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

Final Report

TranLIVE

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16. Abstract

The research team developed a comprehensive 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). The B/C framework for each ITS category was divided into four main areas: Life Cycle Cost Analysis, Analysis of Benefits through Travel Time Savings, Analysis of Benefits through Reductions in Energy Consumption, and Analysis of Benefits through Safety Enhancements. The life cycle cost analysis of an ITS deployment includes infrastructure costs, incremental costs, and O&M costs. The analysis of benefits through travel time savings was grouped into recurring travel time savings analysis and nonrecurring travel time savings analysis. The analysis of benefits through reductions in energy consumption was conducted using a newly-built microscopic scale top-down approach. Analysis of benefits through safety enhancements was mainly focused on fatal crashes. According to the results, the Benefit/Cost ratio (BCR) for a typical ATCS deployment may range between 6.52 and 13.04; whereas the BCR for a typical ramp metering deployment is expected to be around 6.44. We consider the results obtained from our B/C framework as conservative, which means that BCRs calculated in our study can be lower than specific ATCS and ramp metering deployments around the United States.

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transportation system management; highway operations; traffic congestion; environmental impacts; social impacts

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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
CO2e	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
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

1 INTRODUCTION

1.1 Background Information

The primary objective of Transportation Systems Management and Operation (TSM&O) strategies is to optimize the capacity of existing transportation infrastructure by reducing congestion. Over the past decades, agencies and researchers investigated the use of various strategies such as deployment of adaptive traffic control systems (ATCS), ramp metering, surveillance through closed circuit TV cameras, and information sharing systems to achieve this objective. Life Cycle Cost Analysis (LCCA) of various alternative 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.

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 this study is to address this gap in research.

1.2 Project Overview

The research team developed a comprehensive 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). The B/C framework for each ITS category was divided into four main areas:

1. Life Cycle Cost Analysis,
2. Analysis of Benefits through Travel Time Savings,
3. Analysis of Benefits through Reductions in Energy Consumption,
4. Analysis of Benefits through Safety Enhancements.

Literature review and data collection had been finished at the beginning to establish data support for building costs and benefits inventory. Due to the rapid development of ITS and the fluctuations in ITS costs, the inventory was built based on a time span of the past 10 years. Each of the four main areas analyzed is described briefly below:

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. A typical service life was assumed for each ITS.

The analysis of benefits through travel time savings was grouped into recurring travel time savings analysis, and nonrecurring travel time savings analysis. Several existing tools were introduced into this framework including TOPS-BC (developed by USDOT) and IDAS (developed by FHWA). Modifications were performed on these tools in order to make them more suitable for this project. For example, we introduced Akçelik speed-v/c ratio equation to replace the HCM 2010/2000 speed-v/c ratio equation that was adopted in TOPS-BC. IDAS traffic reliability lookup table was used to estimate the amount of nonrecurring travel time savings. In addition, the concepts of Value of Reliability (VOR) and Value of Travel Time (VOT) were used to quantify the overall travel time savings benefits, which combine the recurring and nonrecurring benefits.

The analysis of benefits through reductions in energy consumption was conducted using a newly-built microscopic scale top-down approach. In this method, the existing energy consumption for the link of interest is estimated using field test data, vehicle registration records from local DMV, or default lookup tables. A set of energy consumption reduction factors is assumed based on existing case studies, research studies, and simulations. To make the study more comprehensive and accurate, our team used three matrices to represent the real link traffic conditions considering vehicle type distribution (passenger cars, light trucks, heavy trucks, buses), vehicle age distribution (model years from 1990 to 2013), and traffic flow fuel economy distribution. All of these matrices can be modified based on local conditions for better accuracy. Equivalent existing traffic energy consumption estimation was achieved based on matrix inputs. In quantifying the energy consumption reduction benefits, we fit a linear equation to the recent 20 years' historical gasoline price data to roughly predict the next 20 years' gasoline price trend. Meanwhile, GaBi 6, a commercial LCA analysis software, was used to evaluate the reduction in lifecycle environmental impacts of reductions in gasoline consumption due to better traffic conditions after ITS deployment. Among the outputs of LCA are the amount of emissions including carbon dioxide, carbon monoxide, fluoride, hydrazine, hydrogen families, etc. An LCA-based benefits analysis due to reduction in gasoline consumption was conducted using 2013 Carbon Dioxide price forecast.

Analysis of benefits through safety enhancements was mainly focused on crash rates. A proper ITS deployment will maximize the performance of the existing link segment by increasing the link capacity, which in turn reduces the v/c ratio under same traffic demands. In this project, we started from classifying crashes according to the level of severity, then we calculated the v/c ratios before and after the ITS implementation, followed by determination of the crash rate-v/c ratio relationship and hence, determination of the existing and anticipated crash rates for fatal crashes. The last step was assigning monetary values to each level of crash, and calculating the annual safety benefit.

1.3 Summary of the Results

The B/C framework runs successfully on ATCS and ramp metering systems. We set up a hypothetical case study for each ITS to represent the general deployment. Length of analyzed segment, number of lanes, free flow speed (FFS), link capacity, traffic volume, and link capacity multiplication factor (presented in percentage) were assumed in each case study.

According to the results, for a typical ATCS deployment in the U.S., during an analysis life span of 20 years, a present value (PV) of approximately $1,135,000 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 (approximately 64%). For the remaining benefits, energy saving benefits, excluding the LCA benefits, account for 33%, and safety benefits due to declining crash rates (fatality level) account for 3%.

It is worth noting that the calculated results presented above are based on our hypothetical study, focusing on only one segment (the main segment, say Northbound-Southbound) at the intersection. The deployment of ATCS at an intersection will most likely benefit both segments. To simplify the evaluation of overall benefits from ATCS, we multiply the benefits calculated from the hypothetical study with a factor *k*. The worst case scenario corresponds to the case where ATCS does not benefit the other segment at all, in which scenario k equals to 1.0; while in the best case scenario, ATCS benefits the other segment in the same amount as the main segment, in which case k equals to 2.0. The final benefit to cost ratio (BCR) is presented as a range rather than a fixed-value.

For a typical ramp metering deployment in the U.S., during an analysis life span of 20 years, a PV of approximately $3,811,000 can be expected for the total life cycle benefits of the hypothetical case study. Energy savings benefits (LCA benefits excluded) due to gasoline consumption reduction accounts for the most part in the total life cycle benefits (approximately 78%). For the remaining benefits, travel time savings benefits, including recurring and nonrecurring travel time savings account for 15% and safety benefits due to reduced crash rates (fatality level) account for the remaining 7% of the benefits.

