlow, F. Smith, Xie, & B. Rubinstein, 2012).

2.4.2. RMS

On the other side, an interesting study that evaluated the benefits of RMS implementation was undertaken in 2001 in which Minnesota Department of Transportation (Mn/DOT) closed an extensive RMS on Minneapolis-St. Paul area freeways for evaluation (Cambridge Systematics, Inc., 2001). During the 6-week evaluation period, the average freeway flow speed decreased by 7%, meanwhile, the on-the-road crash rate increased by 26%. On the environmental impacts side, net annual vehicle emissions increased by over 1,000 tons during the shutdown period. The result of this evaluation showed a 15:1 BCR for the ramp metering deployment. In 2000, a study in Scotland (Diakaki, Papageorgiou, & Mclean, 2007) investigated the effects of ATCS integrated with freeway ramp meters in Glasgow, Scotland. The results showed a 20% throughput increase on arterials, and 6% increase on freeways after the adaptive RMS deployment.

One of the most recent studies (Shah, et al., 2013) showed that crash rate dropped by 64% along the analyzed I-435 ramp-metered corridor, and incident clearance time was limited to less than 10 minutes on the ramps in Kansas City. This finding was then deemed to be consistent with other cities with reductions in crash rates ranging from 26% to 50%.

Meanwhile, the corridor throughput increased by as much as 20% with no compromise in average travel time.

2.5. LIFE CYCLE ASSESSMENT

2.5.1. LCA OVERVIEW

Life Cycle Assessment (LCA) is a methodology that is used to estimate and understand the environmental impacts of a product. Just as its name implies, each phase of the life cycle,

from material extraction to end-of-life disposition, is ideally included in the assessment. LCA is an important component in the work for this dissertation.

The concept of using an LCA approach to conduct a real case study was firstly introduced in 1969 by the Coca-Cola Company. After that, the development of LCA experienced several milestones during the next 40 years, including the Environmental Input-Output LCA (EIO-LCA) method which was theorized and developed by economist Wassily Leontief in the 1970s (based on his earlier input-output work from the 1930s for which he received the Nobel Prize in Economics), the process-based LCA introduced by SETAC in 1984, ISO 14040, 41, 42, 43, international series of standard defining the different stages of LCA (1997 to 2000), and ISO 14020, 25, 48, 49, series of standard and technical documents concerning communication, environmental declaration directions and working methods (1999-2001). Currently, there are three different approaches to conducting an LCA: Process LCA, EIO-LCA, and hybrid LCA, which is the combination of the first two approaches.

2.5.2. PROCESS LCA

Process LCA approach, also known as traditional LCA or SETAC LCA, was firstly defined by ISO 14000 standards. Process LCA was described as difficult or impossible to define a complete scope, since use of materials and energy purchased from other firms implies additional use of the materials and energy in a long chain. Process LCA approach shows its strengths in detailed process-specific analysis, weak point analysis, and future product development assessments, while reveals its drawbacks in blur system boundary definition, time-consuming, and data uncertainties (Hendrickson, Lave, & Matthews, 2010).

A process LCA is carried out in four distinct phases (ISO 14040, 2006) (ISO 14044, 2006) which are mostly defined as: Goal and Scope, Life Cycle Inventory, Life Cycle Impact Assessment,

and Life Cycle Interpretation. Process LCA has been used mainly for “tangible” products which can be specified and quantified, like different asphalt and concrete pavements (Hakkinen & Maleka, 1996) (Mroueh, Laine-Ylijoki, & Wellman, 2000) (Stripple, 2001).

2.5.3. EIO-LCA

Economics Inputs-outputs Life Cycle Assessment(EIO-LCA) is a top-down approach which focuses on total outputs, (including direct and indirect outputs), and final demands. EIO-LCA treats the whole economy as the boundary of analysis. A huge strength of EIO-LCA lies in its capacity of solving complex and subtle intermediate sectors' activities, which interdependencies are nearly impossible to handle for the detail-oriented Process LCA Approach.

Due to EIO-LCA approach is based on the economic Input-output matrix, the easiest but most challenging part of EIO-LCA modeling is building, expanding, and filtering matrices, which includes information collection, data organization, and calculation. The accuracy of the final interpretation highly depends on the rationality, veracity and logicity of the EIO-LCA model. Meanwhile, the “black box” style approach decreases the transparency of the LCA study. The biggest drawback of EIO-LCA approach is lacking the ability to research on specific product. For example, LCA of home laundry machine and dryer will be identical, since they are in the same economic sector, which is the smallest unit in the Input-output matrix.

2.5.4. HYBRID LCA

After review on both Process LCA and EIO-LCA, we conclude the pros and cons for both approaches in the figures presented below (Figure 2):

	Process LCA	IO-LCA
Strengths	<ul style="list-style-type: none"> - Detailed process-specific analyses - Specific product comparisons - Process improvements, weak point analyses - Future product development assessments 	<ul style="list-style-type: none"> - Economy-wide, comprehensive assessments (all direct and indirect environmental effects included) - System LCA: industries, products, services, national economy - Sensitivity analyses, scenario planning - Publically available data, reproducible results - Future product development assessments - Information on every commodity in the economy
Weaknesses	<ul style="list-style-type: none"> - System boundary setting subjective - Tend to be time intensive and costly - New process design difficult - Use of proprietary data - Cannot be replicated if confidential data are used - Uncertainty in data 	<ul style="list-style-type: none"> - Many product assessments contain aggregated data - Process assessment difficult - Difficulty in linking dollar values to physical units - Economic and environmental data may reflect past practices - Imports treated as U.S. products - Difficult to apply to an open economy (with substantial non-comparable imports) - Non-U.S. data availability a problem - Uncertainty in data

Figure 2: Strengths and Weakness of LCA Approaches

However, Process LCA and EIO-LCA are not rivals but have comparative advantages (Hendrickson, Lave, & Matthews, 2010). Hybrid LCA approach enhances the value of each approach to give better, more confident answers. Hybrid LCA is a method that combines

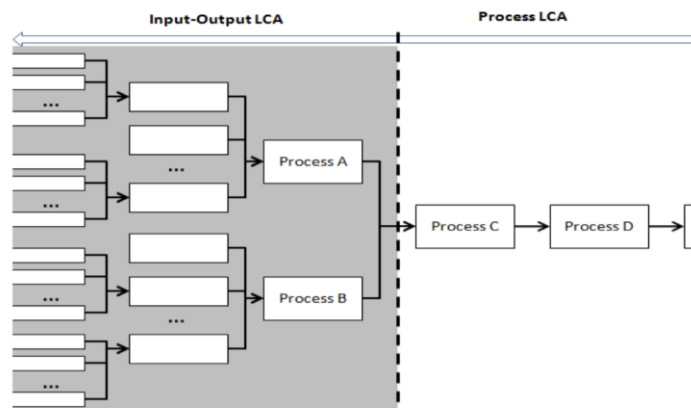


Figure 3: Generic Hybrid LCA Workflow

process LCA and EIO-LCA in a manner that exploits their strengths and offsets their weaknesses. A generic workflow of Hybrid LCA is illustrated below (Figure 3):

Where process A and B are conducted by Process LCA, as well process C and D are conducted by Process LCA. The key point of performing an effective and efficient Hybrid LCA lies on where is the best location of the line between the use of EIO-LCA and Process LCA within the system boundary.

Similar to Process LCA, a hybrid LCA method comprises four phases: derive an EIO-LCA model, extract the critical path, derive case-specific LCA data for the facility and its components, and substitute the pre-derived data into the IO model (Treloar, Love, & Faniran, A hybrid life cycle assessment method for construction, 2000). Strengths of the Hybrid LCA lies on:

- A. Integration of traditional LCA data improve the reliability of those modified components of the IO Model.
- B. Unimportant pathways are filtered out of the system. EIO part of the Hybrid LCA takes charge of calculating and simplifying the complexity, while the process part takes charge of dealing with the simplified results in detail-oriented method.

2.5.5. LCA TOOLS REVIEW

Popular LCA tools/software on the market are reviewed at section 3.5.2 LCA Tools Review

2.6. TRIPLE BOTTOM LINE

2.6.1. TBL OVERVIEW

The term Triple Bottom Line (TBL) was introduced firstly in 1994 (Elkington, November 17, 2009). TBL is a sustainability-focused principal that referencing the economic, social, and

environmental lines (Elkington J. , 1997). Additionally, TBL holds a core value that place equal amount of emphasis on each of the three lines. (Elkington J. , 1997) (Epstein, 2008) (Harmon, 2009). Since its advent, TBL has been introduced into projects and researches as a framework for measuring the performance of the success of achieving three lines (Goel, 2010).

TBL is the guideline that conduct the entire work of this dissertation. Therefore, a thorough literature review of all three concepts of TBL is important. The purpose of the literature review was to understand how each concept appeared in this research.

2.6.2. ECONOMIC BOTTOM LINE

Economic Line, or Profit Line, deals with the economic value created by the organization, product, or activity. On the other word, it refers to the impact of practices on economic system (Elkington J. , 1997). The economic impacts, or “profits” should be considered as real “tangible” economic benefit, not as an internal profit enjoyed by the organization or activity hosts, but on the entire society, even future generations (Spangenberg, 2005).

2.6.3. SOCIAL BOTTOM LINE

The original concept of Social Line, or People Line refers to conducting beneficial and fair business practices to the labor and community (Elkington J. , 1997). Later on this concept has been expanded to reach social development, social responsibility, and other higher-level social aspects (Dhiman, 2008). During recent years, researches introduced social bottom line to measure social performance which focuses on the interaction between the community and the organization, activity, or product (Goel, 2010)

2.6.4. ENVIRONMENTAL BOTTOM LINE

The core value of this Environmental Line, or Planet Line, is very straight forward: reducing energy consumption, reducing greenhouse gas emissions, and minimizing the ecological

footprint (Goel, 2010). Life Cycle Assessment has been heavily involved in the environmental bottom line to determine “cradle to grave” environmental impacts.

Chapter 3. METHODOLOGY

3.1. INTRODUCTION

We address our research focus in line with the Triple Bottom Line (TBL) principal of sustainability which is presented at the following matrix (Table 1). Filled cells are areas that we placed more focus on. Currently, we are studying the feasibility of Environmental Costs which consider the LCA of ITS equipment. Social Costs, which considers the delay on ramp via RMS implementation, is included as a negative impact in the travel time saving benefits for RMS.

Table 1: TBL-based Research Objectives Matrix

TBL PRINCIPAL OF SUSTIANABILITY	COSTS	BENEFITS
ECONOMIC	Life Cycle Agency Costs	Travel Time Saving Benefits
ENVIRONMENTAL	LCA of ITS Equipment	Fuel Consumption Benefits LCA on the Amount of Saved Gasoline
SOCIAL	Delay on Ramp via RMS Implementation	Safety Benefits

3.2. LIFE CYCLE AGENCY COST QUANTIFICATION

The Life Cycle Agency Cost Analysis of an ATCS deployment include initial infrastructure cost, which occur at the "year zero" of system installation; periodical incremental cost; and operation & maintenance costs, which occur along the entire life cycle of the ATCS and RMS deployment. Flowchart (Figure 4) below presents the methodology.

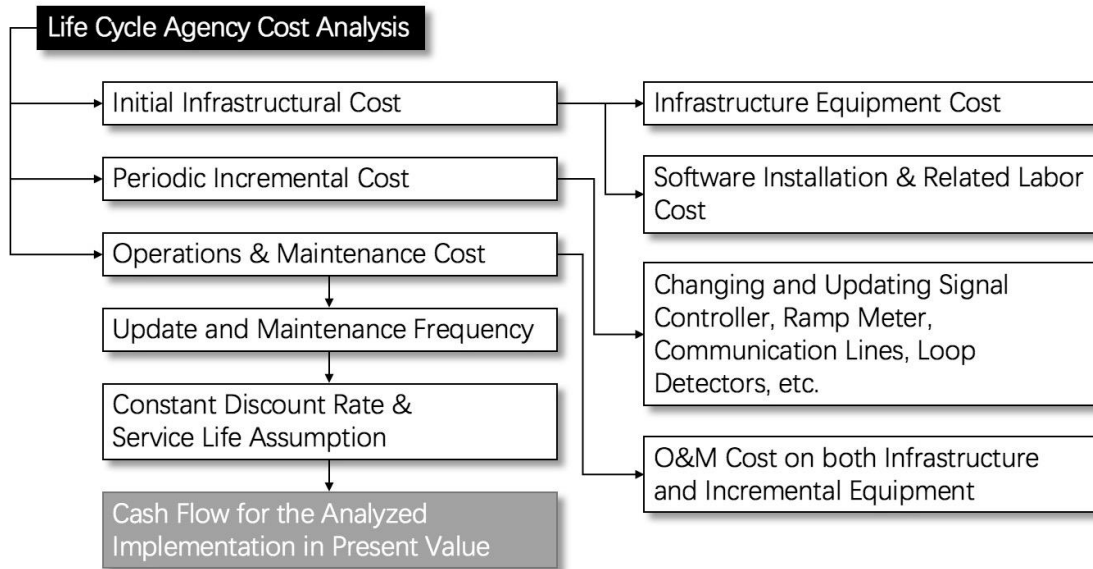


Figure 4: Methodology flowchart of Life Cycle Agency Cost Analysis

3.2.1. INITIAL INFRASTRUCTURE COST FOR ATCS AND RMS

The initial infrastructure cost of deploying an ATCS include the principal cost for the infrastructure equipment, software installations, and labor cost for installing and operating the system. Due to the rapid technological developments in ATCS, and significant variations among different types of ATCS deployments under regional disparities, it is challenging to estimate the initial infrastructure cost for all the ATCS deployments from coast to coast. In this project, an average cost of \$28,725 per intersection was used while performing the LCCA for typical ATCS deployments in the United States. This value is determined based on the results of the latest survey (2013) (excluding extreme values) conducted by Illinois Center for Transportation and corresponds to the cost for the most popular ATCS system in the survey (InSync). For the RMS implementation, the built-in cost inventory obtained from TOPS-BC Tool was considered as an important reference material in the LCCA of RMS at this stage of study. Meanwhile, some other recent studies on the costs of RMS deployment (Bhargava,

Oware, Labi, & Sinha, 2006) (McDOT & KDOT, 2011) (USDOT, 2008) are examined in determining the initial infrastructure cost. Based on review of literature, cost databases, and existing BCA tools, the average initial infrastructure cost is assumed to range from \$100,000 (Traffic Actuated) to \$230,000 (Central Control) per infrastructure deployment, including \$30,000 for freeway control hardware, and the rest for integrated software installation. It is worth noting that the useful life for ramp metering infrastructure hardware and software cannot cover the entire life cycle period, in this case, 20 years. TMC freeway control needs to be updated every 5 years, while software needs to be tuned and upgraded at a similar frequency.

3.2.2. PERIODICAL INCREMENTAL COST FOR ATCS AND RMS

The periodical incremental cost for ATCS includes changing and updating signal controller, communication lines, loops detectors, etc. based on a fixed schedule. Some existing manuals and BCA tools have established periodical incremental cost databases. According to the FHWA Operations Benefit/Cost Analysis Tool's "TOPS-BC" built-in cost analysis module, it is recommended to change the signal controllers every 15 years, and loop detectors every 5 years; communication lines, on the other hand, can serve the entire service life of the ATCS (more than 20 years). The costs for these components were listed as \$6,250, \$11,750, and \$750, respectively. These costs were determined as a result of statistical analysis, large-scale data collection efforts, and on-site surveys regarding the existing ATCS practices throughout the entire United States. At this stage, these costs are preferred to adopt in the LCCA for typical ATCS systems. However, variations with regards to the location of deployment and technologies used will dramatically affect the results of LCCA for ATCS deployments. The local costs obtained from transportation agencies and contractors should have the highest priority

for selection in cost analysis to provide more accurate and realistic results for a local application.

For the RMS implementation, according to TOPS-BC built-in cost analysis module, all the incremental components can last as long as the service life, say 20 years, of the RMS. The costs for these components (ramp meter, loop detector, and communication line) are listed as \$88,000, \$11,000, and \$750, respectively. Currently, these costs are used in the life cycle agency cost analysis. However, the variations in deployment locations and technologies adopted may have drastic impacts on the results of LCCA of ramp metering applications. Use of actual cost values obtained from local transportation agencies and contractors, if accessible, should be preferred in the cost analysis.

3.2.3. O&M COST FOR ATCS AND RMS

During the life cycle of an ATCS deployment, Operation & Maintenance (O&M) activities occur on both infrastructure and incremental equipment. O&M cost vary according to the challenges of the mechanism adapted in the system, and the location of the deployed system. In this study, an annual O&M cost of \$9,000 per intersection was used for a typical ATCS deployment. This value was adopted based on the 2010 SCATS LCCA study (Dutta, McAvoy, Lynch, & Vandeputte, 2010). Due to the higher average O&M cost of SCATS in comparison to other ATCS deployments (InSync, ACS Lite) (Lodes & Benekohal, 2013), using this O&M cost value, resulted in a conservative LCCA.

For RMS Implementation, the cost of O&M varies according to the complexities of the mechanism adapted in the system. In this project, an annual cost of \$25,000 per ramp is used as the average ramp metering operation and maintenance cost. This value is assumed based

on the CALTRANS 2007 Traffic Management System (TMS) Inventory, and Bhargava, Oware, Labi, and Sinha's case study on I-70 (Bhargava, Oware, Labi, & Sinha, 2006).

For both ATCS and RMS costs studies, a fixed discount rate of 7% is assumed during a 20-year lifespan consistent with the procedures outlined by the Office of Management and Budget.

3.3. TRAVEL TIME SAVING BENEFIT EVALUATION

3.3.1. TRAFFIC CAPACITY AND VOLUME/CAPACITY RATIO

Traffic capacity is defined as the maximum rate at which vehicles can pass through a given point in an hour under saturation flow (FHWA, 2004). Several factors determine the capacity including number of lanes, width of lanes, grades, lane use allocation, as well as signalization conditions.

The volume/capacity (v/c) ratio represents the degree of saturation. As the v/c ratio approaches 1.0, traffic flow may become saturated, and delay and queuing conditions may occur. Once the demand exceeds the capacity (a v/c ratio greater than 1.0), traffic flow is unstable and excessive delay and queuing is expected. For design purposes, a v/c ratio between 0.85 and 0.95 generally is used for the peak hour.

In travel time savings analysis for ATCS and RMS deployment, both recurring and nonrecurring travel time savings were considered. For the recurring travel time savings analysis, HCM 2010 was introduced to estimate the existing segment's Free Flow Speed (FFS) and to calculate v/c ratio under certain traffic demands. Akçelik flow rate equation was then used to determine the average travel time and speed for existing and optimized traffic conditions. For the nonrecurring travel time savings analysis, IDAS Travel Reliability Lookup Table was adopted to estimate both the existing and optimized traffic reliability separately. The equivalent travel time savings combined and weighted both recurring and nonrecurring

travel time savings to provide a comprehensive assessment of travel time optimization due to proper ATCS and RMS deployment.

3.3.2. TRAFFIC RELIABILITY ANALYSIS OVERVIEW

Although lacking a common definition of traffic reliability, the term reliable can be considered as “one that performs its required functions under stated conditions for a specified period (OECD, 2010)”. In other words, reliability can be understood as the differential between the driver’s actual travel time and expected travel time. Traffic unreliability can be defined as recurring delay, and nonrecurring delay. Therefore, every traffic scenario can be expressed in terms of no-delay, recurring delay, and nonrecurring delay conditions, which can be perfectly illustrated by the travel time historical data distribution (Loop, Perdok, & Willigers, 2014) as presented in Figure 5 below:

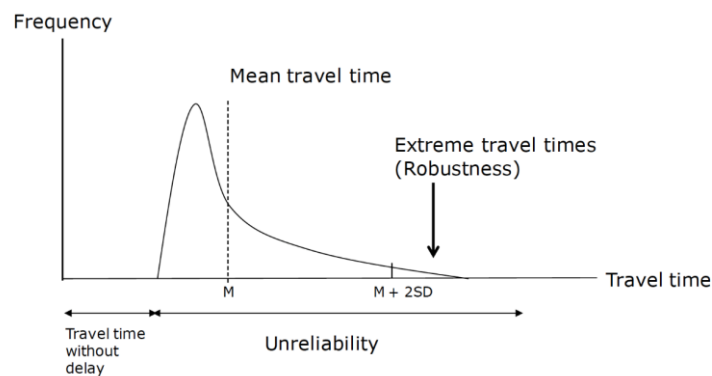


Figure 5: Travel time historical data distribution (Loop, Perdok, & Willigers, 2014).

In the above diagram, the probability distribution curve of traffic delay was introduced to represent the reliability of traffic flow. Under normal circumstances, travel time values exceeding the mean travel time plus two standard deviations (SD) were considered as

nonrecurring delay, which may be caused by traffic accidents, sudden high traffic demand, extreme weather, and other unpredictable factors.

3.3.3. RECURRING TRAVEL TIME SAVINGS

3.3.3.1. Field Measurements

Field measurement of the FFS and the link capacity of every segment can be achieved directly from continuous probe vehicle data, or indirectly from continuous point-based detector data.

In recent years, due to the cost of direct probe measurements, various new convenient and economical technologies have been developed to replace the former approach. The incorporation of ITS and Global Positioning Systems (GPS) has been widely used as a handy and effective method of direct traffic flow measurement. Since GPS equipment sends and receives signals simultaneously, theoretically speaking, each GPS-equipped vehicle can be considered as a component of the field traffic measurement system. The GPS-based traffic data measurement and collection system has become more and more popular in recent years (Venter & Joubert, 2013) (Huang & Levinson, 2013). The introduction of portable vehicle GPS, and GPS-enabled smartphones dramatically reduced the equipment costs, raised the accuracy of the results, and enlarged the coverage of measurements (Yin, Li, Fang, & Qiu, 2013). Currently, per FHWA (Klein, Mills, & Gibson, 2006), indirect data collection (e.g., loop detector) is the most widely used method in field measurements.

3.3.3.2. Free Flow Speed Equation

If field measurements are not applicable, HCM 2010 can be used to estimate on-the-road FFS and to calculate the v/c ratio. During the methodology development stage, both HCM 2000 and HCM 2010 FFS equations were considered as candidates in the FFS analysis. The HCM 2000 FFS equation is presented as follows:

$$FFS = BFFS - f_{LW} - f_{LC} - f_N - f_{ID}$$

In the above HCM 2000 FFS equation, on the right side of the equation, BFFS represents the base FFS, f_{LW} , f_{LC} , f_N , and f_{ID} are adjustments for lane width, right-shoulder lateral clearance, number of lanes, and interchange density, respectively.

There have been major changes to the HCM 2000 FFS equation in the 2010 version. The new HCM 2010 FFS equation is presented as follows (take freeway for example):

$$FFS(\text{freeway}) = 75.4 - f_{LW} - f_{LC} - 3.22TRD^{0.84}$$

Where f_{LW} and f_{LC} remain the same as the former version, and TRD is the total number of on and off ramps within three miles of the midpoint of the study segment (for example, for a study link segment without on or off ramp, TRD is 0). In the new FFS equation, the lane number factor f_N is eliminated, while a recommended BFFS is set as 75.4 mph. These changes are based on the results of recent research, and the average measurements obtained from American freeways. In this project, the HCM 2010 FFS equation was selected to align the study with the latest research results. However, FFS equation was recommended only in the case that field FFS measurements are not applicable. Therefore, if a field measurement is available, using the measured FFS rather than the estimated FFS will lead to more accurate and practical results.

3.3.3.3. Speed-Flow Rate Equation

Aiming at maximizing the performance of an existing transportation system, ATCS was developed to increase the traffic link capacity. Under the same traffic demand (no change in traffic volume), the v/c ratio is decreased due to enlarged link capacity. Average travel time can be estimated according to average traffic flow speed, whose relationship with traffic v/c ratio has been considered as a very important factor in link speed estimation. Several well-known equations had been considered during the methodology development stage, including

HCM 2000/2010 speed-v/c equation, Akçelik speed-v/c ratio equation and updated BPR equation. Because of screening efforts, these equations performed almost equally well in traffic conditions for which the v/c ratio is smaller than 1.0. However, when v/c ratio reaches and exceeds the 1.0, only Akçelik speed-v/c equation produced the expected delays under these conditions (Dowling & Skabardonis, 2008). Both BPR and HCM 2000/2010 equations are only suitable for traffic conditions where v/c ratio is below 1.0. To avoid the duplication in discussion; only BPR and Akçelik equations are discussed below:

BPR (Bureau of Public Roads) speed-v/c ratio equation is one of the most traditional methods used to predict vehicle speeds in travel demand models. This equation is a function of FFS and v/c ratio. The average link speed can be presented as follows:

$$\text{Average link speed} = \frac{FFS}{[1 + a(v/c)^b]}$$

For theoretically oversaturated traffic conditions with v/c ratio 1.0 to 2.0, BPR travel time – v/c ratio curve tends to be very insensitive to the increase in traffic density. However, when v/c ratio is extremely high, the travel time reaches to the estimated value of queue theory and Akçelik prediction (Dowling & Skabardonis, 2008).

Akçelik speed-v/c ratio equation is derived from classical queuing theory; therefore, it performs well in oversaturated traffic conditions, and fits the queue theory curve. The equation that adopted in the analysis is presented below:

$$\text{Average speed} = \frac{FFS}{1 + \frac{FFS}{4} * \left((2x - 1) + \sqrt{(2x - 1)^2 + 0.8 * \frac{4x}{Cp}} \right)}$$

In which Cp is the link capacity of study segment, x is the v/c ratio. Dowling and Skabardonis illustrated the following diagram to represent the difference in performance of BPR and Akçelik travel time - v/c ratio equation curve in undersaturated and oversaturated traffic conditions (Dowling & Skabardonis, 2008). It could be found from Figure 6 that after the traffic v/c ratio reaches 1.0, the travel time represented by BPR curves increases slowly and yields a dramatic difference with the queue theory trend line.

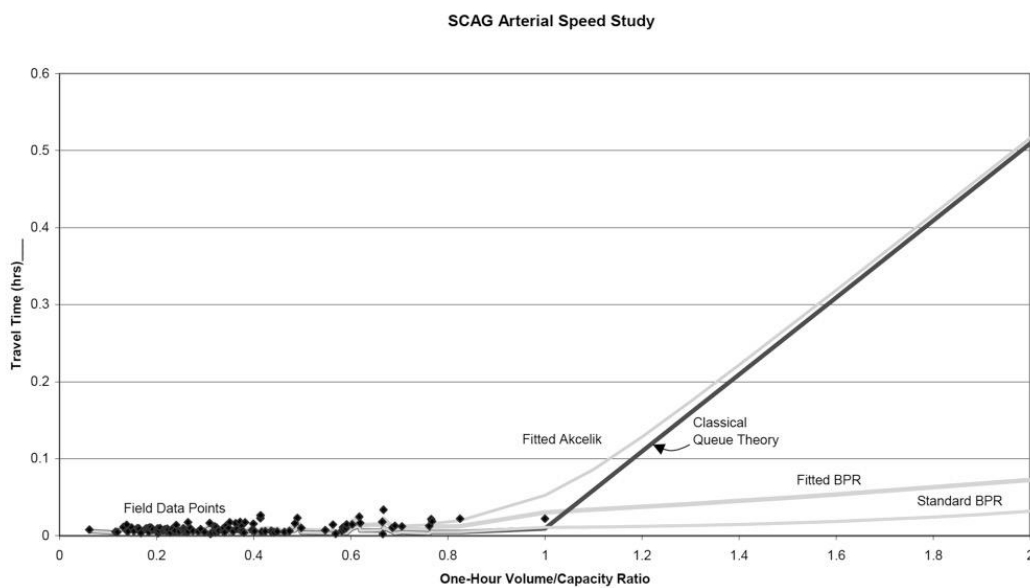


Figure 6 : The differences between BPR and Akçelik curves after the v/c ratio reaches 1.0. (Dowling and Skabardonis, 2008)

3.3.3.4. Link Capacity Multiplication Factor

To better quantify the improvement in link capacity due to ideal ATCS and RMS deployment onsite, an adjustment factor, namely "link capacity multiplication factor", is introduced to estimate the increase in analyzed link segment capacity. Under the same traffic demand conditions, enlarged link capacity will decrease the v/c ratio and raise the average traffic flow speed. The link capacity multiplication factors chosen in this project run from 8% to 12% with an increment of 1%. These values are selected based on the review of current ATCS and RMS

practices, literature and databases and they are in line with the FHWA Operations

Benefit/Cost Analysis Tools.

3.3.3.5. Recurring Travel Time Saving Estimation

Based on all the information provided above, following equation is used to examine recurring travel time savings for a study segment after ATCS deployment:

$$\text{Recurring Time Saving} = \frac{L * V}{4} * \left(2x_e - 2x_a + \sqrt{(2x_e - 1)^2 + 0.8 * \frac{4x_e}{Cp}} - \sqrt{(2x_a - 1)^2 + 0.8 * \frac{4x_a}{Cp}} \right)$$

In the equation above, x_e and x_a represents existing v/c ratio and anticipated v/c ratio, respectively, L is the length of study segment and V is the traffic volume. This equation is developed based on the assumption that traffic demand is constant, which implies the v/c ratio is a function of traffic capacity. Based on this assumption, x_e and x_a can then be presented as follows:

$$x_e = \frac{V}{Cp_e}; x_a = \frac{V}{f * Cp_e}$$

Where Cp_e is the existing segment traffic capacity before ATCS installation, and f is the applied link capacity multiplication factor due to the ATCS deployment.

3.3.4. NONRECURRING TRAVEL TIME SAVINGS

IDAS sketch-planning tool is one of the most widely used tools in planning ITS deployment.

The IDAS Traffic Reliability Look-up Rate Table (IDAS User's Manual – Appendix B.2.14~B.2.18.

Cambridge. Inc.) was developed by IDAS to estimate the incident related nonrecurring traffic

delays. These rates were predicted based on long-term monitoring and analysis of annual

incident delay experiences on many national freeway corridors. The determination of traffic

reliability rates is based on several key traffic factors, including 1) the number of facility lanes,

and 2) the facility v/c ratio. In this project, IDAS look-up table is chosen for nonrecurring travel time savings analysis.

Based on the IDAS Traffic Reliability Look-up Rate Table, a 5-step procedure was followed to perform the nonrecurring travel time savings for ATCS and RMS deployment:

- A. 1st Step - Determine the number of lanes, and the v/c ratio of the analyzed segment.
- B. 2nd Step - Use interpolation method to find the incident traffic delay per vehicle per mile.
- C. 3rd Step - Repeat the 1st and 2nd steps with enlarged v/c ratio to find out the optimized traffic delay.
- D. 4th Step - Calculate the difference in traffic delays before and after the ATCS and RMS deployments.
- E. 5th Step - Calculate the total nonrecurring travel time savings for all vehicles on the segment during analyzed period.

3.3.5. EQUIVALENT TRAVEL TIME SAVINGS ESTIMATION AND VALUATION

For compatibility of valuations of travel time savings benefits in this chapter, and environmental and social benefits in following chapters, in this project, all the benefits are generalized in terms of US Dollars. For example, in travel time savings analysis, the unit of valuation was set as USD per hour saved per vehicle. In fuel consumption analysis, the unit was set as USD per ton of Carbon Dioxide Equivalent (CO₂e). Using dollar values as the units of benefits makes the results straightforward in the benefits analysis, and makes it easy to incorporate it with the results of LCCA in BCA.

In comparison with recurring travel time savings benefits, nonrecurring travel time savings benefits are relatively more difficult to evaluate. After determining the amount of recurring

travel time savings, the entire traffic flow should be categorized per vehicle types, including passenger cars, light duty trucks, heavy-duty trucks, and bus transits. Different vehicle types should be assigned different travel time values per hour saved. For convenience, the vehicle types are usually set as automobiles and trucks, with approximate on-the-road share of 90% and 10%, respectively. If applicable, field measurements and observations for all the analyzed segments may provide more accurate vehicle type distributions. Value of Travel time (VoT) are usually set as \$24 to \$28 for trucks and \$12 to \$14 for cars (Bhargava, Oware, Labi, & Sinha, 2006) (FHWA, 2012). Currently, there is no global agreement on VoT for different transportation agencies. This default value should also be adjusted according to local conditions for regional deployment.

3.3.6. VALUE OF RELIABILITY

Although more and more attention has been placed on the importance of traffic reliability, a commonly accepted method of evaluating travel time reliability is still missing. The value of reliability varies widely according to different locations. The common traveler-oriented traffic reliability measures can be presented as Buffer Index (BI), Planning Time Index (PTI), and 90th / 95th Percentile Index. Another method of incorporating reliability into travel time savings evaluation is by introducing reliability ratio (RR), which represents the ratio of Value of Reliability (VoR) and Value of Travel Time (VoT). This method has been used in several European countries (Denmark, Sweden, and Netherlands), Australia, and New Zealand. In this study, RR method was adopted to evaluate the equivalent travel time savings benefit. A default RR value is set as 1, which indicates the same importance level for VoR and VoT. In the final tool, both VoT and VoR can be customized according to local conditions for regional deployment.

3.4. ENERGY CONSUMPTION REDUCTION BENEFIT EVALUATION

Proper ITS deployments can maximize the performance of existing transportation networks, increase the link capacity, alleviate traffic density, smoothen the traffic flow, and directly reduce the overall energy consumption. In this study, a microscopic scale top-down approach was introduced to estimate the difference between existing and anticipated energy consumptions before and after the ATCS and RMS deployment. In this method, the existing energy consumption for the study link was estimated based on field test data, vehicle registration records from local DMV, or default lookup tables. A range of energy consumption reduction factor was assumed (5% to 25%, 15% used as an average value in this project) based on existing case studies, research studies, and simulations (FHWA, 2012) (Stevanovic A., 2010) (U.S Department of Transportation, 2001). Flowchart (Figure 7) shows below illustrates the methodology used in the energy consumption reduction evaluation.

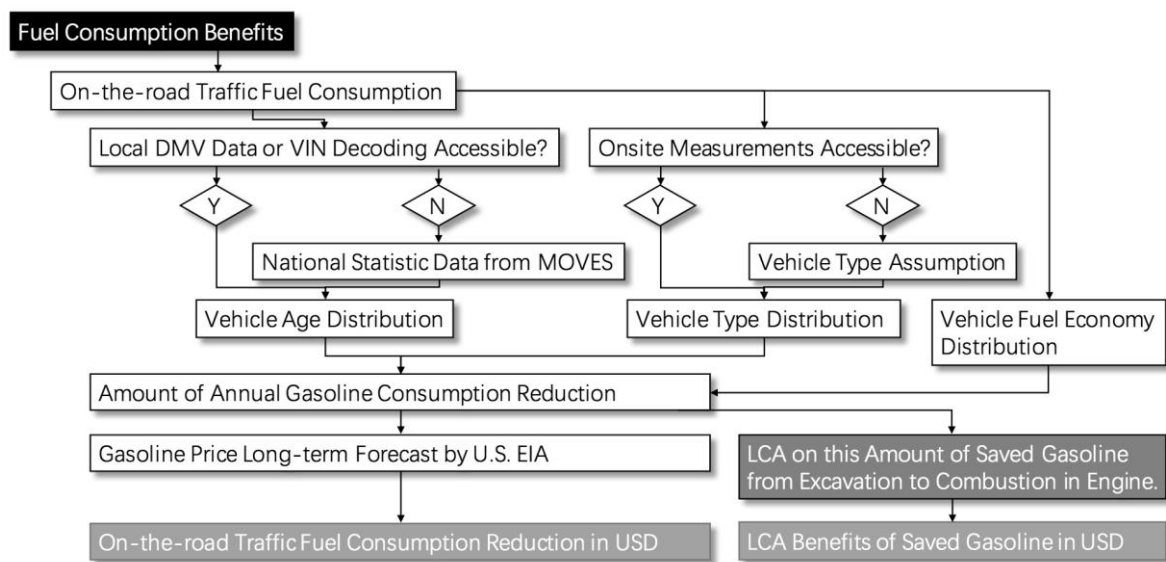


Figure 7 : Methodology flowchart of fuel reduction benefits and LCA benefits evaluation

3.4.1. VEHICLE TYPE DISTRIBUTION MATRIX

Vehicle types vary widely depending on the location. Therefore, when the vehicle characteristics inventory is being built, field measured or observed data should have the highest priority. The vehicle type distribution should be recorded for different periods during weekdays and weekends. The number of records in each field measurement should be at least 100 vehicles. A vehicle type distribution matrix $[T]$ can be established according to the measure, in which $T_{i,j}$ represents the specific vehicle type's (Passenger car, truck, etc.) percentage during a certain measurement period (Weekday on-peak, weekend off-peak, etc.). The columns and rows in matrix $[T]$ are presented as follows:

$$T_{i(i=1,\dots,4),j} = \text{Vehicle Type Distribution, where } T_{1,j} = \text{Passenger Car, } T_{2,j} = \text{Light Duty Truck, } T_{3,j} \\ = \text{Heavy Duty Truck, and } T_{4,j} = \text{Bus}$$

$$T_{i,j(j=1,\dots,4)} = \text{Measurement Period, where } T_{i,1} = \text{Weekday on peak, } T_{i,2} = \text{Weekday off peak, } T_{i,3} \\ = \text{Weekend on peak, and } T_{i,4} = \text{Weekend offpeak; } \sum_{i=1}^4 T_{i,j} = 1$$

In the equations above, Light Duty Truck includes passenger trucks and light commercial trucks, Heavy Duty Truck includes single unit trucks and combination trucks, and Bus includes transit buses, school buses with number of occupants larger than 15. If the scope of study is limited to light duty vehicle only, the share of heavy-duty vehicles and public transit can be ignored, let $T_{3,j} = T_{4,j} = 0$. An example of vehicle distribution matrix $[T]$ is shown below:

$$[T] = \begin{bmatrix} 0.85 & 0.80 & 0.82 & 0.81 \\ 0.10 & 0.10 & 0.12 & 0.10 \\ 0.03 & 0.08 & 0.01 & 0.05 \\ 0.02 & 0.02 & 0.05 & 0.04 \end{bmatrix}$$

3.4.2. VEHICLE AGE DISTRIBUTION MATRIX

Similar to vehicle type distribution, vehicle age distribution varies widely depending on the location. For example, climate factors, including frequent snowfalls and rainfalls, followed by infrastructure degradations can accelerate the vehicle renewal rates (speed up the car renew cycle). Therefore, regional data collection and input for vehicle age distribution can make the results more accurate and reasonable (As an example, it would not be incorrect to think that Michigan and Miami has different vehicle age distribution sets). Currently, one of the most straightforward and effective ways to measure vehicle distribution is based on VIN decoding. The procedure is summarized as follows:

- A. 1st Step - VIN data collection from local DMV
- B. 2nd Step - Build VIN inventory
- C. 3rd Step - VIN Decoding
- D. 4th Step - Vehicle Classification
- E. 5th Step - Age distribution matrix under each vehicle type

According to the built-in database in MOVES (Motor Vehicle Emission Simulator developed by EPA), vehicles with registration dates from 1990 to 2013 account for over 98.5% of the total vehicles. For this reason, vehicles older than 23 years (before 1990) in the analysis are ignored.

When regional data collection is not applicable, default national vehicle age distribution can be used as a substitute. The vehicle distribution matrix $[A]$ derived from MOVES built-in database was introduced and modified in this study. Similar to matrix $[T]$, the rows represent different vehicle types, and columns represent the registration year distribution. Type ID 31 "Passenger Truck row" and Type ID 32 "Light Commercial Truck row" in MOVES matrix is then combined to make the new "Light Truck row". Similarly, Source Type ID 51, 52, 53, 61, and 62

were combined into "Heavy Truck row", and ID 41, 42, and 43 were combined into "Bus Transit row". The vehicle age distribution matrix $[A]$ is presented below in Table 2. The sum of each row may not be exactly equal to 1, since the vehicles before the year 1990 were ignored.