It is worth noting that the efficacy of both ATCS and ramp metering deployments can be maximized under traffic conditions with higher demands. The sensitivity threshold, represented by v/c ratio of 0.4 to 0.5, implies that ATCS applications are more suitable to be deployed at busy traffic segments. The introduction of LCA provides a comprehensive method to evaluate the environmental impacts of energy consumption reduction from a broader perspective. Due to the relatively small contribution in the energy savings value, the LCA part is not taken into the final BCA calculation. However, the importance of LCA impacts cannot be ignored. We consider results obtained from our B/C framework as conservative, which means the BCRs achieved from BCAs in our study can be expected to be lower than specific ATCS and ramp metering deployments around the United States.

2 ADAPTIVE TRAFFIC CONTROL SYSTEMS

2.1 Introduction

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. Rapid development of technologies and regional disparities significantly influence the result of LCCA on current and potential ATCS 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 deployments from a more comprehensive perspective. Therefore, it is necessary to collect updated costs and benefits data for the entire life cycle of ATCS deployments to develop a new Benefit/Cost Analysis (BCA) framework. The objectives of this chapter are to assess the triple bottom line (TBL, includes economic, environmental, and social) benefits, and life cycle cost analysis (LCCA) of a typical ATCS deployment, to perform a BCA for current ATCS practices, and to setup a BCA framework for future deployments.

2.1.1 Background Information

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. We list some control systems that have been installed and operated in the United States as follows:

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).

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.

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.

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.

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.

2.2 Literature Review

Several LCCA and B/C analysis based case studies have been conducted for ATCS deployments in the recent decades. This chapter provides a review of the life cycle benefits and life cycle costs of existing ATCS 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.

2.2.1 ATCS Cost Database

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, 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.

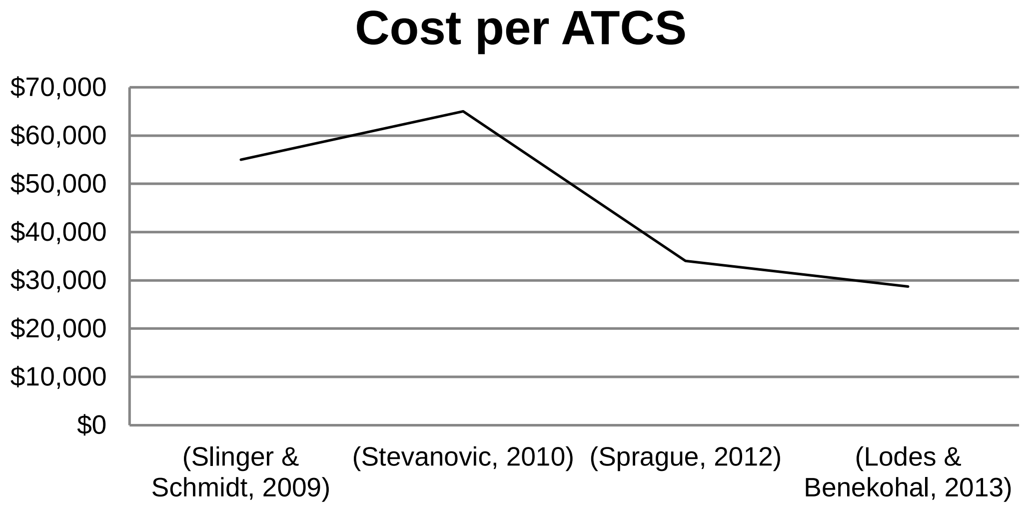

FIGURE 1: THE CHANGE OF ATCS DEPLOYMENT COST FROM 2009 TO 2013.

2.2.2 ATCS Benefits Database

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, 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 to 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).

2.3 Methodology

2.3.1 LCCA of ATCS

The Life Cycle Cost Analysis of an ATCS deployment include infrastructure costs, which occur at the "year zero" of system installation; incremental costs; and operation & maintenance costs, which occur along the entire life cycle of the ATCS deployment. A typical service life of 20 years, and a fixed discount rate of 7% were assumed in this study to perform the LCCA.

2.3.1.1 Infrastructure Costs of ATCS

The infrastructure costs 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 infrastructure costs 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).

2.3.1.2 Incremental Costs of ATCS

The incremental cost for ATCS includes changing and updating signal controller, communication lines, loop detectors, etc. based on a fixed schedule. Some existing manuals and BCA tools have established 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, we preferred to adopt these costs in our 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.

2.3.1.3 Operation & Maintenance Costs of ATCS

During the life cycle of an ATCS deployment, Operation & Maintenance (O&M) activities occur on both infrastructure and incremental equipment. O&M costs vary according to the difficulties 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 all the costs involved in the LCCA, discount rate was assumed to be fixed at 7% through out a service life of 20 years according to the Office of Management and Budget.

In the following content, we used the term "*existing*" to indicate the traffic scenario before ATCS deployment, and the terms "*anticipated*" and "*enhanced*" to indicate the traffic scenario after ATCS deployment for our analysis.

2.3.2 Travel Time Savings Analysis of ATCS

In travel time savings analysis for ATCS 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 Volume/Capacity (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 enhanced traffic conditions. For the nonrecurring travel time savings analysis, IDAS Travel Reliability Lookup Table was adopted to estimate both the existing and enhanced 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 enhancement due to proper ATCS deployment.

2.3.2.1 Traffic Reliability Analysis Overview

Although lacking of 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 of time (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 2 below:

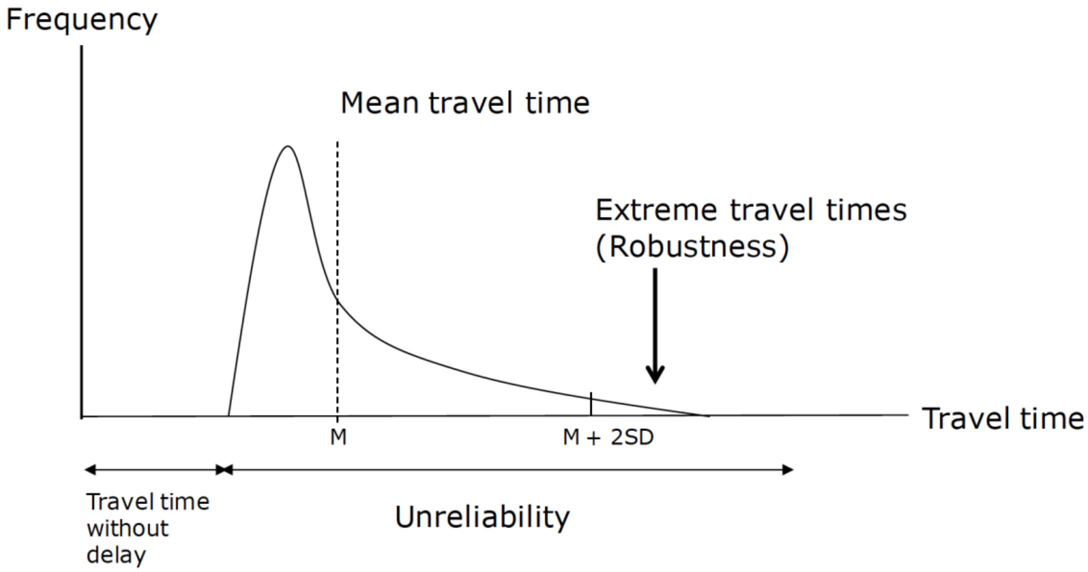

FIGURE 2: TRAVEL TIME HISTORICAL DATA DISTRIBUTION.
(LOOP, PERDOK, & WILLIGERS, 2014)

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.

In this project, the estimation of travel time savings for ATCS deployment included both recurring travel time savings, and traffic reliability, which can be presented as nonrecurring travel time savings. The recurring travel time savings value was estimated based on traffic speed-flow rate relationship. Nonrecurring travel time savings value was estimated using IDAS Travel Time Reliability Lookup Table developed by Cambridge Systematics, Inc. In this project, a 2-cycle method was introduced into travel time savings analysis. A brief summary of this 2-cycle method is presented below. The detailed methodologies for both recurring/nonrecurring travel time savings are discussed in the following sections.

- 1st Cycle - Measure Existing Travel Time (ETT) & Existing Travel Time Reliability (ETTR) (1st Cycle) before ATCS deployment on a given roadway segment.

- 2nd Cycle - Estimate Anticipated Travel Time (ATT) & Anticipated Travel Time Reliability (ATTR) (2nd Cycle) after ATCS deployment on a given roadway segment.

2.3.2.2 Recurring Travel Time Savings

The existing travel time was estimated under the "no ITS" deployed condition, or fixed/preset timing signal control condition. The detailed procedure for analysis is provided below:

- 1st Step - If applicable, perform field measurements of FFS and link capacity for every analyzed segment.
- 2nd Step - If field measurements are not applicable, use HCM 2010 for on-the-road FFS estimation and Akçelik Lookup Table for link capacity estimation.
- 3rd Step - Calculate the v/c ratio from either onsite measurements or the estimated values for every segment.
- 4th Step - Substitute FFS and v/c ratio into Akçelik flow rate equation to determine average travel time and speed.

2.3.2.2.1 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, according to FHWA (Klein, Mills, & Gibson, 2006), indirect data collection (e.g., loop detector) is the most widely used method in field measurements.

2.3.2.2.2 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:

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

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 in order 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.

2.3.2.2.3 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 enhanced 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. As a result of screening efforts, all of 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:

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

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 we adopted in our analysis is presented below:

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

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 BRP and Akçelik travel time - v/c ratio equation curve in undersaturated and oversaturated traffic conditions (Dowling & Skabardonis, 2008). It could be found from Figure 3 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.

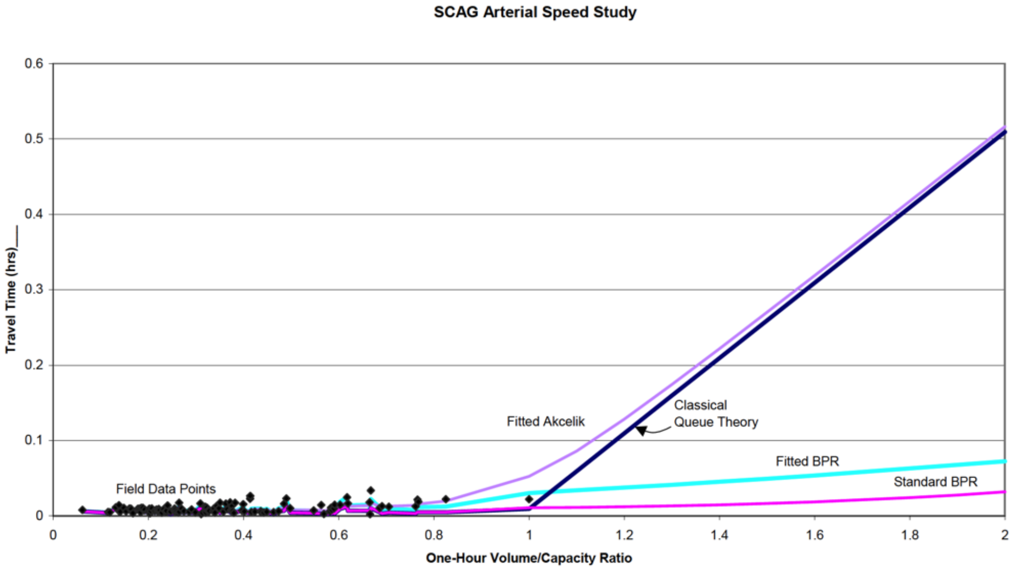

FIGURE 3: THE DIFFERENCES BETWEEN BPR AND AKÇELIK CURVES AFTER THE V/C RATIO REACHES 1.0. (DOWLING AND SKABARDONIS, 2008)

2.3.2.2.4 Link Capacity Multiplication Factor

To better quantify the improvement in link capacity due to ideal ATCS deployment onsite, we introduced an adjustment factor, namely "link capacity multiplication factor", 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 practices, literature and databases and they are in line with the FHWA Operations Benefit/Cost Analysis Tools.

2.3.2.2.5 Recurring Travel Time Savings Estimation

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

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

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.

2.3.2.3 Nonrecurring Travel Time Savings

2.3.2.3.1 IDAS Traffic Reliability Lookup Table

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 a number of national freeway corridors. The determination of traffic reliability rates are based on several key traffic factors, including 1) the number of facility lanes, and 2) the facility v/c ratio. In this project, we introduced IDAS look-up table into nonrecurring travel time savings analysis.

2.3.2.3.2 Nonrecurring Travel Time Savings Estimation

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 deployment:

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

2.3.2.4 Equivalent Travel Time Savings Estimation & Valuation

For compatibility of valuations of travel time savings benefits in this chapter, and environmental and social benefits in following chapters, in this project, we monetized all the benefits and expressed them in 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 nonrecurring travel time savings benefits, recurring travel time savings benefits are relatively easy to be evaluated. After determining the amount of recurring travel time savings, the entire traffic flow should be categorized according to 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. Travel time values are usually set as $24 to $28 for trucks and $12 to $14 for cars (Bhargava, Oware, Labi, & Sinha, 2006) (FHWA, 2012). This value should also be adjusted according to local conditions for regional deployment.

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. This value should be adjusted according to local conditions for regional deployment.

2.3.3 Energy Consumption Reduction Analysis of ATCS

Proper ATCS 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 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, 2010) (U.S Department of Transportation, 2001). The procedure of this approach is summarized below:

- 1st Step - Determine the boundary of study area.
- 2nd Step - Estimate existing traffic flow vehicle type distribution (Passenger Cars, Trucks).
- 3rd Step - For each vehicle type, estimate the age distribution.
- 4th Step - For each vehicle type, use fuel economy by model year to calculate the equivalent average fuel consumption for this vehicle type.