Table 2: The Vehicle Age Distribution Matrix $[A]$

	2013	2012	2011	2010	2009	2008	2007	2006
Passenger Car	0.076	0.093	0.093	0.08	0.075	0.071	0.064	0.069
Light Truck	0.105	0.122	0.103	0.097	0.07	0.076	0.052	0.058
Heavy Truck	0.054	0.071	0.095	0.114	0.064	0.055	0.042	0.087
Bus Transit	0.046	0.097	0.112	0.124	0.087	0.06	0.047	0.08
	2005	2004	2003	2002	2001	2000	1999	1998
Passenger Car	0.056	0.053	0.046	0.043	0.038	0.031	0.025	0.018
Light Truck	0.05	0.042	0.034	0.028	0.024	0.023	0.019	0.013
Heavy Truck	0.044	0.056	0.033	0.048	0.047	0.043	0.029	0.022
Bus Transit	0.039	0.045	0.03	0.034	0.038	0.025	0.02	0.02
	1997	1996	1995	1994	1993	1992	1991	1990
Passenger Car	0.015	0.013	0.01	0.006	0.004	0.003	0.002	0.003
Light Truck	0.014	0.013	0.011	0.006	0.008	0.006	0.003	0.004
Heavy Truck	0.015	0.015	0.015	0.005	0.01	0.007	0.006	0.008
Bus Transit	0.013	0.015	0.011	0.007	0.011	0.009	0.005	0.008

After Matrices $[T]$ and $[A]$ are built, traffic flow on each study segment can be represented according to vehicle age and type distribution using the following equation (weekday on peak time period assumed):

$$\text{Traffic Flow ***} = \text{Volume} * \text{number of lanes} * \text{analyzed period} * \begin{bmatrix} T_{1,1}A_{1,1} & T_{1,1}A_{1,2} & \dots & T_{1,1}A_{1,24} \\ T_{2,1}A_{1,1} & T_{2,1}A_{1,2} & \dots & T_{2,1}A_{1,24} \\ T_{3,1}A_{1,1} & T_{3,1}A_{1,2} & \dots & T_{3,1}A_{1,24} \\ T_{4,1}A_{1,1} & T_{4,1}A_{1,2} & \dots & T_{4,1}A_{1,24} \end{bmatrix}$$

*The numbers of vehicle types defined in this matrix are passenger car, light truck, heavy truck, and bus transit.

**The years that are covered in the age matrix cover a period that starts from 1991 to 2013 (24 years in total).

***The traffic flow here represents the traffic flow on weekdays in peak hours considering all types of vehicles from passenger cars to buses.

3.4.3. MODIFIED TRAFFIC FLOW FUEL ECONOMY MATRIX

Fuel economy varies dramatically according to vehicle type and model year. In 2013, USDOT released the Summary of Fuel Economy Performance report (U.S. Department of Transportation, 2012), in which the model year based fuel `economy for different vehicles types was provided. A Fuel Economy Matrix was also developed by the report as in Table 3:

Table 3: Fuel economy matrix [F]

	2013	2012	2011	2010	2009	2008	2007	2006
Passenger Car	33.5	32.7	30.2	27.5	27.5	27.5	27.5	27.5
Light Truck	25.7	25.2	24.3	23.5	23.1	22.5	22.2	21.6
Heavy Truck	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
Bus	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2
	2005	2004	2003	2002	2001	2000	1999	1998
Passenger Car	27.5	27.5	27.5	27.5	27.5	27.5	27.5	27.5
Light Truck	21	20.7	20.7	20.7	20.7	20.7	20.7	20.7
Heavy Truck	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
Bus	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2
	1997	1996	1995	1994	1993	1992	1991	1990
Passenger Car	27.5	27.5	27.5	27.5	27.5	27.5	27.5	27.5
Light Truck	20.7	20.7	20.6	20.5	20.4	20.2	20.2	20
Heavy Truck	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
Bus	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2

Meanwhile, since the passenger car and light truck fuel economies provided are tested under ideal conditions, a fuel economy reduction factor “ α ” was introduced to adjust the MPG values reported in USDOT’s report. The value of α was estimated according to the rule of thumb that states vehicles reach their ideal fuel economy at 55 mph. The α table is presented as Table 4:

Table 4: Fuel economy reduction factor table

MPH	35	40	45	50	55	60	65	70	75
Value	0.81	0.85	0.93	0.97	1	0.97	0.93	0.85	0.81

The modified fuel economy matrix $[F]$ was determined by multiplying fuel economy reduction factor α and USDOT fuel economy matrix under a certain average traffic flow speed for the study. Determination of average traffic flow speed value was described previously in the travel time savings analysis section using Akçelik speed-v/c ratio equation.

3.4.4. EQUIVALENT EXISTING TRAFFIC ENERGY CONSUMPTION ESTIMATION

The overall equivalent existing traffic energy consumption (Q) can be estimated using the equation presented below:

$$Q = \text{Volume} * \text{number of lanes} * \text{analyzed period} * \begin{bmatrix} \frac{T_{1,1}A_{1,1}}{F_{1,1}} & \frac{T_{1,1}A_{1,2}}{F_{1,2}} & \dots & \frac{T_{1,1}A_{1,24}}{F_{1,24}} \\ \frac{T_{2,1}A_{2,1}}{F_{2,1}} & \frac{T_{2,1}A_{2,2}}{F_{2,2}} & \dots & \frac{T_{2,1}A_{2,24}}{F_{2,24}} \\ \frac{T_{3,1}A_{3,1}}{F_{3,1}} & \frac{T_{3,1}A_{3,2}}{F_{3,2}} & \dots & \frac{T_{3,1}A_{3,24}}{F_{3,24}} \\ \frac{T_{4,1}A_{4,1}}{F_{4,1}} & \frac{T_{4,1}A_{4,2}}{F_{4,2}} & \dots & \frac{T_{4,1}A_{4,24}}{F_{4,24}} \end{bmatrix}$$

The challenges in this approach lie in determining the existing vehicle type and age distribution. In cases where on-site inspection is not applicable, a default database from software, for example MOVES, can be used to perform the estimation. Next step is to calculate the average fuel economy for different passenger car percentages ranging from 60% to 100% (excluding heavy duty trucks and buses). The results are presented in the following Table 5.

Table 5: Average on-the-road fuel economy for different passenger car percentages

Average Fuel Economy (gpm)		Fuel Economy Reduction Factor				
		0.81	0.85	0.93	0.97	1.00
Passenger Car Percentage	100%	0.04260	0.04060	0.03711	0.03558	0.03451
	95%	0.04314	0.04111	0.03757	0.03602	0.03494
	90%	0.04368	0.04162	0.03804	0.03647	0.03538
	85%	0.04421	0.04213	0.03851	0.03692	0.03581
	80%	0.04475	0.04265	0.03898	0.03737	0.03625
	75%	0.04529	0.04316	0.03945	0.03782	0.03668
	70%	0.04583	0.04367	0.03991	0.03827	0.03712
	65%	0.04636	0.04418	0.04038	0.03872	0.03756
60%	0.04690	0.04469	0.04085	0.03917	0.03799	

3.4.5. ENERGY CONSUMPTION REDUCTION BENEFITS ESTIMATION AND VALUATION

The historical data and long-term predictions for motor gasoline prices provided by U.S. Energy Information Administration (U.S. Energy Information Administration, 2016) (trend shown with the reference line) are used to evaluate the benefits that can be achieved

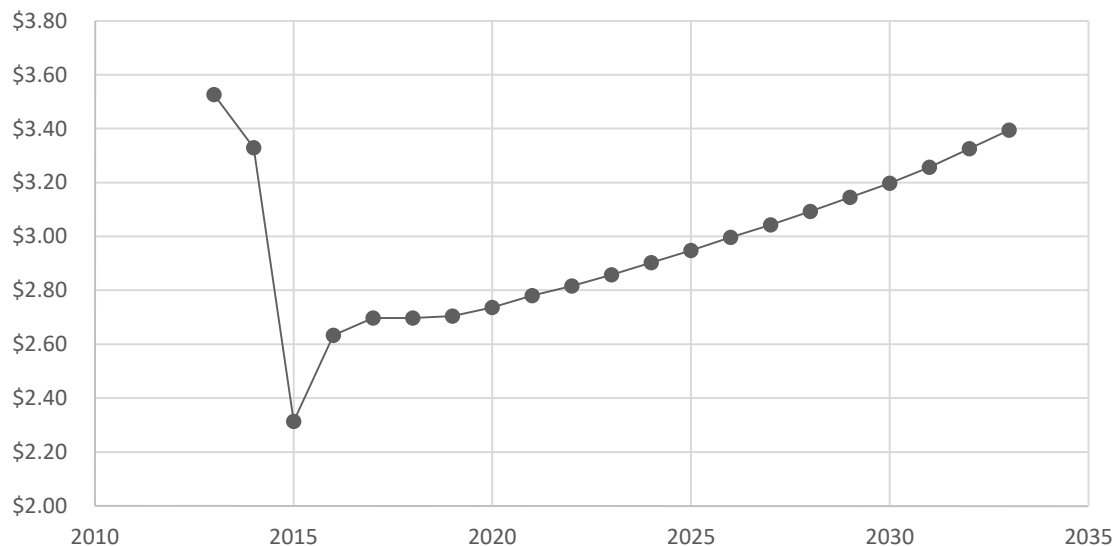


Figure 8: Historical Data and Long-term Predictions for Motor Gasoline Prices (U.S. EIA 2016)

through reductions in energy consumption. Figure 8 below presents the linear equation obtained by analyzing the historical fuel price changes in the recent 20 years.

A fuel consumption reduction factor is estimated for given ATCS and RMS deployment and the annual reduction in fuel consumption (in gallons) is multiplied by the estimated price of the fuel in each year. In order to find the present worth of the total fuel consumption savings, each yearly savings value is multiplied by the corresponding discount factor.

3.5. LCA OF REDUCED ENERGY

3.5.1. LCA METHODS OVERVIEW

LCA is a methodology that is used to estimate and understand the environmental impacts of a product. Just as its name implies, each phase of the life cycle, from material extraction to end-of-life disposition, is ideally included in the assessment. Generally, there are three

different approaches to conducting an LCA: (1) process LCA; (2) EIO-LCA; and (3) hybrid LCA, which is a combination of the first two approaches. Each of these three approaches has been discussed in the literature review section. In the following sections we will focus on the LCA tools available on the market.

3.5.2. LCA TOOLS REVIEW

Several LCA Tools were considered during the methodology development stage. The list includes CMU EIO-LCA Online Tool, Open LCA, and GaBi 6. All of these candidates' applicability is examined and the results are presented in the following content.

3.5.2.1. CMU EIO-LCA

CMU EIO-LCA is a free online LCA tool developed by Carnegie Mellon University. CMU EIO-LCA Online Tool is an "academic-oriented" software that is designed with the EIO-LCA concept, which divided the whole U.S. economic market into 428 sectors and formed a 428 by 428 requirements matrix. Due to the limitation in evaluating specific products, in this case the reduced fuel consumption value, this tool was eliminated during the preliminary development stage.

3.5.2.2. OpenLCA

The OpenLCA project is an open source LCA software supported by PRe Consultants and PE International GmbH since 2007. As a process-LCA tool, OpenLCA has the ability of evaluating life cycle environmental impacts on specific products. However, due to its challenging user interface and insufficient database support for this study, OpenLCA is not selected.

3.5.2.3. GaBi 6

GaBi 6, a large-scale commercial LCA software, has been widely used by over 10000 users including Fortune 500 companies (pe-international, 2014), leading industry associations and innovative small and medium enterprises. GaBi is introduced into the project mainly due to

its 1) sufficient LCA database and inventory; 2) rapid upgrade pace and strong technical support; 3) friendly user interface; and 4) reliable LCA results.

3.5.3. LCA MODELING

GaBi 6 was introduced into the project to evaluate the comprehensive environmental benefits of energy consumption reduction due to ATCS and RMS deployment. The Model, presented in Figure 9, was built to calculate the cradle-to-grave environmental impacts of combusted gasoline on the road.

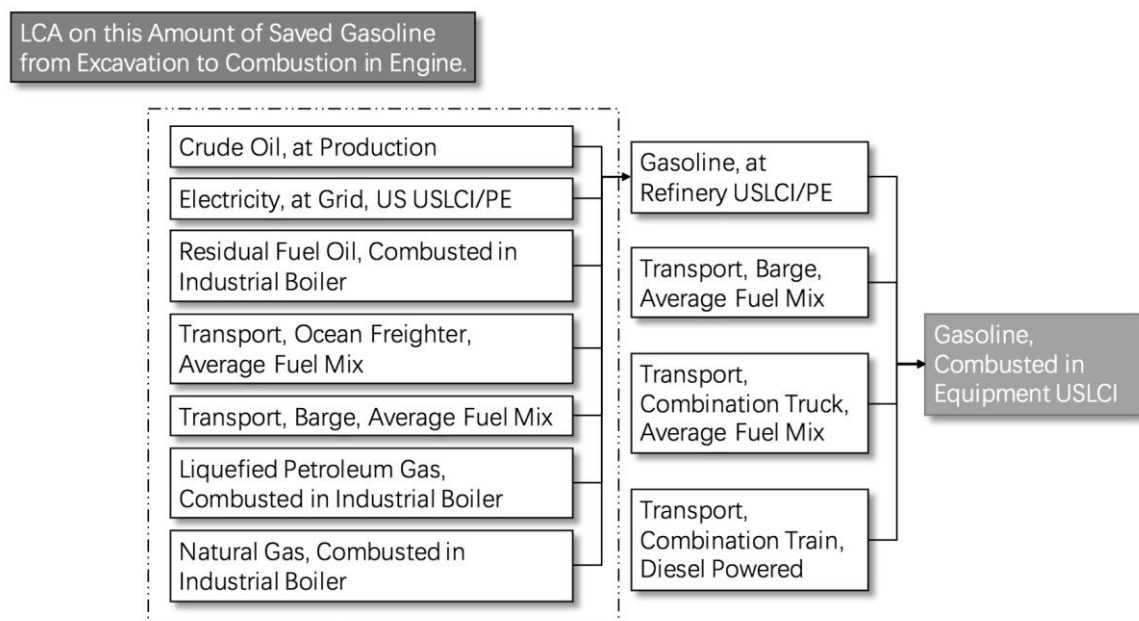


Figure 9: I/O flows for gasoline combusted in equipment.

The input and output flows are summarized below:

- Inputs Parameter Flow:
 - Gasoline (regular) [Refinery Products]
 - Amount: 735kg
 - US: Transport, barge, average fuel mix
 - Amount: $2.84 \cdot 10^4$ kgkm
 - US: Transport, combination truck, average fuel mix
 - Amount: $5.25 \cdot 10^3$ kgkm
 - US: Transport, train, diesel powered

- Amount: 3.36 10³ kgkm
 - Output Parameter Flow:
 - Gasoline, combusted in equipment
 - Amount: 1m³

Considering the cubic meter to US gallon conversion rate as 264.172 US gal/m³, Table 6 below shows all the air emissions per gallon of combusted gasoline calculated using the GaBi model:

Table 6: GaBi LCA Result of Air Emissions per Gallon of Combusted Gasoline.

EMISSIONS/GALLON OF GASOLINE	AMOUNT (KG)	%
Carbon Dioxide	9.084	92.77%
Carbon Monoxide	0.556	5.68%
Nitrogen Oxides	0.136	1.39%
Sulphur Dioxide	0.016	0.16%

From the table above we can see that Carbon Dioxide and Carbon Monoxide account for over 98% of the total emissions. The life cycle carbon dioxide emission per gallon of combusted gasoline was calculated as 9.08 kilogram. Due to the minor amount of Nitrous Oxide and Sulphur Dioxide in the results, the 9.08 kg/gallon can be considered as the amount of GWP emission to the air.

3.5.4. GWP PRICING PREDICTION

The 2013 Carbon Dioxide Price Forecast (Luckow, et al., 2013) developed low, medium, and high case forecast for CO₂ prices from 2013 to 2040. The prediction is based on comprehensive reviews on historical data, and existing models. The Synapse 2013 CO₂ price Trajectories are cited in Figure 11 below:

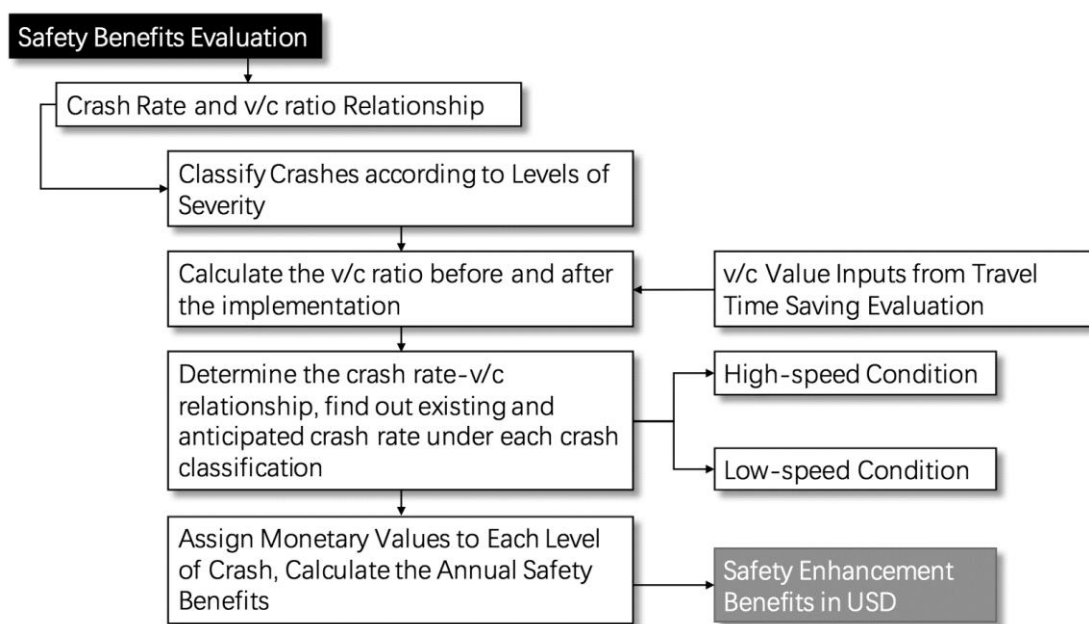


Figure 10: Methodology flowchart of Safety Benefits Evaluation

The mid case price was selected to monetize the reduced fuel consumption due to ATCS and RMS deployment.

3.6. SAFETY BENEFIT EVALUATION

As the third component in the TBL approach, safety enhancements contribute to the social benefits of ATCS and RMS deployment. A proper ITS deployment maximizes the performance of the existing link segment by increasing the link capacity, which reduces the v/c ratio under the same traffic demand, then directly influences the on-the-road safety issues. The

methodology of estimating and evaluating safety benefits is presented in this section. The methodology flowchart (Figure 10) is presented as follow:

3.6.1. CRASH RATE AND V/C RATIO RELATIONSHIP

In this project, the procedure of estimating and evaluating safety benefits due to ATCS and RMS deployment is concluded as follows:

- 1st Step – Classify crashes according to their levels of severity.
- 2nd Step – Calculate the v/c ratios before and after the ATCS implementation.
- 3rd Step – Determine the crash rate – v/c ratio relationship, and find out the existing and anticipated crash rate under each crash classification.
- 4th Step – Assign monetary values to each level of crash, and calculate the annual safety benefits.

One of the most commonly used methods to classify traffic crashes is according to the consequences of the crash. According to NHTSA (National Highway Traffic Safety Administration), crashes are categorized into crashes that result in fatality, injury, and PDO (Property Damage Only). FHWA's TOPS-BC tool adopted NHTSA's classification and crash rate – v/c ratio relationship into the safety benefit calculations. Figure 12 below was derived from the NHTSA's crash rate estimation table, and TOPS-BC's built-in database.