- 5th Step - Calculate the equivalent average fuel economy for the entire study segment.
- 6th Step - Define the fuel consumption reduction factor for ATCS deployment.
- 7th Step - Quantify and monetize the fuel consumption reduction benefits.
- 8th Step - Perform an LCA for calculated fuel consumption reduction.

2.3.3.1 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:

$$\begin{aligned} T_{i\,(i=1,\ldots,4),j} &= Vehicle\ Type\ Distribution, where\ T_{1,j} = Passenger\ Car, T_{2,j} \\ &= Light\ Duty\ Truck, T_{3,j} = Heavy\ Duty\ Truck, and\ T_{4,j} = Bus \end{aligned}$$

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

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:

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

2.3.3.2 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:

- 1st Step - VIN data collection from local DMV
- 2nd Step - Build VIN inventory
- 3rd Step - VIN Decoding
- 4th Step - Vehicle Classification
- 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, we ignored vehicles older than 23 years (before 1990) in our analysis.

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. We combined Type ID 31 "Passenger Truck row" and Type ID 32 "Light Commercial Truck row" in MOVES matrix 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 1. The sum of each row may not be exactly equal to 0, since the vehicles before the year 1990 were ignored.

TABLE 1: 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):

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

*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.

2.3.3.3 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 DOT, 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 2:

TABLE 2: 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 3:

TABLE 3: 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.

2.3.3.4 Equivalent Existing Traffic Energy Consumption Estimation

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

$$Q = Volume\ * number\ of\ lanes * analyzed\ period$$

$$* \begin{bmatrix} \frac{T_{1,1}A_{1,1}}{F_{1,1}} & \frac{T_{1,1}A_{1,2}}{F_{1,2}} & \cdots & \frac{T_{1,1}A_{1,24}}{F_{1,24}} \\ \frac{T_{2,1}A_{1,1}}{F_{1,1}} & \frac{T_{2,1}A_{1,2}}{F_{1,2}} & \cdots & \frac{T_{2,1}A_{1,24}}{F_{1,24}} \\ \frac{T_{3,1}A_{1,1}}{F_{1,1}} & \frac{T_{3,1}A_{1,2}}{F_{1,2}} & \cdots & \frac{T_{3,1}A_{1,24}}{F_{1,24}} \\ \frac{T_{4,1}A_{1,1}}{F_{1,1}} & \frac{T_{3,1}A_{1,2}}{F_{1,2}} & \cdots & \frac{T_{4,1}A_{1,24}}{F_{1,24}} \end{bmatrix}$$

The difficulties 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 a software, for example MOVES, can be used to perform the estimation. We calculated 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.

TABLE 4: 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

2.3.3.5 Energy Consumption Reduction Benefits Estimation & Evaluation

According to the Independent Statistics & Analysis from U.S. Energy Information Administration, until May 2014, the average gasoline price for the U.S. was $3.549. Considering that the historical average gasoline retail price increased from below $1.2/gallon (1995) to over $3.5/gallon (2014) in the recent 10 years (data acquired from U.S. Energy Information Administration, accessed date April 2014), the rate of increase in the average gasoline price can be assumed using a curve fitting procedure. Figure 4 below presents the linear equation obtained by analyzing the historical fuel price changes in the recent 20 years.

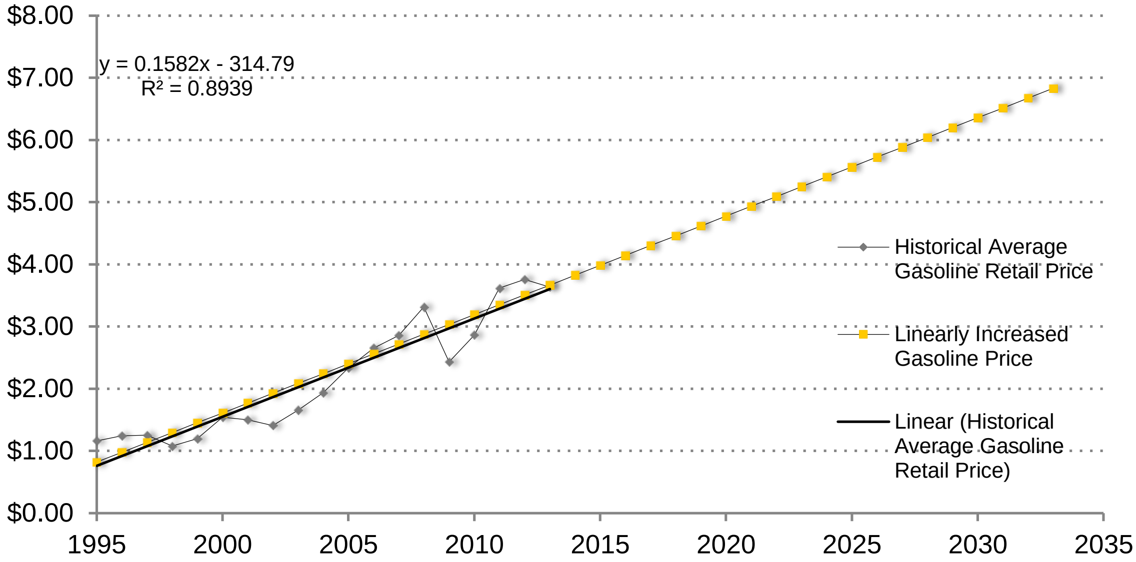

FIGURE 4: LINEAR CURVE FIT FOR THE HISTORICAL FUEL PRICE CHANGES IN THE RECENT YEARS.

The annual average gasoline price for the next 20 years can be roughly estimated according to equation presented in Figure 4.

2.3.4 LCA of ATCS

2.3.4.1 Overview of LCA Approaches

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 is briefly discussed in the following sections:

Process LCA approach, the traditional LCA approach, was firstly defined by ISO 14000 standards, and then specified in ISO 14001:2004 (ISO/IEC, 2004), and ISO 14006:2011 (ISO/IEC, 2011). Process LCA offers the advantages/strengths of 1) detailed process-specific analysis ability, 2) working on specific products, 3) weak point analysis, and 4) future product development. Meanwhile, it comes with the drawbacks of 1) vague system boundary, 2) high costs and time intensiveness, 3) complicated process design, and 4) difficulties in data collection (Carnegie Mellon University). This bottom-up LCA approach has not been widely adopted in engineering and management areas.

Contrary to Process LCA, Economics Inputs-Outputs Life Cycle Assessment (EIO-LCA) (Carnegie Mellon University) is a top-down approach that (1) focuses on total outputs, (including direct and indirect outputs), and final demands; (2) treats the whole economy as the boundary of analysis. One of the biggest advantages of EIO-LCA lies in its capacity of solving complex and subtle intermediate sectors' activities, for which the interdependencies are nearly impossible to handle using the detail-oriented Process LCA approach. Meanwhile, based on large economy sectors, EIO-LCA lacks the ability in analyzing some specific products, and cannot define the weak points in the supply chain. The "black box" type analysis procedure has raised concerns about the accuracy of the results.

Hybrid LCA is a method that combines process LCA and IO-LCA approaches in a manner that exploits their strengths and curtails their weaknesses.

2.3.4.2 LCA Tools Overview

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

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, which in this case the reduced fuel consumption value, this tool was eliminated during the preliminary development stage.

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 our study, we did not select OpenLCA in our project.

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. We introduced GaBi into our 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. The LCA of reduced on-the-road fuel consumption was modeled in GaBi 6 and discussed in the next section.

2.3.4.3 GaBi 6 Model

GaBi 6 was introduced into our project to evaluate the comprehensive environmental benefits of energy consumption reduction due to ATCS deployment. The Model, presented in Figure 5, was built to calculate the cradle-to-grave environmental impacts of combusted gasoline on the road.

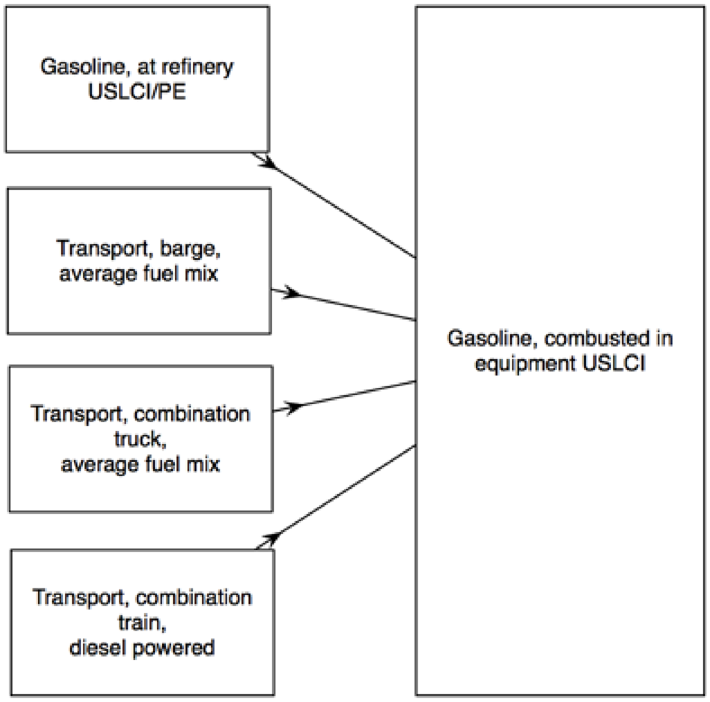

FIGURE 5: I/O FLOWS FOR GASOLINE COMBUSTED IN EQUIPMENT.

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 10^4 kgkm
  - US: Transport, combination truck, average fuel mix
    - Amount: 5.25 10^3 kgkm
  - US: Transport, train, diesel powered
    - Amount: 3.36 10^3 kgkm
- Output Parameter Flow:
  - Gasoline, combusted in equipment
    - Amount: $1m^3$

Although gasoline at refinery is used directly as an input, the LCA for the combusted gasoline used in transportation involves stages from crude oil to gasoline at refinery, and to the finished vehicle-consumed gasoline. Figure 6 below illustrates the input flows to the gasoline at refinery.

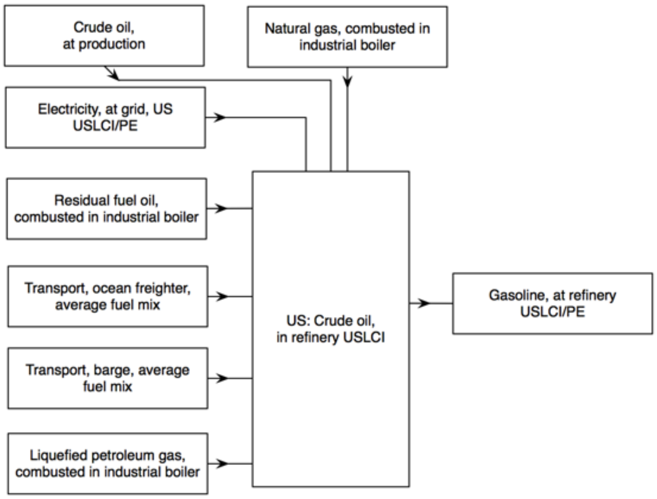

FIGURE 6: I/O FLOWS FOR GASOLINE AT REFINERY.

Considering the cubic meter to US gallons conversion rate as 264.172 US gal/m^3, Table 5 below shows all the air emissions per gallon of combusted gasoline calculated using the GaBi model:

TABLE 5: GABI LCA RESULT OF AIR EMISSIONS PER GALLON OF COMBUSTED GASOLINE

Emissions/gallon of gasoline	Amount (kg)	%
Ammonia	6.51091E-05	0.00%
Beryllium	2.1274E-09	0.00%
Carbon Dioxide	9.084990082	92.77%
Carbon Monoxide	0.556455643	5.68%
Fluoride	6.39735E-12	0.00%
Hydrazine	6.09451E-12	0.00%
Hydrogen Chlorde	9.61495E-05	0.00%
Hydrogen Fluoride	1.1167E-05	0.00%
Hydrogen Sulphide	1.86999E-13	0.00%
Nitrogen Oxides	0.13589631	1.39%
Nitrous Oxide	0.00023886	0.00%
Sulphur Dioxide	0.015558046	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.

2.3.4.4 GWP Pricing Prediction

The 2013 Carbon Dioxide Price Forecast (Luckow, Stanton, Biewald, Fisher, Ackerman, & Hausman, 2013) developed low, medium, and high case forecast for CO_2 prices from 2013 to 2040. The prediction is based on comprehensive reviews on historical data, and existing models. The Synapse 2013 CO_2 price Trajectories are cited in Figure 7 below:

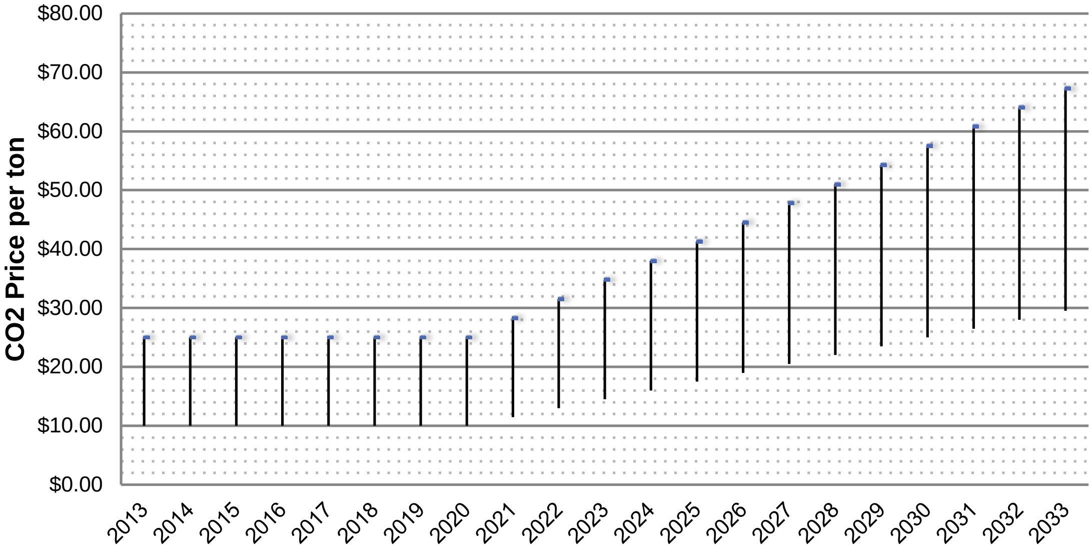

FIGURE 7: THE SYNAPSE 2013 CO2 PRICE TRAJECTORIES.
(LUCKOW, STANTON, BIEWALD, FISHER, ACKERMAN, & HAUSMAN, 2013)

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

2.3.5 Safety Analysis of Typical ATCS

As the third component in the TBL approach, safety enhancements contribute to the social benefits of ATCS 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 issue. The methodology of estimating and evaluating safety benefits is presented in this section.

2.3.5.1 Crash Rate and V/C Ratio Relationship

In this project, we developed the procedure of estimating and evaluating safety benefits due to ATCS deployment 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 8 below was derived from the NHTSA’s crash rate estimation table, and TOPS-BC's built-in database.

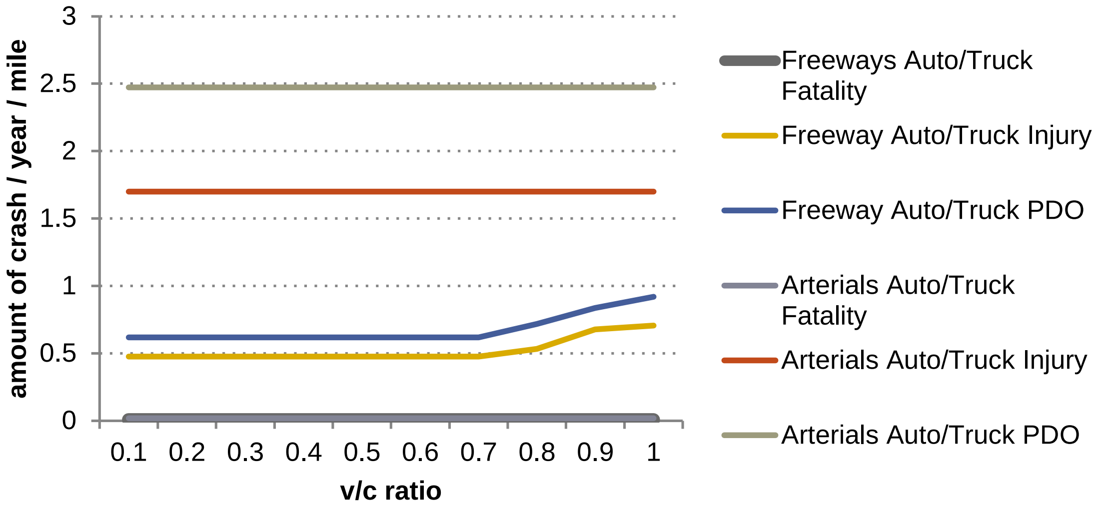

FIGURE 8: THE AMOUNT OF CRASH TO V/C RATIO RELATIONSHIP CURVES DERIVED FROM NHTSA'S CRASH RATE ESTIMATION TABLE.

From the diagram above, we may find that only freeway auto/truck injury and PDO crash rates change with increasing levels of traffic density, 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:

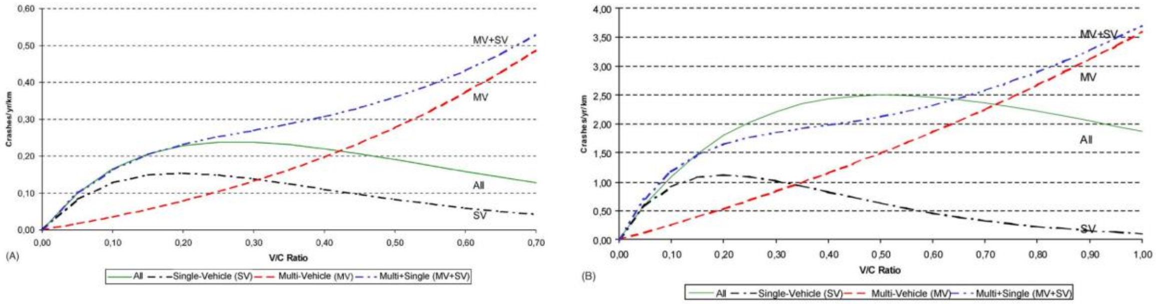

FIGURE 9: CRASH RATE TO TRAFFIC DENSITY RELATIONSHIP UNDER RURAL AND URBAN CONDITIONS.

Figure 9 above 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 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 enhanced v/c ratio are then substituted into above equation to calculate the total number of crashes on the analyzed segment per year.

2.3.5.2 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.

2.4 Analysis Results

2.4.1 LCCA Results of ATCS

With all the information collected as described in the methodology chapter, the present value (PV) for the life cycle cost of the ATCS deployed per intersection for a time period of 20 years was estimated. In this LCCA, the infrastructure cost in the initial year (2013) was assumed as $28,725 per intersection, incremental costs for the following 20 years are summarized in the following table. ATCS life cycle cost item breakdown are listed as follows:

- Signal controller: $6,250 (every 15 years)
- Loop detectors: $11,750 (every 5 years)
- Communication lines: $750 (over 20 years)
- Meanwhile, an annual $9,000 O&M cost is assumed.