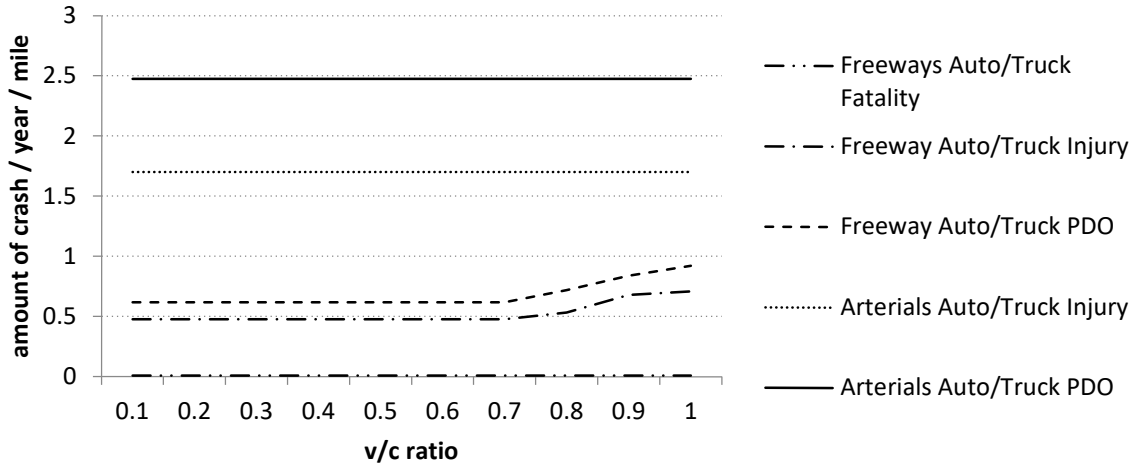


Figure 12: The amount of crash to v/c ratio relationship curves derived from NHTSA's crash rate estimation table.

From the diagram (Figure 12) above, we may find that only freeway auto/truck injury and PDO crash rates change with increasing levels of traffic demand, while the rest of the crash types remain constant under conditions that range from zero saturated to saturated traffic conditions. The curves used by TOPS-BC were deemed not representing the expected relationship between crash rate and traffic density. In fact, traffic flow characteristics such as traffic volume, vehicle density, and the v/c ratio have a direct influence on the likelihood and severity of a crash (Lord, Manar, & Vizioli, 2005). In this paper, the relationship between crash rate and v/c ratio was given as:

$$\mu = \beta_0 L F e^{(\beta_1 X)}$$

Where, μ is the estimated number of crashes per year; L is the length of analyzed link segment; F is the hourly traffic volume; X is the v/c ratio; and β_0, β_1 are the coefficients to be estimated. The crash rate-v/c ratio relationship obtained from the above equation is shown below (Figure 13):

Figure 13 illustrates the relationship between crash rate and traffic density under rural and urban conditions. The black, red and blue dotted lines represent single vehicle (SV), multi

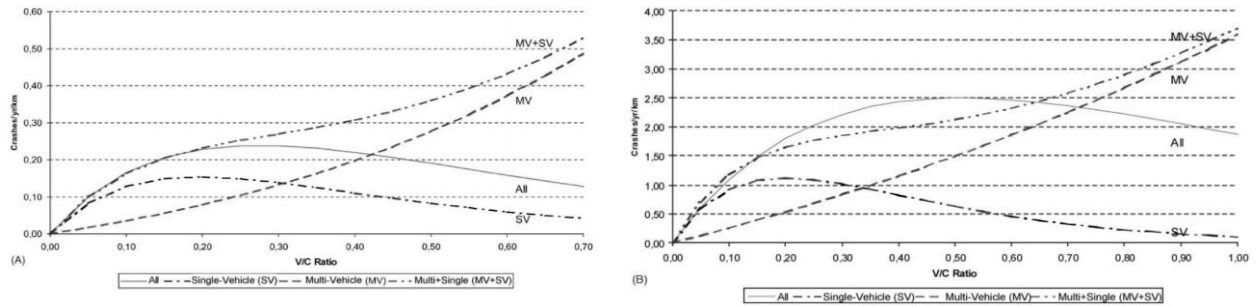


Figure 13: Crash Rate to Traffic Density Relationship Under Rural and Urban Conditions (Lord, Manar, & Vizioli, 2005).

vehicle (MV) and multi + single (SV + MV), respectively. The green dotted line represents all vehicles. The x and y axis stands for v/c ratio and amount of crash / year / mile. It is worth noting from the diagram that the curves representing the sum of single and multi-vehicle crashes for both the rural and urban segments indicate that an approximately linear relationship exists between crashes and v/c ratio. The following exponential equations were then derived by curve-fitting procedures for the two MV+SV curves given above:

$$\mu(Rural) = 8.23 \times 10^{-5} \cdot L \cdot V \cdot e^{(1.05x)}$$

$$\mu(Urban) = 6.25 \times 10^{-4} \cdot L \cdot V \cdot e^{(0.37x)}$$

The pre-ATCS existing v/c ratio and after-ATCS optimized v/c ratio are then substituted into above equation to calculate the total number of crashes on the analyzed segment per year*.

*Above exponential equations that derived by curve-fitting procedures are generated for mid to high speed traffic conditions, which do not include low speed traffic scenarios, for example, urban roadway segment approaching the traffic intersection. In this research, the equation for mid speed traffic condition is used to evaluate the safety benefits. As a result, the final result of safety benefit for ATCS deployment is exaggerated. Although the safety benefit takes the smallest share of the overall benefits pie (Figure 23: Life cycle benefits distribution.), which somehow minimize the inaccurate impacts to the final outputs. See Section 6.2.2 Low-speed Traffic Condition Safety Benefit Analysis for detailed description.

3.6.2. CRASH COST VALUATION

Commonly, on-the-road crashes are categorized into crashes with fatality, injury, and PDO (Property Damage Only). Another popular crash scale system is KABCO severity scale, which is used by the police officers on the scene to classify injury severity. Five categories are classified in this scale system, which are: K (Killed), A (Disabling Injury), B (Evident Injury), C (Possible Injury), and O (No Apparent Injury). A comprehensive report (U.S. Department of Transportation, 2005) on crash cost estimation using KABCO system has been published by USDOT in the year 2005. In this report, crash related costs have been divided into medical costs, emergency services costs, property damage costs, and lost productivity cost. Crashes were categorized into levels between 1 and 6 according to their severity level. The data were collected from a large number of crash observations and records. The results were presented according to different crash severity levels (level 1, 2), and each crash geometry (for example, single vehicle struck human at intersection) under each severity level. Similarly, by analyzing over 4000 crashes and collecting data on rural and urban conditions, Lord, Manar, and Vizioli (Lord, Manar, & Vizioli, 2005) determined the proportion of fatal and severe crashes to the total number of cases. Based on existing studies, the fatal and severe crash rate is defined as 4% and 1% for rural and urban conditions, respectively.

The monetary value of each crash severity level varies dramatically. A comprehensive crash cost list based on crash type, traffic condition, and with or without speed limits were given in the 2005 report (Lord, Manar, & Vizioli, 2005). In 2011, based on its collected data, auto club AAA estimated an average \$6 million per fatal accident (Copeland, 2011), and \$126,000 per injury-only accident. Both of these numbers doubled since 2005. In TOPS-BC tool, costs for different levels of crashes were set as follows: \$6.5 million for fatality level, \$67,000 for injury

level, and \$2,300 for PDO level. In this study, to eliminate uncertainties, only the top-level crash severity – crashes involving fatalities – is considered in the cost calculations. The cost per fatality crash is assumed as \$7 million.

Chapter 4. FRAMEWORK DEMONSTRATION

4.1. INTRODUCTION

In this work of dissertation, Hypothetical case studies are used to demonstrate the utilization of the framework to calculate the Benefit / Cost Ratio (BCR) of typical ATCS and RMS deployment. Hypothetical case studies feature the following general traffic condition related characteristics (Table 7):

Table 7: General Traffic Condition Related Characteristics for Hypothetical Case Studies.

<i>CHARACTERISTICS</i>	<i>ATCS</i>	<i>RMS</i>
<i>Length of the freeway segment</i>	1 mile	10 miles
<i>Length of the ramp segment</i>	N/A	0.2 mile
<i>Number of lanes on the freeway</i>	2	2
<i>Number of metered ramps</i>	N/A	1

4.2. LIFE CYCLE COST ANALYSIS

Based on the collected information a service life of 20 years is assumed for the ATCS deployment with the following costs: Infrastructure cost: \$28,725; incremental cost items: Signal controller = \$6,250 (service life of 20 years), Loop detectors = \$11,000 (every 5 years), Communication lines = \$750 (service life of 20 years); and Annual O&M cost: \$9,000.

Table 8: Life Cycle Cost Breakdown for Typical ATCS Deployment.

Year	Infrastructure Costs (F)	Infrastructure Cost (P)	O&M Cost (F)	O&M Cost (P)	Incremental Costs (A)	Incremental Costs (P)	Total Annual Cost (F)	Total Annual Cost (P)
2013	\$28,725	\$28,725	\$0*	\$0	\$18,750	\$18,750	\$47,475	\$47,475
2014	\$0	\$0	\$9,000	\$8,411	\$0	\$0	\$9,000	\$8,411
2015	\$0	\$0	\$9,000	\$7,861	\$0	\$0	\$9,000	\$7,861
2016	\$0	\$0	\$9,000	\$7,347	\$0	\$0	\$9,000	\$7,347
2017	\$0	\$0	\$9,000	\$6,866	\$0	\$0	\$9,000	\$6,866
2018	\$0	\$0	\$9,000	\$6,417	\$11,750	\$8,378	\$20,750	\$14,794
2019	\$0	\$0	\$9,000	\$5,997	\$0	\$0	\$9,000	\$5,997
2020	\$0	\$0	\$9,000	\$5,605	\$0	\$0	\$9,000	\$5,605
2021	\$0	\$0	\$9,000	\$5,238	\$0	\$0	\$9,000	\$5,238
2022	\$0	\$0	\$9,000	\$4,895	\$0	\$0	\$9,000	\$4,895
2023	\$0	\$0	\$9,000	\$4,575	\$11,750	\$5,973	\$20,750	\$10,548
2024	\$0	\$0	\$9,000	\$4,276	\$0	\$0	\$9,000	\$4,276
2025	\$0	\$0	\$9,000	\$3,996	\$0	\$0	\$9,000	\$3,996
2026	\$0	\$0	\$9,000	\$3,735	\$0	\$0	\$9,000	\$3,735
2027	\$0	\$0	\$9,000	\$3,490	\$0	\$0	\$9,000	\$3,490
2028	\$28,725**	\$10,411	\$9,000	\$4,284	\$18,000	\$6,524	\$55,725	\$20,197
2029	\$0	\$0	\$9,000	\$3,049	\$0	\$0	\$9,000	\$3,049
2030	\$0	\$0	\$9,000	\$2,849	\$0	\$0	\$9,000	\$2,849
2031	\$0	\$0	\$9,000	\$2,663	\$0	\$0	\$9,000	\$2,663
2032	\$0	\$0	\$9,000	\$2,489	\$0	\$0	\$9,000	\$2,489
2033	\$0	\$0	\$9,000	\$2,326	\$0***	\$0	\$9,000	\$2,326
TOTAL PV								\$174,107

Using these cost figures, the total present worth of the life cycle costs for a typical ATCS deployment is determined as around \$175,000 (Table 8).

A similar cost setup for RMS deployment during a 20 years' service life with the following cost breakdown: Infrastructure cost: \$130,000 to be renewed every five years (8); incremental

cost items: Ramp meter = \$88,000 (service life of 20 years), Loop detectors = \$11,000 (service life of 20 years), Communication lines = \$750 (service life of 20 years); and Annual O&M cost: \$25,000. The total present worth of the life cycle costs for a typical RMS deployment is determined as around \$700,000 (Table 9).

Table 9: Life Cycle Cost Breakdown for Typical RMS Deployment.

Year	Infrastructure Costs (F)	Infrastructure Cost (P)	Incremental Costs (A/P)	O&M Costs (F)	O&M Costs (P)	Total Annual Cost (F)	Total Annual Cost (P)
2013	\$130,000	\$130,000	\$99,750	\$0*	\$0	\$229,750	\$229,750
2014	\$0	\$0	\$0	\$25,000	\$23,364	\$25,000	\$23,364
2015	\$0	\$0	\$0	\$25,000	\$21,836	\$25,000	\$21,836
2016	\$0	\$0	\$0	\$25,000	\$20,407	\$25,000	\$20,407
2017	\$0	\$0	\$0	\$25,000	\$19,072	\$25,000	\$19,072
2018	\$130,000.	\$92,688	\$0	\$25,000	\$17,825	\$155,000	\$110,513
2019	\$0	\$0	\$0	\$25,000	\$16,659	\$25,000	\$16,659
2020	\$0	\$0	\$0	\$25,000	\$15,569	\$25,000	\$15,569
2021	\$0	\$0	\$0	\$25,000	\$14,550	\$25,000	\$14,550
2022	\$0	\$0	\$0	\$25,000	\$13,598	\$25,000	\$13,598
2023	\$130,000	\$66,085	\$0	\$25,000	\$12,709	\$155,000	\$78,794
2024	\$0	\$0	\$0	\$25,000	\$11,877	\$25,000	\$11,877
2025	\$0	\$0	\$0	\$25,000	\$11,100	\$25,000	\$11,100
2026	\$0	\$0	\$0	\$25,000	\$10,374	\$25,000	\$10,374
2027	\$0	\$0	\$0	\$25,000	\$9,695	\$25,000	\$9,695
2028	\$130,000	\$47,118	\$0	\$25,000	\$9,061	\$155,000.00	\$56,179
2029	\$0	\$0	\$0	\$25,000	\$8,468	\$25,000	\$8,468
2030	\$0	\$0	\$0	\$25,000	\$7,914	\$25,000	\$7,914
2031	\$0	\$0	\$0	\$25,000	\$7,397	\$25,000	\$7,397
2032	\$0	\$0	\$0	\$25,000	\$6,913	\$25,000	\$6,913
2033	\$0**	\$0	\$0	\$25,000	\$6,460	\$25,000	\$6,460
TOTAL PV							\$700,492

**Since the "end of time" convention is used in the analysis, the O&M cost for year 0 (2013) is not taken into calculation.*

***According to the FHWA TOPS-BC tools, a new cycle of infrastructure deployment is required at year 15. Due to its small effect in comparison to the result of entire life cycle analysis, the salvage value of the second life cycle of infrastructure deployment is ignored.*

****Since a 20-year life-cycle is considered in the analysis, the incremental cost that would occur if a new life-cycle was initiated is not considered.*

4.3. ANALYSIS OF BENEFITS ACHIEVED THROUGH TRAVEL TIME SAVINGS

4.3.1. TRAVEL TIME SAVINGS

The travel time savings benefits analysis followed the methodology described in the previous chapter. The recurring and nonrecurring travel time savings were calculated separately and combined at the end. Dollar value was assigned to the saved travel time per hour per vehicle.

4.3.1.1. Hypothetical Case Study Overview

The recurring travel-time savings benefits of ATCS and RMS deployment cases all around the country were examined. The achieved percentage of recurring travel time savings varies widely according to the location of deployment, as well as the sophistication of the algorithm used (Preset timing, adaptive signal etc.). Reported travel time savings vary from 8% to 25% (U.S. Department of Transportation, 2001) from coast to coast. Under these conditions, estimating travel time savings based on observed link capacity and demand values will lead to more reasonable results, in comparison to using a national average travel time savings factor. The method discussed previously in the methodology section was used to estimate and evaluate travel time savings benefits. In this section, a hypothetical case study is examined to estimate the travel time savings benefits for a typical highway segment before and after ATCS deployment. The basic infrastructure and traffic information are summarized below. The 35 mph free flow speed is assumed based on the average speed limits collected by the NYS

Traffic Data Viewer database (gis3.dot.ny.gov). In this hypothetical intersection scenario, only one segment (the main segment, say Northbound-Southbound) is described below. We introduced a factor k to simplify the evaluation of the enlarged traffic capacity caused by ATCS implementation on both segments. The ideal case would be achieving the same benefits in the other segment as the main segment, which would indicate that the result will be doubled ($k=2.0$). The worst case would be observing no improvements in the other segment after the ATCS implementation, which implies a k factor equal to 1.0. As a result, the result for both segments at the intersection will have a value ranging from 1.0 to 2.0 times the calculated result.

As in the analysis for ATCS, the time savings estimation for RMS deployment was undertaken using the link capacity and demand, rather than by using a national average travel time savings factor. The 2-cycle method discussed previously in the methodology section is used to quantify travel time savings benefits. In this section, a hypothetical case study is developed to estimate the travel time savings benefits for a typical freeway segment after ramp metering deployment. The basic infrastructure and traffic information are summarized as follows. The 55 mph free flow speed is according to the rule of thumb (HCM 2000/2010) that states calculated FFS should be 10 to 15 mph lower than the nominated speed limit, which ranges from 65 to 70 mph for most areas of the United States.

Table 10 below concludes our hypothetical on-the-road characteristics setup for both RMS and ATCS deployment.

Table 10: General Traffic Demand Characteristics for Hypothetical Case Studies

CHARACTERISTICS	ATCS	RMS
<i>Free Flow Speed (FFS) for the freeway segment</i>	35 mph	55 mph
<i>Average ramp Free Flow Speed (RFFS)</i>	35 mph	35 mph
<i>Freeway link capacity per lane</i>	2000 vph / lane	2000 vph / lane
<i>Ramp link capacity</i>	N/A	2000 vph
<i>Traffic demand on the freeway segment</i>	1000 vph / lane	1000 vph / lane
<i>Traffic demand on the ramp</i>	N/A	1000 vph
<i>Estimated link capacity multiplication factor for the freeway segment</i>	8% to 12%	8% to 12%

Above characteristics are also used to examine the travel time savings benefits estimation in this section, and the energy consumption reduction estimation, and safety estimation in the following sections.

4.3.1.2. Recurring Travel Time Saving Estimation

We assumed v/c ratio values ranging from 0.1 (400/4000 vph) to 1.0 (4000/4000 vph) in 200 vph increments. Akçelik speed-v/c ratio equation is introduced to draw the speed curve under each selected traffic demand. Figure 14 below (showing the relationship between speed and traffic demand) exhibits the existing traffic flow average speed before the ATCS deployment (similar for RMS deployment) under different levels of congestion (from not congested to extremely congested).

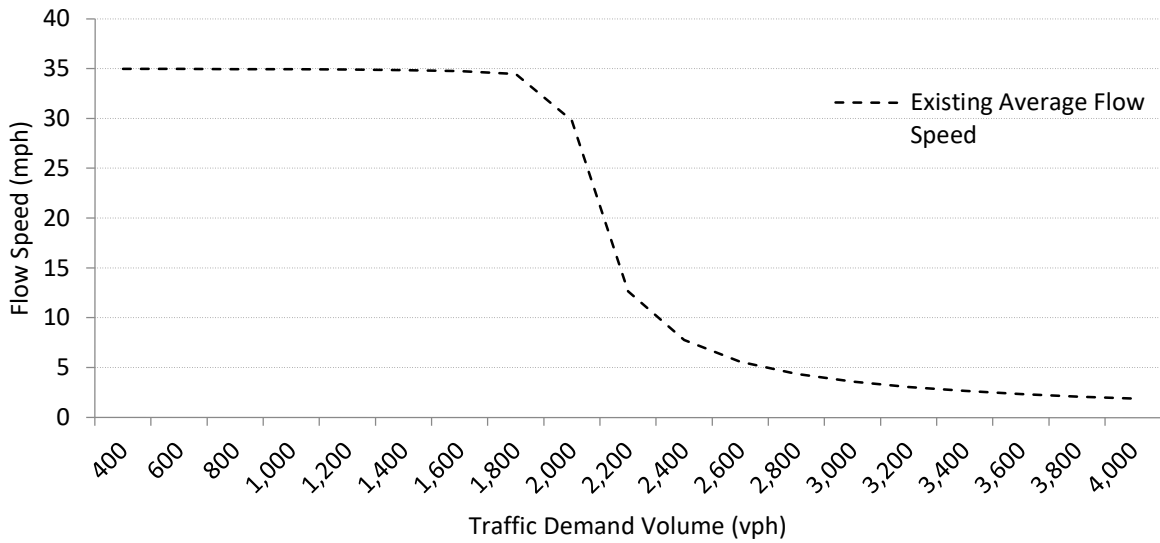


Figure 14: Speed and traffic demand relationship before ATCS deployment under different levels of congestion.