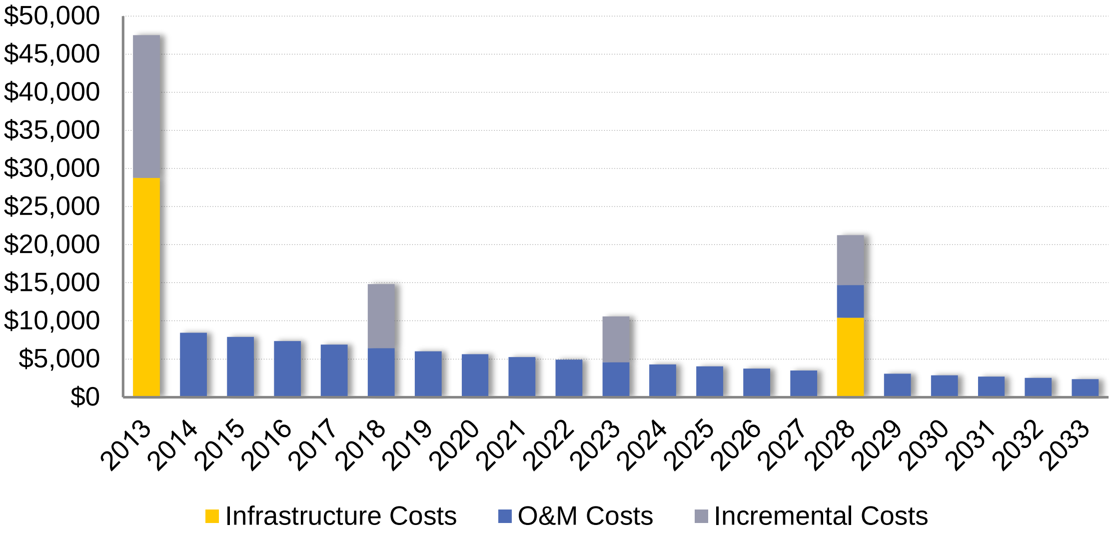

FIGURE 10: LIFE CYCLE COST ANALYSIS FOR TYPICAL ATCS DEPLOYMENT IN PRESENT VALUE.

TABLE 6: LIFE CYCLE CCST 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

It could be found from Figure10 and Table 6 that the total PV for life cycle cost of a typical ATCS deployment in the United States is around $174,000. This number will be used as the baseline for the BCA in the following sections.

*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 the 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.

2.4.2 Travel Time Savings Benefits of ATCS

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. A BCA was performed at the end to present the B/C scenario considering only the travel time savings benefit.

2.4.2.1 Hypothetical Case Study Overview

The recurring travel-time savings benefits of ATCS 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 and 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 enhanced 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 final 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 final result for both segments at the intersection will have a value ranging from 1.0 to 2.0 times the calculated result.

- *Length of analyzed segment: 1 mile*
- *Number of lanes: 2 (1 for each direction)*
- *Free Flow Speed (FFS): 35 mph*
- *Link Capacity per lane: 2000 vph*
- *Traffic Demand (Volume): 400 vph to 4000 vph, which implies the v/c ratio ranges from 0.10 to 1.0.*
- *Link Capacity Multiplication Factor: 8% to 12%*

The above hypothetical case study will be 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.

2.4.2.2 Recurring Travel Time Savings Estimation

In the recurring travel time savings 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 11 below (showing the relationship between speed and traffic demand) exhibits the existing traffic flow average speed before the ATCS deployment under different levels of congestion (from not congested to extremely congested).

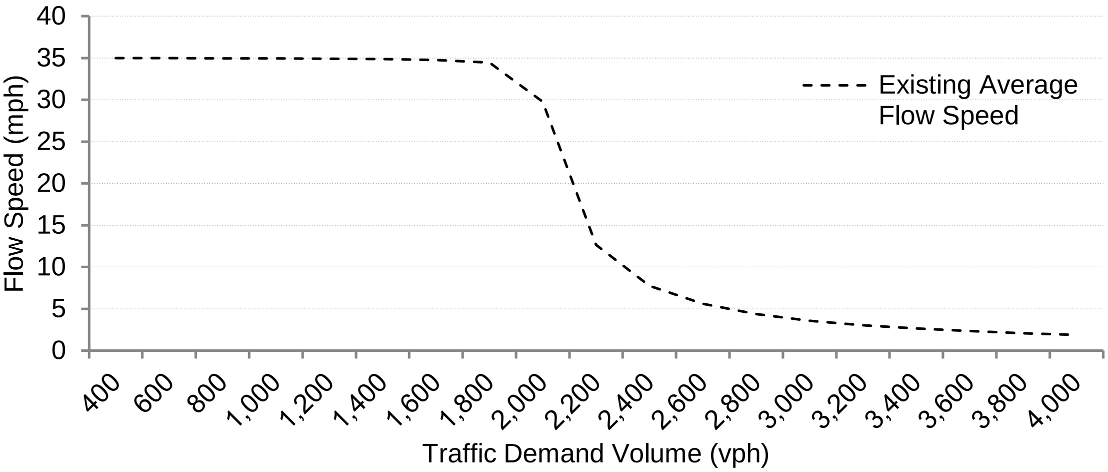

FIGURE 11: SPEED AND TRAFFIC DEMAND RELATIONSHIP BEFORE ATCS DEPLOYMENT UNDER DIFFERENT LEVELS OF CONGESTION.

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

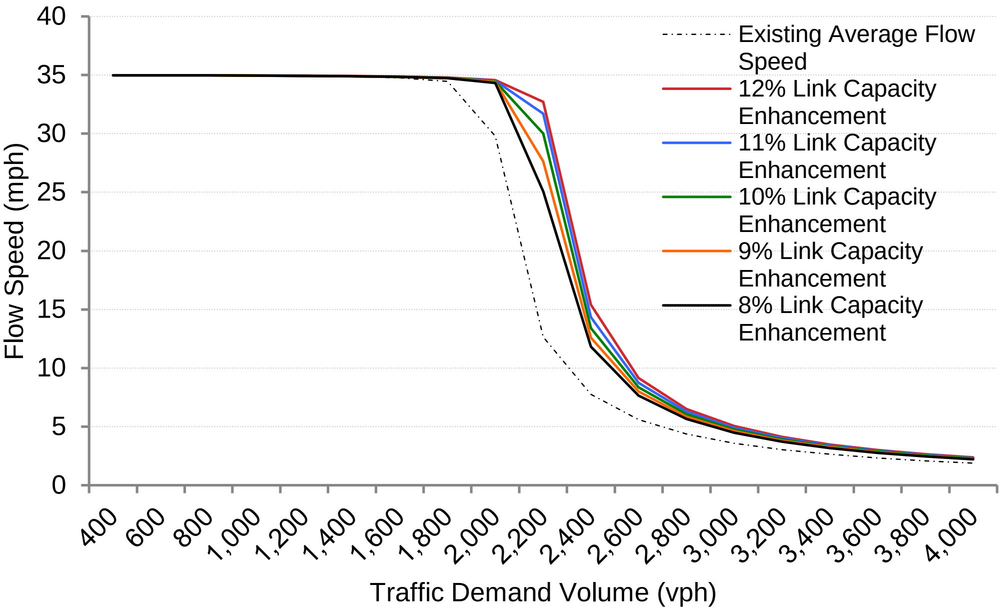

FIGURE 12: THE CHANGE OF AVERAGE FLOW SPEED DUE TO ENLARGED LINK CAPACITY AND REDUCED V/C RATIO UNDER SAME TRAFFIC DEMAND.