A range of link capacity multiplication factors from 8% to 12% is then introduced into the estimation to represent the scenario after ATCS deployment (also apply to RMS). Figure 15 illustrates the change of average flow speed due to enlarged link capacity and reduced v/c ratio under same traffic demand.

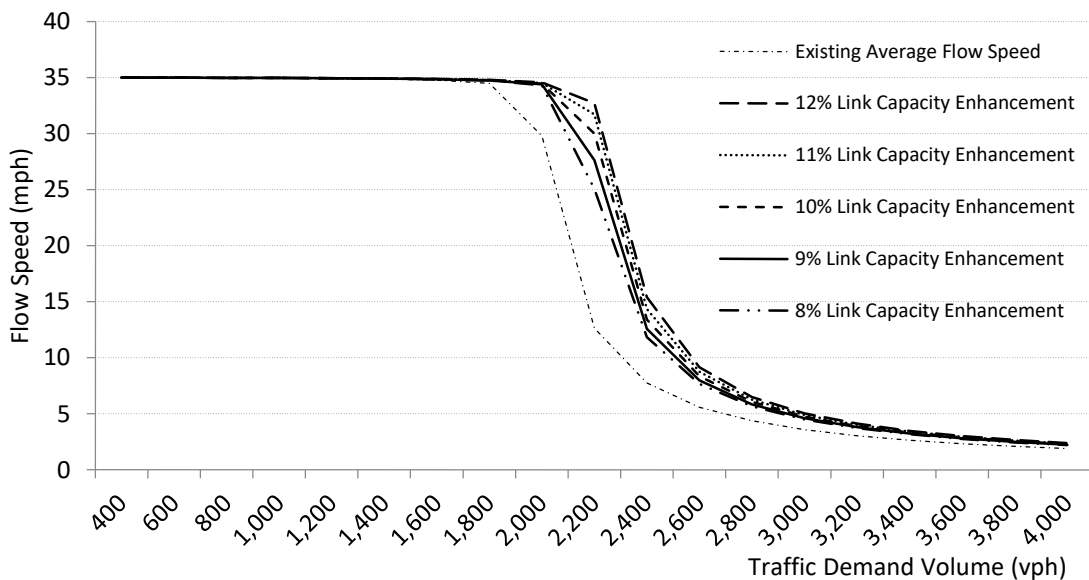


Figure 15: The change of average flow speed due to enlarged link capacity and reduced v/c ratio under same traffic demand.

It is interesting to note from the diagram that the enlarged link capacity “postpones” the saturation point of the current traffic. For example, if ATCS deployment increases the link capacity by 8%, under 2000 vph traffic demand, the enlarged v/c ratio is 0.46

($2000/(4000*1.08)$), while the traffic without ATCS deployment has already reached a v/c ratio of 0.5.

On the other hand, we can observe a dramatic speed drop after the v/c ratio reaches to a value around 0.4. This is because Akçelik speed-flow model highlights the impacts from traffic queuing as congestion is increased. Therefore, we may consider the traffic flow is insensitive to ATCS deployment in undersaturated traffic conditions, which will be considered as a very important factor in decision-making.

Table 11 concludes the detailed process of recurring travel time savings calculation with a value of 12% for the link capacity multiplication factor taken into consideration. It could be observed from the table that the recurring travel time savings due to increased link capacity are not obvious until the threshold is reached.

Table 11: Travel Time Saving Calculation with A 12% Link Capacity Multiplication Factor.

Traffic Demand Volume (vph)	0	400	600	800	1000	1200	1400	1600	1800	2000
Existing Link capacity (vph)	-	4000	4000	4000	4000	4000	4000	4000	4000	4000
Enhanced Link Capacity (vph)	-	4480	4480	4480	4480	4480	4480	4480	4480	4480
Existing v/c ratio	-	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
Enhanced v/c ratio	-	0.09	0.14	0.18	0.23	0.27	0.32	0.36	0.40	0.45
Existing Travel Time per vehicle (hr)	-	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Existing Vehicle Speed (mph)	-	34.98	34.97	34.96	34.94	34.91	34.86	34.76	34.46	29.79
Existing Speed/FFS ratio	-	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.85
Existing VHT (hr)	-	11.43	17.16	22.88	28.62	34.38	40.16	46.03	52.23	67.14
Enhanced Travel Time per vehicle (hr)	-	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Enhanced Vehicle Speed (mph)	-	34.99	34.98	34.97	34.96	34.94	34.91	34.86	34.78	34.55
Enhanced Speed/FFS ratio	-	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99
Enhanced VHT (hr)	-	11.43	17.15	22.88	28.61	34.35	40.10	45.89	51.76	57.88
Difference in Travel Time per Vehicle (hr)	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Difference in VHT (hr)	-	0.00	0.00	0.01	0.01	0.03	0.06	0.14	0.47	9.26
Traffic Demand Volume (vph)	2200	2400	2600	2800	3000	3200	3400	3600	3800	4000
Existing Link capacity (vph)	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
Enhanced Link Capacity (vph)	4480	4480	4480	4480	4480	4480	4480	4480	4480	4480
Existing v/c ratio	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Enhanced v/c ratio	0.49	0.54	0.58	0.63	0.67	0.72	0.76	0.80	0.85	0.90
Existing Travel Time per vehicle (hr)	0.08	0.13	0.18	0.23	0.28	0.33	0.38	0.43	0.48	0.53
Existing Vehicle Speed (mph)	12.64	7.76	5.60	4.37	3.59	3.04	2.64	2.33	2.09	1.89
Existing Speed/FFS ratio	0.36	0.22	0.16	0.13	0.10	0.09	0.08	0.07	0.06	0.05
Existing VHT (hr)	174.05	309.29	464.85	640.49	836.16	1051.86	1287.56	1543.26	1818.97	2114.69
Enhanced Travel Time per vehicle (hr)	0.03	0.06	0.11	0.15	0.20	0.24	0.29	0.33	0.38	0.42
Enhanced Vehicle Speed (mph)	32.70	15.40	9.15	6.50	5.04	4.12	3.48	3.01	2.65	2.37
Enhanced Speed/FFS ratio	0.93	0.44	0.26	0.19	0.14	0.12	0.10	0.09	0.08	0.07
Enhanced VHT (hr)	67.27	155.86	284.05	430.62	595.17	777.62	977.94	1196.14	1432.20	1686.12
Difference in Travel Time per Vehicle (hr)	0.05	0.06	0.07	0.07	0.08	0.09	0.09	0.10	0.10	0.11
Difference in VHT (hr)	106.79	152.50	180.80	209.87	240.99	274.24	309.61	347.12	386.77	428.57

Figure 16 illustrates the dramatic trend of travel time reductions under various traffic demand conditions after ATCS deployment.

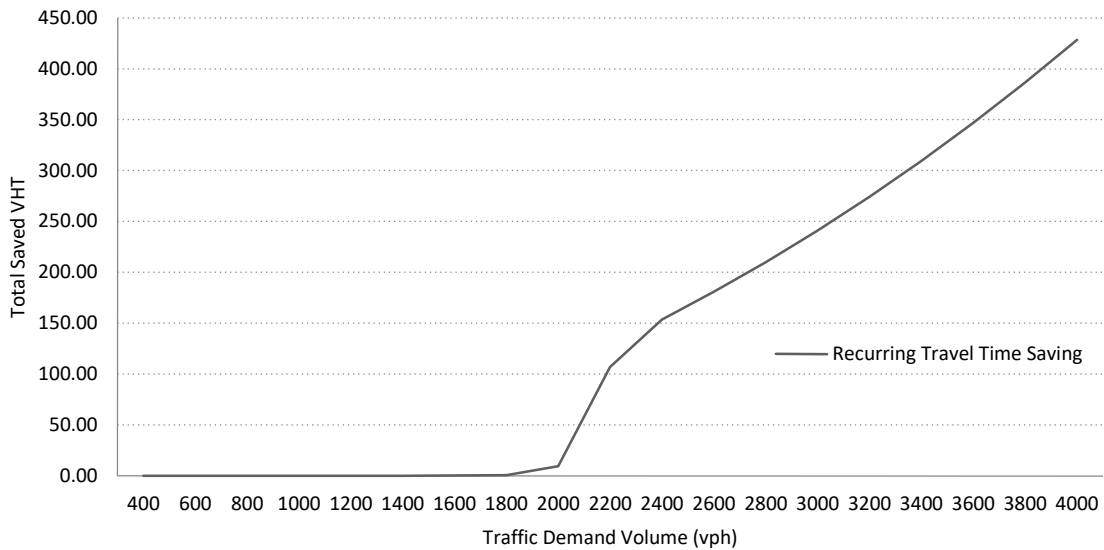


Figure 16: Travel Time Reductions under Various Traffic Demands after ATCS Deployment.

The recurring travel time savings under different v/c ratios were calculated using the above-mentioned methodology and the results are summarized in Table 12 (ATCS). Link capacity multiplication factors ranging from 8% to 12% were used to represent the efficacy of ATCS and RMS deployment from below average, average, to above average. The sensitivity row at the bottom of the table indicates if the travel time saving is sensitive to related traffic demand. It implies that when v/c ratio is smaller than 0.4, the efficacy of deployments on recurring travel time reduction is very limited. However, when the v/c ratio reaches the threshold and continues to increase, the total saved VHT increases dramatically due to the occurrence of queuing effect. Therefore, saturated and oversaturated traffic segments may achieve the maximum benefits through ATCS and RMS deployments.

Table 12: Recurring Travel Time Savings for ATCS Deployment under Different Traffic Demands.

v/c ratio	0.10	~	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.9	0.95	1.0
Travel Time Saving (hr) [12%]	~		0.14	0.47	9.26	106.79	153.43	180.80	209.87	240.99	274.24	309.61	347.12	386.77	428.57	
Travel Time Saving (hr) [11%]	~		0.13	0.46	9.19	104.64	142.00	167.24	194.12	222.90	253.65	286.37	321.06	357.74	396.39	
Travel Time Saving (hr) [10%]	~		0.13	0.44	9.10	100.71	130.33	153.43	178.08	204.48	232.69	262.70	294.53	328.17	363.63	
Travel Time Saving (hr) [09%]	~		0.12	0.41	8.99	94.43	118.43	139.37	161.75	185.73	211.34	238.60	267.51	298.07	330.27	
Travel Time Saving (hr) [08%]	~		0.11	0.39	8.86	86.25	106.28	125.04	145.11	166.62	189.60	214.06	239.99	267.40	296.29	
SENSITIVITY		INSENSITIVE	THRESHOLD				SENSITIVE									

Meanwhile, due to the ramp metering deployment, the capacity of ramp segment is decreased. Table 13 below summarizes the results of recurring travel time savings calculation with negative 12% link capacity multiplication factor (12% was assumed here for being consistent with travel time saving on freeway segment) for the 0.2-mile ramp segment.

Table 13: The Recurring Travel Time Savings on Ramp Segment with -12% Capacity Multiplication Factor.

Traffic Demand (vph)	100	200	300	400	500	600	700	800	900	1000
VHT Differential (hr)	0.00	0.00	0.00	0.00	-0.00	-0.01	-0.02	-0.09	-2.51	-12.39
Traffic Demand (vph)	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000
VHT Differential (hr)	-16.37	-19.58	-23.01	-26.70	-30.66	-34.89	-39.40	-44.17	-49.22	-54.54

The total equivalent recurring travel time savings considering both the freeway and ramp segment is calculated as the sum of the two travel time differentials. The results are presented in Table 14.

Table 14: Total Equivalent Travel Time Savings Considering both the Freeway and Ramp Segments

v/c ratio	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Travel Time Saving (hr) [12%]	0.01	0.04	0.20	1.10	79.34	1512.82	2071.20	2706.90	3426.54	4230.63
Travel Time Saving (hr) [11%]	0.01	0.04	0.19	1.04	78.60	1398.88	1913.79	2501.09	3165.99	3908.93
Travel Time Saving (hr) [10%]	0.01	0.04	0.17	0.97	77.72	1282.47	1753.49	2291.53	2900.71	3581.38
Travel Time Saving (hr) [09%]	0.00	0.03	0.16	0.90	76.65	1163.63	1590.23	2078.12	2630.55	3247.82
Travel Time Saving (hr) [08%]	0.00	0.03	0.14	0.82	75.32	1042.37	1423.93	1860.75	2355.38	2908.08

The v/c ratio for both the freeway segment and the on-ramp is 0.5. Furthermore, it is assumed that the ramp metering deployment results in a capacity enlargement of 10% on the freeway segment, and a capacity reduction of 12% on the on-ramp. These values and

other assumed values are inserted in equation 1 to determine the annual travel time savings in vehicle hours traveled (VHT) for two-hour traffic conditions with $v/c = 0.5$. According to the results, such a ramp metering deployment results in a recurring travel time savings value of around 75 VHT.

4.3.1.3. Nonrecurring Travel Time Savings

The v/c ratio is interpolated from the curve derived from IDAS Travel Time Reliability Lookup Tables (Figure 17) to determine the related incident traffic delay. It should be noted that the nonrecurring travel time savings value was only calculated for the freeway segment (for RMS).

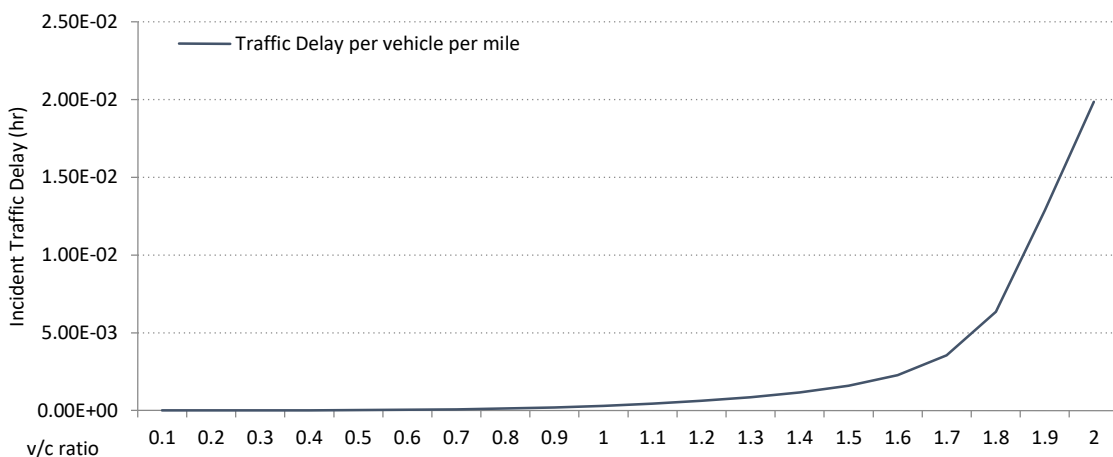


Figure 17: Incident Traffic Delay - V/C Ratio derived from IDAS Travel Time Reliability Lookup Tables (IDAS User's Manual, Appendix B.2.15).

The amount of nonrecurring travel time savings was found to be relatively small in comparison to the recurring travel time savings. According to the "National Summary of the Sources of Congestion" (Cambridge Systematics, Inc.; Texas Transportation Institute, 2004), incident-related nonrecurring traffic delay accounts for approximately 25 percent of all congestion delays and the most substantial proportion of nonrecurring delay sources in most urban areas. Therefore, the importance of nonrecurring travel time savings cannot be

ignored. Due to the unpredictable uncertainties, weather was not considered as a factor in the nonrecurring travel time savings estimation. Table 15 concludes the nonrecurring travel time saving for 1 mile analyzed freeway segment with different link capacity multiplication factors from 8% to 12% under a set of traffic demands.

Table 15: Incident Travel Time Saving with Different Link Capacity Multiplication Factors.

Traffic Demand Volume (vph)	400	800	1200	1600	2000	2400	2800	3200	3600	4000
Incident Travel Time Saving (hr) [12%]	0.00	0.00	0.01	0.06	0.19	0.49	1.14	3.06	14.14	55.22
Incident Travel Time Saving (hr) [11%]	0.00	0.00	0.01	0.05	0.17	0.45	1.05	2.83	13.08	53.57
Incident Travel Time Saving (hr) [10%]	0.00	0.00	0.01	0.05	0.16	0.41	0.96	2.59	12.00	49.14
Incident Travel Time Saving (hr) [09%]	0.00	0.00	0.01	0.04	0.15	0.38	0.88	2.35	10.90	44.63
Incident Travel Time Saving (hr) [08%]	0.00	0.00	0.01	0.04	0.13	0.34	0.79	2.11	9.78	40.04

4.3.1.4. Equivalent Travel Time Savings Estimation and Valuation

Total travel time savings for this ATCS and RMS deployment are presented in Table 16 and Table 17. Assuming a Value of Time (VoT) as \$12 for passenger cars and \$24 for trucks, a traffic composition consisting of 9 passenger cars for every truck, and a Reliability Ratio of 1 (i.e. equal importance of VoT and Value of Reliability (VoR)), meanwhile, considering a service life of 20 years and a discount rate of 7%, the total present worth of the benefits achieved through travel time savings is equal to \$715,786 for ATCS and \$6,191,061 for RMS. When these values are compared with the present worth of life cycle costs, B/C ratios of 4.11:1 for ATCS and 8.84:1 for RMS are found.

Table 16: Equivalent Travel Time Savings for ATCS Study

v/c ratio	0.10	~	0.35	0.40	0.50	0.60	0.70	0.80	0.90	1.00
Equivalent Travel Time Saving (hr) [12%]		~		0.20	9.45	153.92	211.01	277.30	361.26	483.79
Equivalent Travel Time Saving (hr) [11%]		~		0.19	9.36	142.45	195.17	256.48	334.14	449.96
Equivalent Travel Time Saving (hr) [10%]		~		0.17	9.26	130.75	179.04	235.28	306.53	412.77
Equivalent Travel Time Saving (hr) [09%]		~		0.16	9.14	118.80	162.62	213.70	278.41	374.91
Equivalent Travel Time Saving (hr) [08%]		~		0.15	8.99	106.62	145.89	191.71	249.77	336.34
<i>SENSITIVITY</i>			INSENSITIVE	THRESHOLD				SENSITIVE		

Table 17: Equivalent Travel Time Savings for RMS Study

v/c ratio	0.10	~	0.35	0.40	0.50	0.60	0.70	0.80	0.90	1.00
Equivalent Travel Time Saving (hr) [12%]	0	~	0.6	1.7	81.2	1517.7	2082.6	2737.5	3567.9	4782.8
Equivalent Travel Time Saving (hr) [11%]	0	~	0.6	1.5	80.3	1403.4	1924.3	2529.4	3296.8	4444.6
Equivalent Travel Time Saving (hr) [10%]	0	~	0.5	1.5	79.3	1286.6	1763.1	2317.4	3020.7	4072.8
Equivalent Travel Time Saving (hr) [09%]	0	~	0.5	1.3	78.2	1167.4	1599.0	2101.6	2739.6	3694.1
Equivalent Travel Time Saving (hr) [08%]	0	~	0.4	1.2	76.6	1045.8	1431.8	1881.9	2453.2	3308.5
<i>SENSITIVITY</i>			INSENSITIVE	THRESHOLD				SENSITIVE		

4.4. ANALYSIS OF BENEFITS ACHIEVED THROUGH REDUCTIONS IN ENERGY CONSUMPTION

4.4.1. VEHICLE TYPE, AGE, AND FUEL ECONOMY DISTRIBUTIONS

A traffic composition, which has a passenger car to truck ratio of 9:1, was assumed in the demonstration. The decision of removing heavy-duty truck from the composition was made due to the current trend of switching to off-peak delivery times to reduce city congestion. Several studies have pointed out the potential benefits of banning heavy-duty truck during peak-hour for more efficient transportation (KTH the Royal Institute of Technology, 2017). The vehicle age distribution matrix was prepared by analyzing the MOVES built-in database. The resultant vehicle type, and age values for a traffic demand of 2000 vph is provided in Figure 18.

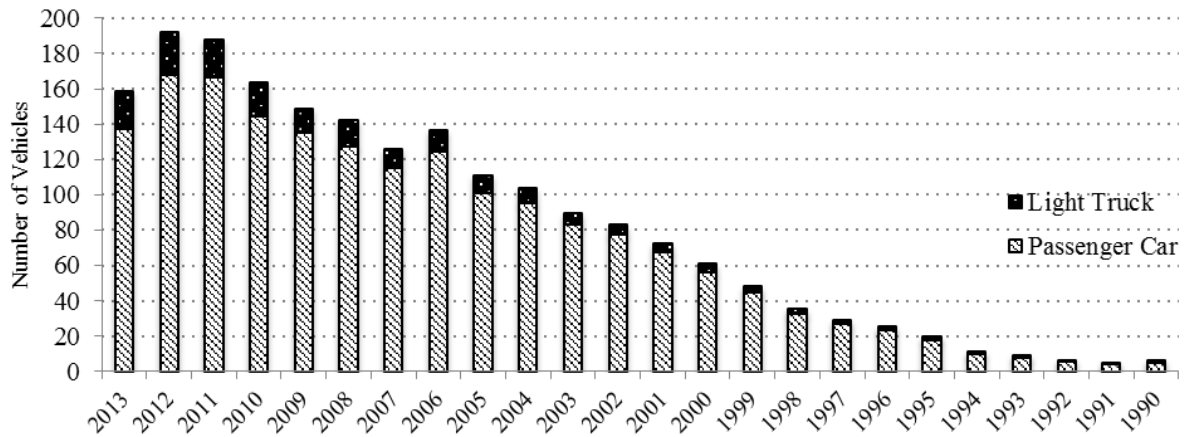


Figure 18: Vehicle Type and Age Distribution.

Under the given traffic conditions, the free flow speed drops from 55 mph down to approximately 43 mph based on Akçelik speed-flow equation. The fuel economy matrix $[F]$ is then modified according to the fuel economy reduction factor, which is approximately 0.89. Figure 19 presents the modified fuel economy values for different vehicle types and vehicle model years.

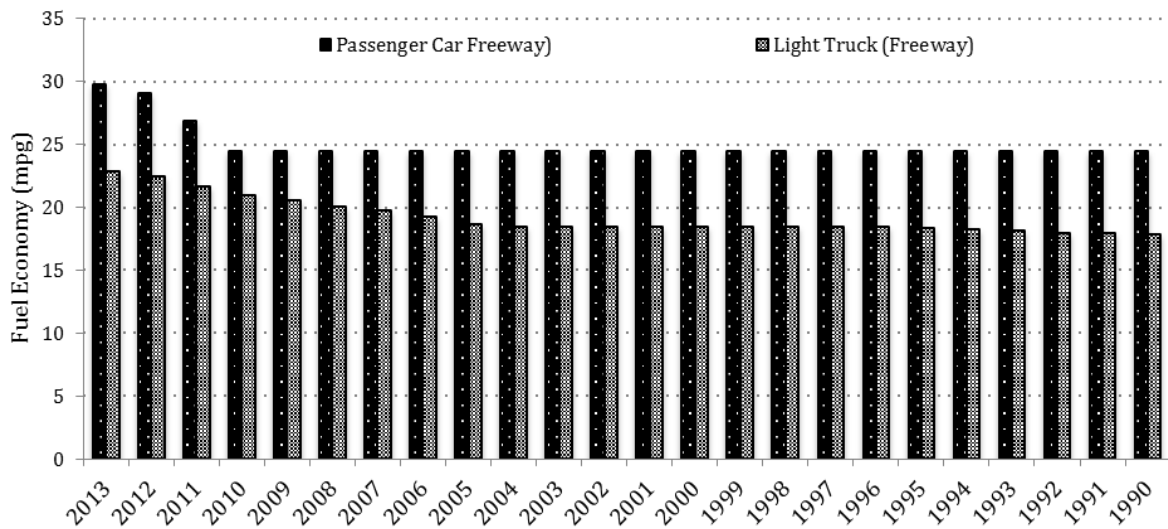


Figure 19: Modified Fuel Economy Values for Different Vehicle Types and Model Years.

The annual fuel consumption for a 1 mile analyzed freeway segment before deployment is approximately 5,500 gallons for light trucks, and 39,500 gallons for passenger vehicles under 2-hour traffic conditions with $v/c = 0.5$.

4.4.2. ENERGY CONSUMPTION REDUCTION BENEFITS EVALUATION

Assuming a 15% energy consumption reduction factor for the ATCS and RMS deployment, Using EIA's projected gasoline prices, as indicated in the methodology section, and a 7% discount rate, the total present worth of the energy consumption reduction benefits can be determined as approximately \$380,000 for ATCS and \$2,270,000 for RMS. If only energy savings are considered, a B/C ratio of 2.16:1 for ATCS and 3.24:1 for RMS can be achieved.

4.4.3. LIFE CYCLE ASSESSMENT ON ENERGY CONSUMPTION REDUCTION

Based on Table 6 presented in the methodology section, Carbon Dioxide and Carbon Monoxide account for over 98% of the total emissions. Due to the minor amounts of Nitrous Oxide and Sulphur Dioxide and due to the fact that carbon monoxide is not regarded as a direct greenhouse gas, the amount of emissions that have a Global Warming Potential (GWP) is considered as 9.08 kg per one gallon of combusted gasoline. Following the carbon price prediction discussed previously, the total present worth of reduced carbon emissions for a period of 20 years can be found as around \$15,000 for ATCS and \$149,000 for RMS (calculated based on the mid-value of the 2013 Carbon Dioxide Price Forecast (27), which is \$17.5/ton from 2013 to 2020, and then linearly increasing up to \$48/ton in 2033). If only carbon emissions savings are considered, a B/C ratio of 0.09:1 for ATCS and 0.21:1 for RMS can be expected.

4.5. ANALYSIS OF BENEFITS ACHIEVED THROUGH REDUCTIONS IN NUMBER OF ACCIDENTS

The safety benefits analysis was undertaken using the methodology presented in the previous chapter. The crash rates before and after deployments were estimated separately. A dollar value was assigned to the reduced amount of accidents. BCA was performed at the end to present the B/C for scenarios that consider only the safety benefits, and all the TBL benefits.

4.5.1.1. Crash Rate Estimation

Lord, Manar, and Vizioli’s crash rate-v/c ratio curve (Lord, Manar, & Vizioli, 2005) was introduced into this section for estimating the existing and optimized total crash rates before and after the ATCS deployment. The equation derived from the curve and adopted in this analysis is presented below:

$$\mu(\text{Urban}) = 6.25 \times 10^{-4} \cdot L \cdot V \cdot e^{(0.37x)}$$

Where L is the length of the analyzed segment in kilometers, V is the hourly traffic volume, and x is the v/c ratio. According to the previously mentioned hypothetical case study, L is 1.61 kilometers (1 mile). Table 18 below presents the expected safety enhancements for link capacity multiplication factors ranging from 8% to 12% under different traffic demands ranging from 200 vph to 2000 vph (1-hour peak traffic conditions are considered). It is observed that the maximum safety benefit occurs when the demand equals 2000 vph. In the following safety benefits evaluation section, a v/c ratio of 0.5 was taken into consideration.

Table 18: Safety enhancement for link capacity multiplication factors (8% to 12%) under different traffic demands (200 to 2000 vph)

Traffic Demand (vph)	200	400	600	800	1000
Safety Enhancement	0.17%±0.03%	0.34%±0.06%	0.50%±0.09%	0.67%±0.12%	0.84%±0.15%
Traffic Demand (vph)	1200	1400	1600	1800	2000
Safety Enhancement	1.00%±0.18%	1.17%±0.21%	1.34%±0.24%	1.50%±0.28%	1.67%±0.30%

4.5.1.2. Safety Benefits Evaluation

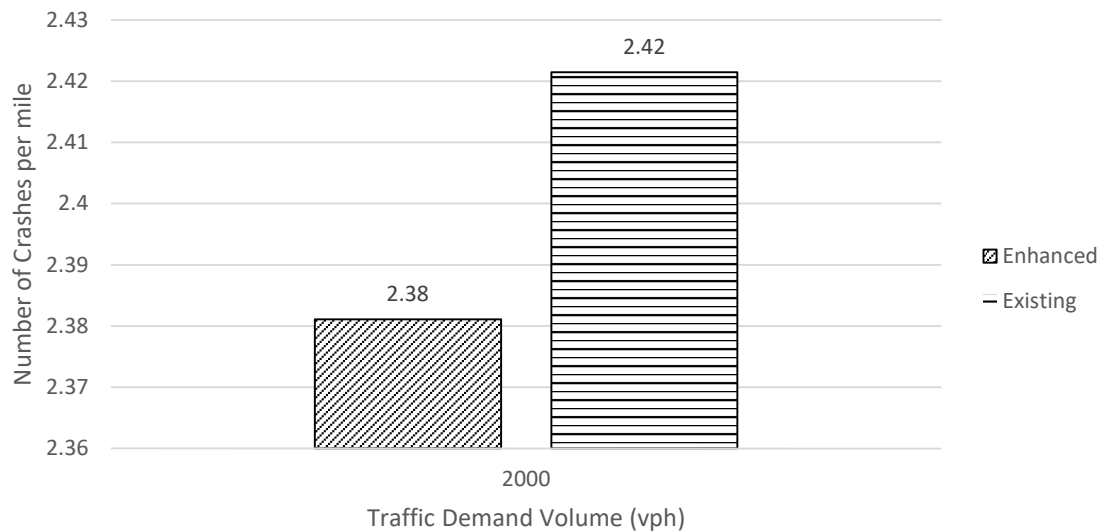


Figure 20: Annual crashes under existing and optimized traffic conditions ($v/c = 0.5$).

Figure 20 above exhibits, within the 10-mile long freeway segment, the total number of crashes drops from 24.2 per year to 23.8 per year for a period of 1 hour when the demand / capacity ratio (v/c ratio) before ramp metering deployment is 0.5 and the capacity is enlarged by 10% after deployments. It is assumed that 1% of all crashes are fatal accidents and the cost of a fatal accident is \$7 million (28). Using a service life of 20 years, a fixed discount rate of 7%, and considering a 2-hour traffic condition with $v/c = 0.5$ per day, the total present worth of the benefits is determined as approximately \$65,000 and \$660,000 for RMS. For RMS deployment, the change in number of accidents on the ramp is not considered due to low number of fatal accidents that are expected to occur on the ramp. If only the reduction in fatal accidents is considered a B/C ratio of 0.38:1 for ATCS and 0.87:1 for RMS can be expected.

Chapter 5. RESULTS

5.1. SUMMARY OF RESULTS FOR ATCS

Based on *section 4.2, 4.3, 4.4, and 4.5*, the overall BCA for a typical ATCS deployment is completed. The life cycle BCR is estimated during a 20 years' service life span, with a fixed discount rate of 7%. The 1-mile segment capacity is assumed as 2000 vph/lane. The analyzed period is set as the 2-hr peak time for all the 255 workdays during a year with a v/c ratio of 0.5. Each annual cost and benefit value during the next 20 years is discounted back to the PV.

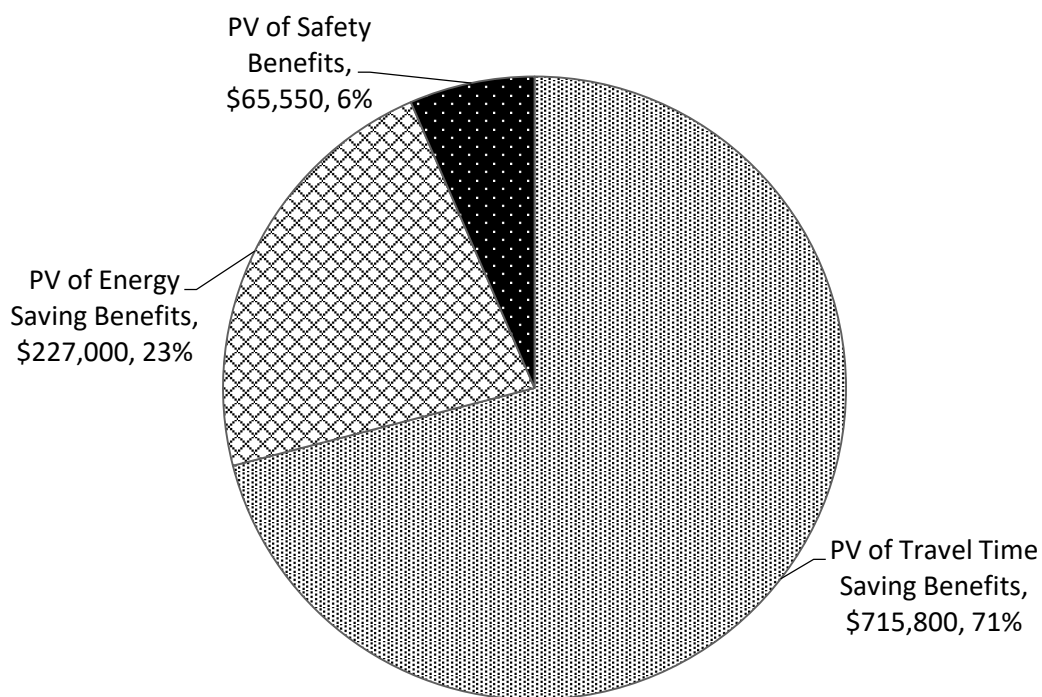


Figure 21: Life cycle benefits distribution for ATCS.

A life cycle benefits distribution pie chart is presented above in Figure 21. For a typical ATCS deployment in the US, during the analyzed service life, approximately \$1,008,357 PV for the total life cycle benefits can be expected for the hypothetical case study. Travel time savings benefits, including recurring and nonrecurring travel time savings, account for the most part in the total life cycle benefits (around 71%). For the remaining benefits, energy saving

benefits, excluded LCA benefits account for 23%, and safety benefits due to reduced fatal crashes account for 6%. Table 19 concludes the annual PV benefits flow for the analyzed period (from 2013 to 2033).

Table 19: Annual benefits flow breakdown in present value during the 20 years' life of service for ATCS.

Year	ATCS PV Costs	Travel Time Saving PV Benefits	Energy Saving PV Benefits	Safety PV Benefits	Net PV Benefit
2013	(\$47,475)	\$61,738	\$23,572	\$5,654	\$43,488
2014	(\$8,411)	\$57,699	\$20,797	\$5,284	\$75,368
2015	(\$7,861)	\$53,924	\$13,505	\$4,938	\$64,506
2016	(\$7,347)	\$50,396	\$14,364	\$4,615	\$62,029
2017	(\$6,866)	\$47,099	\$13,750	\$4,313	\$58,297
2018	(\$14,794)	\$44,018	\$12,853	\$4,031	\$46,107
2019	(\$5,997)	\$41,138	\$12,043	\$3,767	\$50,952
2020	(\$5,605)	\$38,447	\$11,387	\$3,521	\$47,750
2021	(\$5,238)	\$35,932	\$10,815	\$3,290	\$44,800
2022	(\$4,895)	\$33,581	\$10,239	\$3,075	\$42,000
2023	(\$10,548)	\$31,384	\$9,710	\$2,874	\$33,420
2024	(\$4,276)	\$29,331	\$9,217	\$2,686	\$36,958
2025	(\$3,996)	\$27,412	\$8,749	\$2,510	\$34,675
2026	(\$3,735)	\$25,619	\$8,310	\$2,346	\$32,540
2027	(\$3,490)	\$23,943	\$7,887	\$2,193	\$30,532
2028	(\$20,197)	\$22,377	\$7,492	\$2,049	\$11,721
2029	(\$3,049)	\$20,912	\$7,119	\$1,915	\$26,898
2030	(\$2,849)	\$19,545	\$6,765	\$1,790	\$25,251
2031	(\$2,663)	\$18,266	\$6,439	\$1,673	\$23,715
2032	(\$2,489)	\$17,071	\$6,145	\$1,563	\$22,291
2033	(\$2,326)	\$15,954	\$5,863	\$1,461	\$20,952

It should be noted that life cycle environmental impact benefits due to reduced CO_{2e} emissions as a result of reduced combustion of fuel is not included in the final result. For a single intersection, the contribution of the cradle-to-grave environmental benefits of gasoline

consumption reduction to energy savings benefits is relatively small. However, considering the large number of potential ATCS-deployed intersections, the importance of LCA on gasoline related environmental impacts could not be ignored. The importance of environmental benefits cannot always be evaluated simply in monetary terms. For this reason, LCA benefits will be considered as an additional component to the entire life cycle benefits. Figure 22 illustrates the cost and benefit values during the next 20 years (2013 to 2033), considering all TBL benefits.

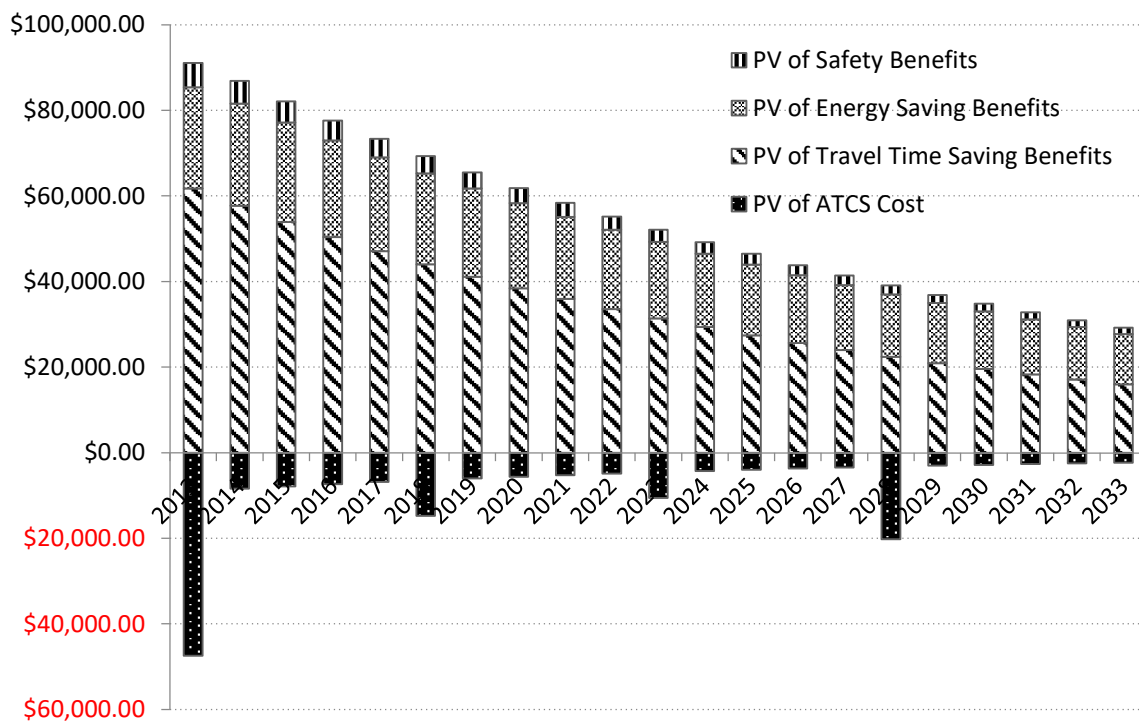


Figure 22: Overall Life Cycle Benefits and Costs Flow in Present Value for ATCS.

The total BCR calculated for the hypothetical case study is approximately 5.79:1. This ratio is calculated based on the ratio of benefits to costs in the PV flow table presented above. All the data used in building the travel time savings model, energy consumption reduction model, and crash rate reduction model are generalized national average values. Therefore, results of this hypothetical BCA may not be applicable to specific locations, but reflect the expected Benefit and Cost values based on the national average values. For this reason, we

strongly recommend using local data, and data from on-site measurements, if applicable, for a better representation of the real local traffic conditions.

It is worth noting that the calculated BCR of 5.79:1 is for one segment only (say, Northbound-Southbound). The deployment of an ATCS at an intersection will most likely benefit both segments. To simplify the evaluation, as we mentioned in the hypothetical study, we quantify the benefits from travel time savings, energy consumption reduction, and safety optimization for the main segment, and apply a factor k (1.0 to 2.0) to provide a range of benefits for both segments. The scenario in which k equals to 1.0 refers to the worst condition where ATCS does not benefit the other segment at all, while the scenario in which k equals to 2.0 implies that ATCS benefits the other segment in the same way as the main segment. The introduction of factor k will enlarge our calculated BCR to a value ranging from 5.79:1 to 11.58:1.

The review of literature and previous ATCS benefits databases indicates that the BCR for real cases in the US that were deployed within the past 10 years ranges up to 25:1. Our result can be considered conservative since we 1) use the typical ATCS that offer on average a link capacity optimization of 8% to 12%; 2) only consider the benefits during 2-hr peak period during the workdays with a v/c ratio of 0.5; 3) ignore the injury level crashes and PDO level crashes due to the uncertainties associated with quantification of costs of these crashes. For all these reasons above, we consider our resultant ratio (5.79:1 to 11.58:1) as the minimum, or “highly expected” BCR that can be expected for a typical ATCS deployment.

5.2. SUMMARY OF RESULTS FOR RMS

The life cycle BCR is estimated for a life cycle of 20 years, using a fixed discount rate of 7%.

The 10-mile freeway segment capacity is assumed as 2000 vph/lane. The analyzed period is

set as 2-hr peak time (with a $v/c = 0.5$) for 255 workdays during a year. Each annual cost and benefit value during the 20 years is discounted to the PV.

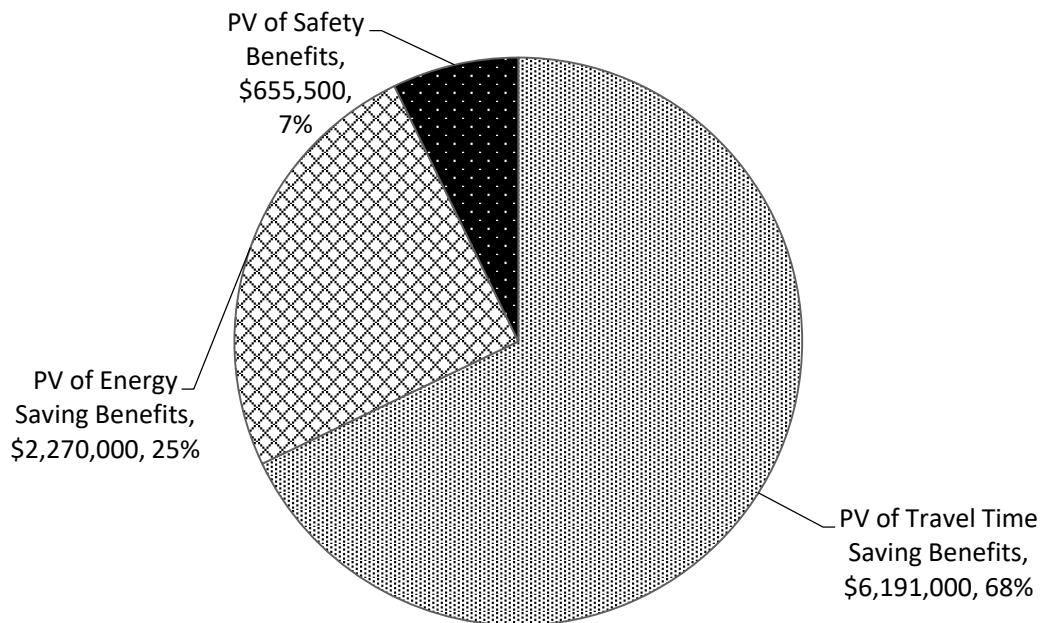


Figure 23: Life cycle benefits distribution.

Figure 23 above presents the distribution of life cycle benefits. For a typical ramp metering deployment in the U.S., the PV of total life cycle benefits is expected to be \$9,116,776. Travel time savings benefits consisting of recurring and nonrecurring travel time savings account for the most part in the total life cycle benefits with an approximate share of 68%. For the remaining benefits, energy savings benefits (LCA benefits excluded) due to gasoline consumption reduction account for 25%, and safety benefits due to crash rate drop accounts for rest (7%). Table 20 below concludes the annual PV benefits flow for the analyzed time period (2013 to 2033).

Table 20: Annual benefits flow breakdown in present value during the 20 years' life of service for RMS.

Year	Ramp Metering PV Costs	Travel Time Saving PV Benefits	Energy Saving PV Benefits	Safety PV Benefits	Net PV Benefit
2013	(\$229,750)	\$533,988	\$235,717	\$56,538	\$597,355
2014	(\$23,364)	\$499,054	\$207,965	\$52,839	\$767,120
2015	(\$21,836)	\$466,406	\$135,048	\$49,382	\$726,274
2016	(\$20,407)	\$435,893	\$143,642	\$46,152	\$687,489
2017	(\$19,072)	\$407,377	\$137,501	\$43,133	\$650,671
2018	(\$110,513)	\$380,726	\$128,526	\$40,311	\$523,039
2019	(\$16,659)	\$355,819	\$120,431	\$37,674	\$582,571
2020	(\$15,569)	\$332,541	\$113,870	\$35,209	\$550,702
2021	(\$14,550)	\$310,786	\$108,155	\$32,906	\$520,898
2022	(\$13,598)	\$290,454	\$102,387	\$30,753	\$492,637
2023	(\$78,794)	\$271,452	\$97,102	\$28,741	\$399,758
2024	(\$11,877)	\$253,694	\$92,167	\$26,861	\$440,448
2025	(\$11,100)	\$237,097	\$87,489	\$25,104	\$416,382
2026	(\$10,374)	\$221,586	\$83,099	\$23,461	\$393,301
2027	(\$9,695)	\$207,090	\$78,872	\$21,926	\$371,718
2028	(\$56,179)	\$193,542	\$74,921	\$20,492	\$304,158
2029	(\$8,468)	\$180,880	\$71,190	\$19,151	\$331,917
2030	(\$7,914)	\$169,047	\$67,654	\$17,898	\$313,588
2031	(\$7,397)	\$157,988	\$64,392	\$16,728	\$296,039
2032	(\$6,913)	\$147,652	\$61,452	\$15,633	\$279,629
2033	(\$6,460)	\$137,993	\$58,632	\$14,611	\$264,098

It is also worth noting that life cycle environmental impact benefits due to reduced CO₂e emissions as a result of combusted gasoline saving is not included in the above table. For a single ramp metering deployment, the contribution of the cradle-to-grave environmental benefits of reduced gasoline consumption to the energy savings benefits is relatively small. However, when the potential for deployment at a large number of ramps is considered, the importance of the results of LCA on gasoline related environmental impacts cannot be

ignored. Therefore, LCA benefits will be considered as an additional, but important component to the entire life cycle benefits. Figure 24Figure 22 illustrates the cost and benefit values during the next 20 years (2013 to 2033), considering all TBL benefits.

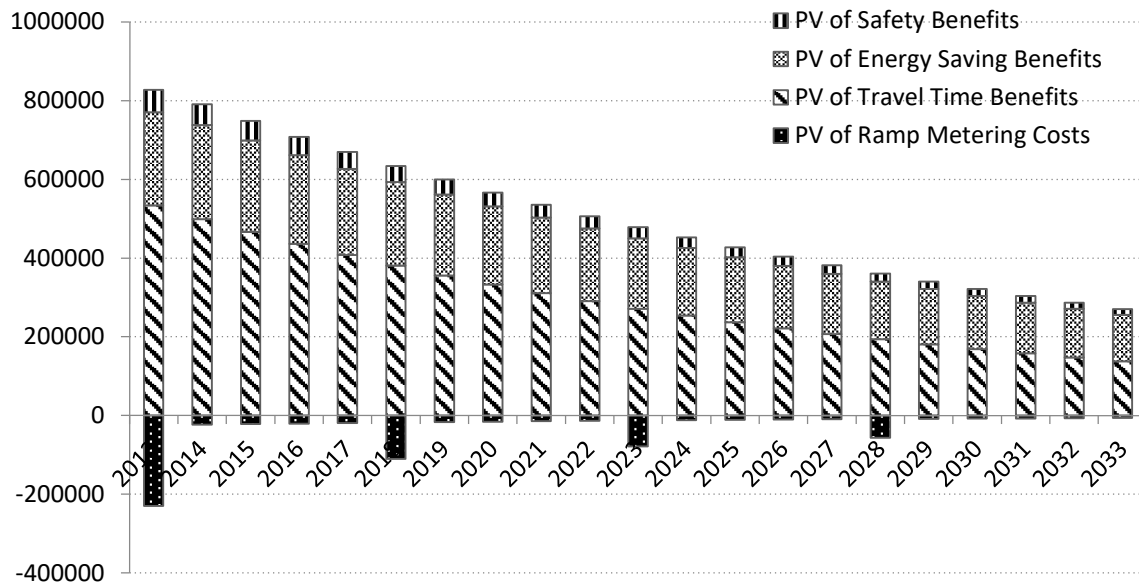


Figure 24: Overall Life Cycle Benefits and Costs Flow in Present Value for RMS.

The total BCR calculated for the hypothetical case study is approximately 13.01:1. Similar to the ATCS study, the results of this hypothetical BCA do not apply to a specific location, but they reflect the results based on the national average. The local data or data from onsite measurements should be preferred whenever available. It is worth noting that the analyzed length for the freeway segment is assumed to be 10 miles long, which implies a proportional increase in energy consumption rates and the number of accidents.

5.3. SENSITIVITY ANALYSIS

Sensitivity of the benefits achieved in travel time savings and safety benefits to demand / capacity ratio (v/c ratio) and capacity optimization factors was examined along with the sensitivity of the benefits achieved in reduced energy consumption to the v/c ratio. Table 16 and Table 17 show the resultant total equivalent time savings for various v/c ratios ranging

between 0.1 and 1.0 and capacity optimization factors ranging from 8% to 12%. As it can be seen in Table 16 and Table 17, a significant increase in travel time savings is not observed until a v/c ratio of 0.5 is observed. The introducing of non-recurring travel time savings in the research is an important component to make the result comprehensive. Figure 25 indicates the difference between the travel time saving estimation with and without considering nonrecurring travel time saving.

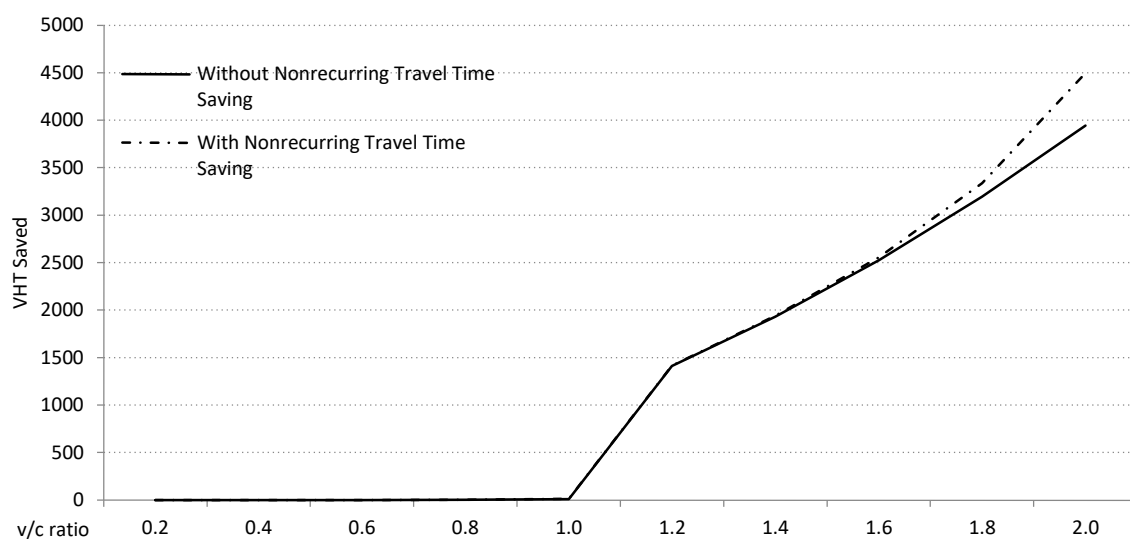


Figure 25: Travel Time Savings Estimation with and Without Considering Nonrecurring Travel Time Savings for Ramp Metering.

Energy savings (in gallons) that can be achieved under a v/c ratio of 0.1 is determined as 13,366 gallons. Since there is a linear relationship between energy savings and v/c ratio, the maximum energy savings that can be obtained is observed at a v/c ratio of 1.0 and it is equal to 133,660 gallons.

Table 21 shows the reductions in yearly accidents for 2-hour traffic conditions under various v/c ratios ranging between 0.1 and 1.0 and capacity optimization factors ranging from 8% to 12%. It can be seen that the reductions in yearly accidents increase rapidly as v/c ratio

increases. It should be noted that reductions shown in Table 3 indicate reductions in all types of accidents (i.e. fatal and non-fatal).

Table 21: Reductions in Yearly Accidents for Different v/c Ratios and Capacity Enhancement Factors.

Reductions in Annual Accidents	v/c ratio										
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	
Capacity Enhancement = 12%	0.03	0.14	0.32	0.59	0.95	1.42	2.00	2.70	3.54	4.53	
Capacity Enhancement = 11%	0.03	0.13	0.30	0.54	0.88	1.31	1.85	2.50	3.28	4.20	
Capacity Enhancement = 10%	0.03	0.12	0.27	0.50	0.81	1.20	1.70	2.30	3.01	3.85	
Capacity Enhancement = 9%	0.03	0.11	0.25	0.45	0.73	1.10	1.54	2.09	2.74	3.51	
Capacity Enhancement = 8%	0.02	0.09	0.22	0.41	0.66	0.98	1.39	1.88	2.46	3.15	

5.4. VALIDATIONS

Framework and the corresponding tool has been submitted to asset management division and operation division of Port Authority of New York & New Jersey (PANYNJ) for expert opinions. Framework has been partially applied (for validation purpose only) on N57 to 59, N60, N61 to 63, and N64 highway bridges, which are projects of the undergoing Newark International Airport (EWR) Redevelopment Program.

A similar validation process has been tested on Harrison PATH station redevelopment project, where ATCS has been implemented on both ends of traffic corridor.

Results show a match to the proposed traffic scenario, which was setup for the framework demonstration. Feedbacks from director of asset management for PANYNJ proved the reasonability of the traffic capacity multiplication factor and the overall BCR for ATCS and RMS. Meanwhile, expert opinions also agreed on the logic of the methodology used to conduct this research. These are a necessary, though not sufficient, part of the overall

construct framework testing process. Further application of the framework is required to accumulate more test results.

Chapter 6. RECOMMENDATION

6.1. RESEARCH OVERVIEW

The object of the work in this dissertation is to present a new tool that can be used to determine the anticipated monetary return of typical ATCS and RMS deployments at a high-level rather than to develop tools to determine the exact values of these parameters. As a decision-making-oriented tool, this framework takes not only agency costs, but environmental-related savings, user-related savings, and safety-related savings into consideration, making the outputs substantially comprehensive, while compatible with the sustainable triple bottom line principle. However, due to limitations of the research boundary, there are several research areas remain for future studies.

6.2. RECOMMENDATION FOR FUTURE WORKS

6.2.1. AGENCY SAVINGS DUE TO ATCS AND RMS DEPLOYMENTS

In this research, the life cycle cost analysis covered infrastructural costs, incremental costs, and O&M costs. The user savings due to optimized traffic condition have been categorized into user benefits. From the other side, according to FHWA, the cost of signal retiming generally lies within the range of \$2,500 to \$3,000 per intersection per time (U.S. Department of Transportation, 2006) (U.S. Department of Transportation, 2009). The person hours currently spent on signal retiming add up to around 43 hours per intersection. The study of agency savings due to less frequent signal retiming activities because of adaptive traffic signal deployments on both intersection and ramp metering will be an important complement for the benefit/cost framework.

6.2.2. LOW-SPEED TRAFFIC CONDITION SAFETY BENEFIT ANALYSIS

As mentioned in section 3.6.1 Crash Rate and v/c Ratio Relationship, the exponential equations that derived by curve-fitting procedures are generated for mid to high speed traffic conditions, which do not include low speed traffic scenarios, for example, urban roadway segment approaching the traffic intersection. In this research, the equation for mid speed traffic condition is used to evaluate the safety benefits. As a result, the final result of safety benefit for ATCS deployment is exaggerated. Although the safety benefit takes the smallest share of the overall benefits pie (Figure 23: Life cycle benefits distribution.), which somehow minimize the inaccurate impacts to the final outputs. Microscope traffic simulation software, like VisSim or Paramics, will be the best approach to deal with the safety benefit in low-speed traffic condition. Meanwhile, due to the nature of microscope simulation, the microsimulation can be customized according to real local condition, which will substantially increase the accuracy of final outputs.

Due to the limitation of research boundary, Microsimulation could not be introduced to this work to quantify the amount of accidents differentials before and after ATCS deployments. On the other hand, the work of this dissertation is aiming at delivering high-level decision-making framework for evaluate the overall TBL performances, the quantitative analysis will somehow distract the center of this research.

6.2.3. ADVANCED LCA MODELING AND ANALYSIS

Gabi 6 is used to perform life cycle assessment on reduced gasoline due to ATCS and RMS deployments. The commercial database we purchased is up to 2010. Because of advances of technology, like large data mining, and the release of latest database updates, the LCA modeling can be more comprehensive, detailed, and accurate. Big data is playing a more and

more important role in LCA, future work should pay more attention to welcome a broader and more advanced approaches driven by data.

6.2.4. SOCIAL BENEFITS ON SURROUNDING AREAS DUE TO OPTIMIZED TRAFFIC CONDITION

As mentioned in the section 2.6.3 Social Bottom Line, the original concept of Social Line has been expanded to reach social development, social responsibility, and other higher-level social aspects (Dhiman, 2008), with focuses on the interaction between the community and the organization, activity, or product (Goel, 2010). Interactions between the community and the activity, in this work of dissertation, traffic segment surrounding areas and ATCS/RMS deployments, are social development due to better traffic condition. People will more likely to use this corridor due to optimized traffic condition; surrounding areas will have bigger change to welcome neighborhood development because of induced traffic volume; the induced traffic will incur higher traffic demands and create new volume/capacity balance. On the other hand, induced traffic may also happen on surrounding areas due to either RMS deployment on ramp, or optimized traffic corridor reaches a new saturated point. It is obvious out of the boundary of this research to evaluate the “butterfly effects” of ATCS/RMS deployment, or research the driving behavior, however, this is a very interesting topic that will bridge the gap in between engineering, facility management, social science, and economic research.

6.2.5. INTRODUCTION OF ADVANCED VEHICLE TECHNOLOGIES

It has been a new fad that consumers place on automotive technology during their shopping process at local dealers and online website. Automotive technologies will go from theory study to commonplace in a timeframe shorter than we expected. For future study in this

area, several current and upcoming technological advancements that are worthy of attention are listed below:

1. Autonomous Vehicle with Driver Override Systems
2. Comprehensive Vehicle Tracking
3. Active Window Displays (HUD)
4. Hybrid / Electric Car

The introduction of advanced vehicle technologies will have substantial influence on the life-cycle cost/benefit analysis framework and its outputs, especially on emission and crash rate reduction. Meanwhile, the LCA on embodied energy of reduced gasoline will be expanded to reduced electric power consumed by hybrid car or electric car.

Chapter 7. CONCLUSION

This work of dissertation develops a Benefit/Cost (B/C) analysis framework to evaluate existing and anticipated intelligent transportation system (ITS) strategies, particularly, adaptive traffic control systems and ramp metering systems, in terms of the triple bottom line (TBL) of sustainability (i.e. social, economic, and environmental impacts). For both ATCS and Ramp Metering systems, four main research areas were highlighted as:

- A. Life Cycle Cost Analysis,
- B. Analysis of Benefits through Travel Time Savings,
- C. Analysis of Benefits through Reductions in Energy Consumption,
- D. Analysis of Benefits through Safety Enhancements.

The life cycle cost analysis of ITS deployment includes infrastructure costs, which feature the principal cost of equipment, software installed, and labor cost for installation and operation; incremental costs, which feature costs due to changes and upgrades on ITS components based on a fixed schedule; and O&M costs, which vary according to the system complexity. Due to the rapid development of technology used in ITS, a typical service life of 20 years was assumed for each ITS, instead of a longer time period to limit the uncertainties associated with the analyses. It is worth noting that the salvage value was ignored in this life cycle cost analysis due to the limitations in data collection. However, consideration of salvage values for ITS components are highly recommended for future studies.

The analysis of benefits through travel time savings was grouped into recurring travel time savings analysis and nonrecurring travel time savings analysis. We introduced and modified several existing tools, including TOPS-BC (developed by USDOT) and IDAS (developed by

FHWA) into this framework, as well as the concepts of Value of Reliability (VoR) and Value of Travel Time (VoT) to quantify the overall travel time savings benefits.

Travel time savings benefits constitute an important component in the total life cycle benefits of ATCS and Ramp Metering deployment. As a result of our hypothetical case studies, the BCR (considering only the benefits obtained through time savings) is calculated as 4.11:1 for ATCS, and 8.84:1 for Ramp Metering.

Considering Travel time saving benefits only, BCR 1.0 will be achieved over the analyzed period (20 years), if a constant 0.50% link capacity multiplication factor is assumed for ATCS, and 0.46% for RMS.

The analysis of benefits through reductions in energy consumption was conducted using a microscopic scale top-down approach. Our team used three customizable matrices to represent the real link traffic conditions to make the study more comprehensive and accurate. We fit equation to roughly predict the next 20 years' gasoline price trend to quantify the energy consumption reduction benefits. In addition, GaBi 6 was used to evaluate the reduction in lifecycle environmental impacts of gasoline as a result of the expected reduction in gasoline consumption due to better traffic conditions after ITS deployment.

Energy savings benefits account for the second largest percentage in the total life cycle benefits of ramp metering deployments and ATCS deployments. The life cycle benefits for the 2-hr peak time fuel consumption reduction can be around five times the cost of ramp metering deployments, and twice of the ATCS costs over a service life of 20 years. It is worth noting that the calculation for the analyzed hypothetical case study is based on generalized

national data, rather than regional data. In order for the results to represent the local traffic features, on site measurements and local observations would be preferred.

The Introduction of LCA provides a comprehensive method to evaluate the environmental impacts of reducing energy consumption from a broader perspective. However, due to its relatively small contribution to the results of energy savings analysis, the LCA part is not taken into account in the BCA calculations. Nonetheless, the importance of LCA impacts due to fuel savings cannot be ignored. According to the LCA calculations, savings of 61,290 kg CO₂e/intersection were achieved annually due to ATCS deployment. For ramp metering deployments, savings of 606,820 kg CO₂e can be achieved annually. Considering the total number of intersections and ramp metering deployments for a county, a state, or multi-states, the overall environmental benefits will be significant.

Considering environmental benefits only, BCR 1.0 will be achieved over the analyzed period (20 years), if a constant 7.0% fuel consumption reduction is assumed for ATCS, and 4.6% for RMS.

Analysis of safety benefits was mainly focused on crash rates. In this project, we examined a method in which the v/c ratios before and after the ITS deployment are calculated, followed by determination of the crash rate-v/c ratio relationship and hence, determination of the existing and anticipated crash rates under each crash classification. The last step of the method involves assigning monetary values to each level of crash and calculating the annual safety benefit.

It is worth noting that the safety benefits calculated in this project only accounts for the reductions in the fatality level crash rates during the daily 2-hr peak times (v/c assumed to be

0.5). For the ramp metering calculations, the crashes on the 0.2-mile ramp were ignored. The other crash levels, including crashed featuring injuries, and PDO, were not taken into consideration due to the large variations in the data collected.

It should also be noted that the efficacy of both ATCS and ramp metering deployments can be maximized in high traffic demand cases (v/c ratio > 0.5). The sensitivity threshold, represented by v/c ratio, in the study is about 0.4 for ATCS and 0.5 for ramp metering, which may vary according to the location of deployment and technologies adopted. The number implies that, under the same traffic demands, both ITS deployments are more suitable to be deployed under traffic segments with low link capacities.

A factor k , which ranges from 1.0 to 2.0 representing the worst and ideal conditions, was introduced for ATCS overall life cycle benefits quantification, in order to account for improvements in the other segment. Therefore, the final calculated BCR for the ATCS deployment is presented as a range (5.79:1 to 11.58:1) rather than a fixed value. According to the literature and review of databases in case studies, due to regional disparities, technical varieties, and traffic condition differences, the BCR may vary dramatically up to a value of 25:1. Therefore, we believe these values could be considered as a conservative BCR estimation.

Another point that is worth noting is regarding the limitation of the crash rate – v/c ratio curve we introduced in our study. Since the curve is based on HCM equations, which cannot handle the oversaturated traffic conditions (v/c ratio > 1), the crash rate estimation using this equation can only be limited to solve undersaturated and saturated conditions. Future studies are required on crash rate estimation under oversaturated traffic conditions.

Chapter 8. APPENDIX

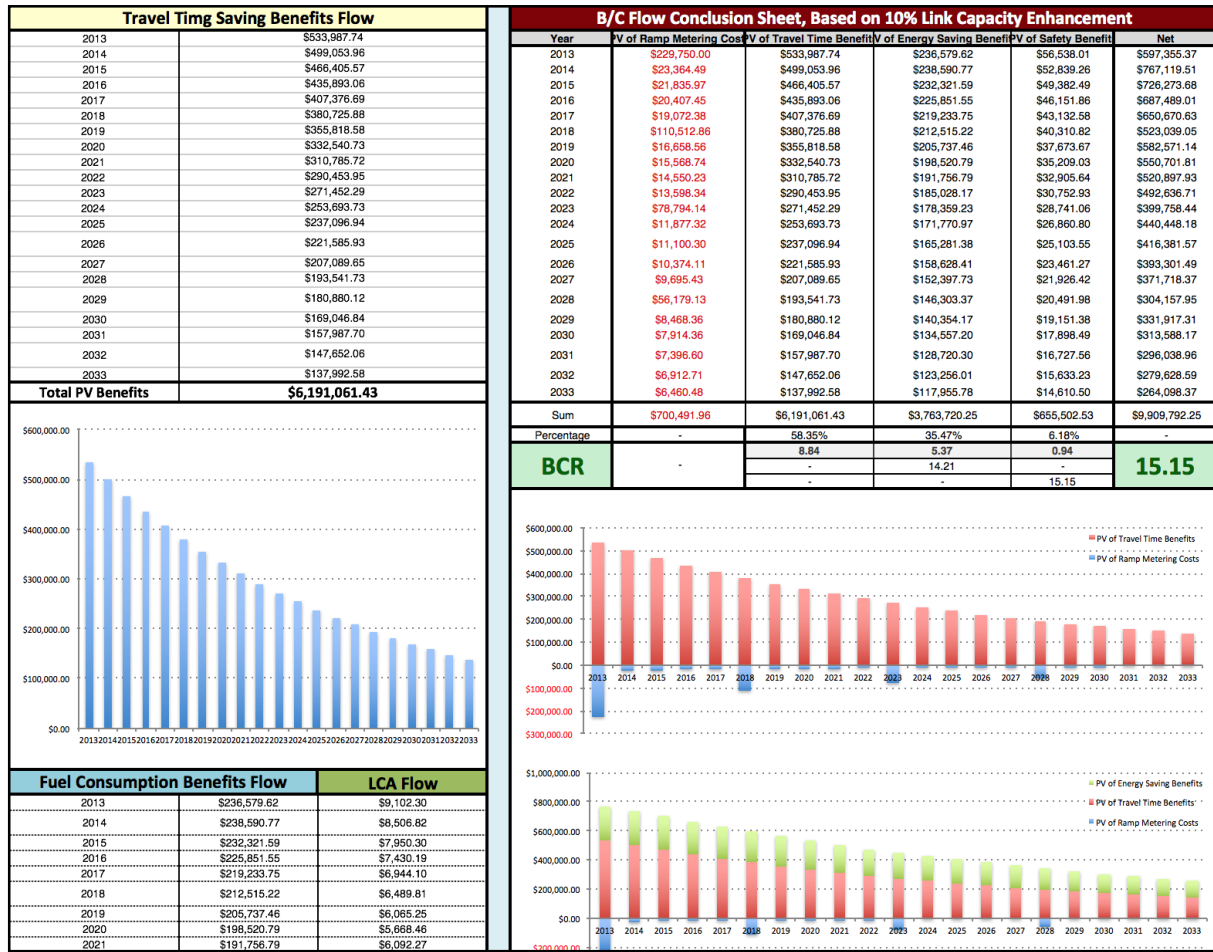
8.1. LIFE CYCLE BENEFIT/COST ANALYSIS FRAMEWORK WORKING SPACE (EXCEL BASED)

Recurring Travel Time Saving Calculation Sheet, Based on 10 miles Freeway																			
Set the Traffic Demands (vph)	400	600	800	1000	1200	1400	1600	1800	2000	2200	2400	2600	2800	3000	3200	3400	3600	3800	4000
Set the FFS (mph)	55	55	55	55	55	55	55	55	55	55	55	55	55	55	55	55	55	55	55
Set the Multiply Coefficient (8% to 12%)	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Set the Existing Link Capacity (vph)	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
Existing v/c ratio	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Enhanced v/c ratio	0.09	0.14	0.18	0.23	0.27	0.32	0.36	0.41	0.45	0.50	0.55	0.59	0.64	0.68	0.73	0.77	0.82	0.86	0.91
Existing Vehicle Speed (mph)	54.96	54.94	54.90	54.85	54.77	54.65	54.40	53.68	43.14	14.55	8.44	5.94	4.58	3.73	3.14	2.72	2.39	2.14	1.93
Enhanced Vehicle Speed (mph)	54.97	54.94	54.91	54.87	54.82	54.74	54.60	54.33	53.54	43.14	15.57	9.14	6.46	5.00	4.07	3.44	2.97	2.62	2.34
Existing Travel Time per Vehicle (hr)	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.19	0.23	0.69	1.18	1.68	2.18	2.68	3.18	3.68	4.18	4.68	5.18
Enhanced Travel Time per Vehicle (hr)	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.19	0.23	0.54	1.09	1.55	2.00	2.46	2.91	3.36	3.82	4.27
Existing VHT (hr)	72.78	109.22	145.72	182.32	219.08	256.18	294.10	335.30	463.64	1511.97	2843.54	4378.35	6113.99	8049.95	10188.08	12522.31	15058.59	17794.92	20731.27
Enhanced VHT (hr)	72.77	109.20	145.68	182.23	218.80	255.77	293.04	331.31	373.53	510.00	1541.49	2844.78	4333.79	6005.62	7859.66	9895.72	12113.72	14813.80	17709.35
Difference in VHT (hr)	0.01	0.02	0.04	0.08	0.18	0.41	1.06	3.99	90.11	1001.97	1302.05	1533.57	1780.19	2044.33	2326.42	2626.99	2944.88	3281.32	3635.92
Recurring Travel Time Saving Conclusion Sheet, Based on 10% Link Capacity Enhancement																			
Traffic Demands (vph)	400	800	1200	1600	2000	2400	2800	3200	3600	4000									
Recurring Travel Time Saving (hr)	0.01	0.04	0.18	1.06	90.11	1302.05	1780.19	2326.42	2944.88	3635.92									
Nonrecurring Travel Time Saving Conclusion Sheet, Based on 10% Link Capacity Enhancement																			
Traffic Demands (vph)	400	800	1200	1600	2000	2400	2800	3200	3600	4000									
Nonrecurring Travel Time Saving (hr)	0.00	0.00	0.10	0.50	1.80	4.10	9.60	25.90	120.00	491.40									
Equivalent Travel Time Saving Conclusion Sheet, Based on 10% Link Capacity Enhancement																			
Traffic Demands (vph)	400	800	1200	1600	2000	2400	2800	3200	3600	4000									
Equivalent Travel Time Saving (hr)	0.01	0.04	0.28	1.56	91.71	1306.15	1789.79	2352.32	3064.88	4127.32									
Negative Travel Time Saving On the Ramp Conclusion Sheet, Based on -12% Link Capacity Enhancement, 0.2 miles Ramp																			
Set the Traffic Demands (vph)	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000
Set the FFS (mph)	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35
Set the Multiply Coefficient (8% to 12%)	-12%	-12%	-12%	-12%	-12%	-12%	-12%	-12%	-12%	-12%	-12%	-12%	-12%	-12%	-12%	-12%	-12%	-12%	-12%
Set the Existing Link Capacity (vph)	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
Existing v/c ratio	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Enhanced v/c ratio	0.11	0.17	0.23	0.28	0.34	0.40	0.45	0.51	0.57	0.63	0.68	0.74	0.80	0.85	0.91	0.97	1.02	1.08	1.14
Existing Vehicle Speed (mph)	34.97	34.95	34.92	34.88	34.82	34.72	34.52	33.95	28.06	12.56	7.74	5.59	4.57	3.59	3.04	2.64	2.33	2.09	1.89
Enhanced Vehicle Speed (mph)	34.98	34.94	34.90	34.84	34.74	34.53	33.84	23.05	10.29	6.49	4.74	3.74	3.08	2.62	2.28	2.02	1.81	1.64	1.50
Existing Travel Time per Vehicle (hr)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11
Enhanced Travel Time per Vehicle (hr)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.03	0.04	0.05	0.06	0.08	0.09	0.10	0.11	0.12	0.13
Existing VHT (hr)	1.14	1.72	2.29	2.87	3.45	4.03	4.64	5.30	7.13	17.52	31.00	46.54	64.10	83.66	105.23	128.80	154.37	181.94	211.51
Enhanced VHT (hr)	1.14	1.72	2.29	2.87	3.45	4.05	4.73	5.41	7.24	17.52	33.90	50.58	69.05	90.80	114.33	140.12	168.19	198.54	231.16
Difference in VHT (hr)	0.00	0.00	0.00	0.00	0.01	0.02	0.09	2.81	12.39	16.37	19.58	23.01	26.70	30.66	34.89	39.40	44.17	49.22	54.84
Combined Travel Time Saving Conclusion Sheet (10 miles Freeway + 0.2 miles Ramp)																			
Traffic Demands (vph)	400	800	1200	1600	2000	2400	2800	3200	3600	4000									
Difference in VHT (hr)	0.01	0.04	0.27	1.47	79.32	1286.57	1783.09	2317.43	3020.71	4072.78									
Equivalent Travel Time Saving Benefits in Dollar Value (255 Workdays per year)																			
Traffic Demands (vph)	400	800	1200	1600	2000	2400	2800	3200	3600	4000									
Parameters	VOT (Passenger Cars)(\$/hr)	\$12.00	VOT (Trucks)(\$/hr)	\$24.00	Vehicle Type Distribution (Passenger Cars - Trucks)	0.3	0.1	Peak Hour Duration (hr) per day	2										
Travel Time Saving in Dollar Value	\$36.21	\$247.43	\$12.00	\$1,832.18	\$9,892.63	\$53,987.74	\$81,600.19	\$11,869,101.35	\$15,800,913.13	\$20,335,988.97	\$27,417,973.16								
Fuel Consumption Reduction Conclusion Sheet (255 Workdays per year)																			
Traffic Demands (vph)	400.00	800.00	1000.00	1200.00	1400.00	1600.00	1800.00	2000.00	2200.00	2400.00	2600.00	2800.00	3000.00	3200.00	3400.00	3600.00	3800.00	4000.00	
Parameters	Average On-the-road Fuel Economy, Based on 90% Passenger Car						0.0437	Fuel Consumption Reduction Factor						-15%	Peak Hour Duration (hr) per day				2
Existing Fuel Consumption (gallon)	89107.20	178214.40	267321.60	356428.80	445536.00	534643.20	623750.40	712857.60	801964.80	891072.00									
Enhanced Fuel Consumption (gallon)	75741.12	151482.24	227223.36	302964.48	378705.60	454446.72	530187.84	605928.96	681670.08	757411.20									
Difference in Fuel Consumption (gallon)	13366.08	26732.16	40098.24	53458.32	66818.40	80196.48	93562.56	106928.64	120294.72	133660.80									
Annual LCA Benefits of Reduced Fuel Consumption Conclusion Sheet (255 Workdays per year)																			
Traffic Demands (vph)	400	800	1200	1600	2000	2400	2800	3200	3600	4000									
Annual CO2 Emission Reduction (ton)	121364.01	242728.01	364092.02	485456.03	606820.03	728184.04	849548.04	970912.05	1092276.06	1213640.06									

Appendix 1: Life Cycle Benefit/Cost Analysis Framework Working Space (Excel Based).

Orange-coded cells represent the primary parameters of the tool. These parameters regulate the basic properties of the analyzed traffic condition. Detailed parameters can be customized by accessing linked database sheets in the same excel file.

8.2. LIFE CYCLE BENEFIT/COST ANALYSIS FRAMEWORK OUTPUT SPACE (EXCEL BASED)



Appendix 2: Life Cycle Benefit/Cost Analysis Framework Output Space (Excel Based)

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Education

- Ph.D. student in Civil & Environmental Engineering at Syracuse University, Dec 2012 – present. Dissertation Title: “A LIFE-CYCLE BENEFIT / COST ANALYSIS FRAMEWORK FOR ITS DEPLOYMENTS”
- Master of Science (Oct 2011) in Civil & Environmental Engineering at Syracuse University, Syracuse, New York.
- Bachelor of Engineering (Aug 2009) in Civil Engineering at Nanjing Tech University, Nanjing, Jiangsu, China.

ACADEMIC EMPLOYMENT

- Research Assistant, Department of Civil & Environmental Engineering, Syracuse University, Spring 2013 – Spring 2015. Responsibilities includes: Developing Life Cycle Benefit/Cost Analysis and implement sustainable asset management on TSM&O systems for TranLIVE project.
- Teaching Assistant, Department of Civil & Environmental Engineering, Syracuse University, Spring 2015 – Fall 2015. Responsibilities include: assisting professors with the preparation and presentation of undergraduate courses, grading, and tutoring.

INDUSTRIAL EMPLOYMENT

- BIM Manager, Port Authority of New York & New Jersey, Jul 2016 – present. Responsibilities include: Manage all BIM projects / programs for Port Authority; Create and maintain BIM languages and standards for Port Authority.

- BIM Specialist, Louis Berger, Oct 2015 – Jun 2016. Responsibilities include: BIM coordination for international BIM projects. BIM modeling and detailing.

PUBLICATIONS

- Chen, X., Salem, O. and Salman, B., 2016. Life-Cycle Benefit–Cost Analysis Framework for Ramp-Metering Deployments. *Transportation Research Record: Journal of the Transportation Research Board*, (2554), pp.69-76.
- Salem, Ossama Sam, Jeff Xifan Chen, and Baris Salman. *Enhancing TSM&O Strategies through Life Cycle Benefit/Cost Analysis: Life Cycle Benefit/Cost Analysis & Life Cycle Assessment of Adaptive Traffic Control Systems and Ramp Metering Systems*. No. N15-03. 2015.

PRESENTATIONS AT PROFESSIONAL MEETINGS

- Chen, Xifan, Ossama Salem, and Baris Salman. "A Life-Cycle Benefit/Cost Analysis Framework for Ramp Metering Deployments." *Transportation Research Board 95th Annual Meeting*. No. 16-1477. 2016.

ACADEMIC AWARDS

- National Grand Winner of U.S. DOE 2014 Design Competition for Zero Energy Ready Homes, Golden, Colorado, Mar 2014.

PROFESSIONAL MEMBERSHIP

- Green Building Certification Institute (GBCI)
- Project Management Institute (PMI)
- American Society of Civil Engineers (ASCE)