It is interesting to note from the diagram that the enhanced link capacity “postpones” the saturation point of the current traffic. For example, if the ATCS increases the link capacity by 8%, under 2000 vph traffic demand, the enhanced 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 7 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 is not obvious until the threshold is reached. In this hypothetical case, the threshold point can be considered as when traffic v/c ratio reaches 0.4. Figure 13 illustrates the dramatic trend of travel time reductions under various traffic demand conditions after ATCS deployment.

TABLE 7: 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**

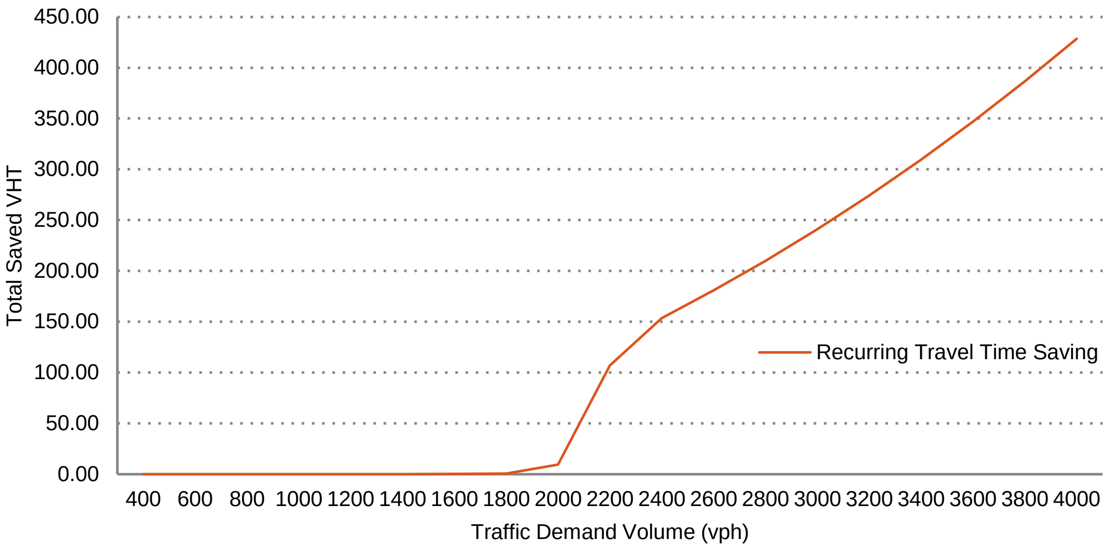

FIGURE 13: TRAVEL TIME REDUCTIONS UNDER VARIOUS TRAFFIC DEMANDS AFTER ATCS DEPLOYMENT.

The recurring travel time savings under different v/c ratios were calculated using the above-mentioned methodology and the results are summarized in Table 8. Link capacity multiplication factors ranging from 8% to 12% were used to represent the efficacy of ATCS 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 ATCS deployment 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 deployments.

TABLE 8: RECURRING TRAVEL TIME SAVINGS 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**										

2.4.2.3 Nonrecurring Travel Time Savings Estimation

In this section, we follow the nonrecurring travel time savings estimation methodology discussed in the previous chapter. For the consistency of TBL benefits life cycle analysis, we use the same hypothetical case provided in Recurring Travel Time Savings Estimation section to predict the nonrecurring travel time savings, then to calculate the total equivalent travel time savings which combines both recurring and incident travel time savings.

Figure 14 was derived from IDAS Travel Time Reliability Lookup Tables (IDAS User's Manual, Appendix B.2.15). The v/c ratio is then interpolated to determine the related incident traffic delay.

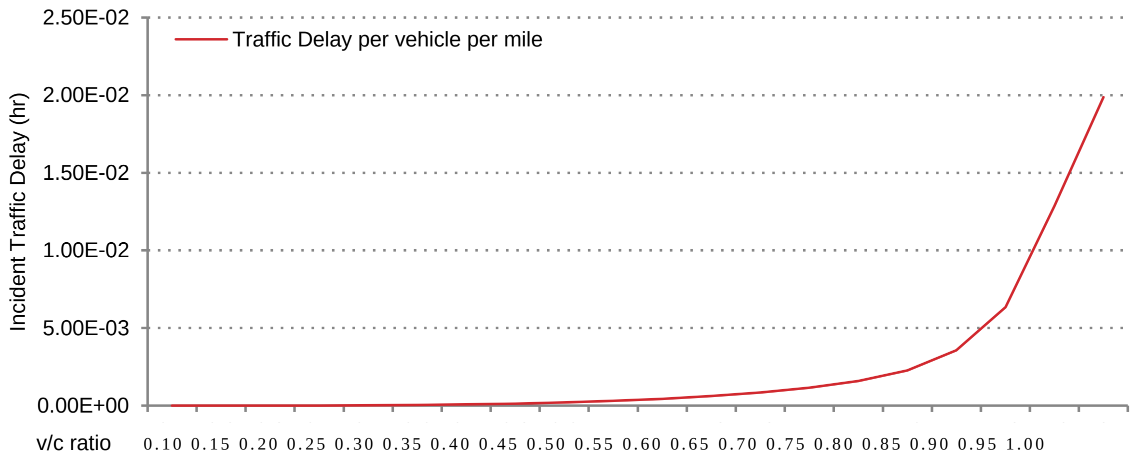

FIGURE 14: INCIDENT TRAFFIC DELAY - V/C RATIO RELATIONSHIP.

Table 9 below concludes the incident travel time savings with different link capacity multiplication factors ranging from 8% to 12% under different traffic demands ranging from 400 vph (v/c ratio = 0.1) to 4000 vph (v/c ratio = 1.0).

TABLE 9: 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

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 Institue, 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.

2.4.2.4 Total Equivalent Travel Time Savings Estimation

By combining the results from *Recurring Travel Time Savings Estimation*, and *Nonrecurring Travel Time Savings Estimation*, the total equivalent travel time savings for the hypothetical case study is calculated in Table 10:

TABLE 10: EQUIVALENT TRAVEL TIME SAVINGS FOR HYPOTHETICAL 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
SENSITIVITY	INSENSITIVE	THRESHOLD	SENSITIVE					

Figure 15 presents the travel time savings estimation with and without considering nonrecurring travel time savings (12% link capacity multiplication factor assumed). It could be noted from the diagram that the VHT saved becomes significant with the increasing levels of traffic demand （as v/c exceeds 0.5).

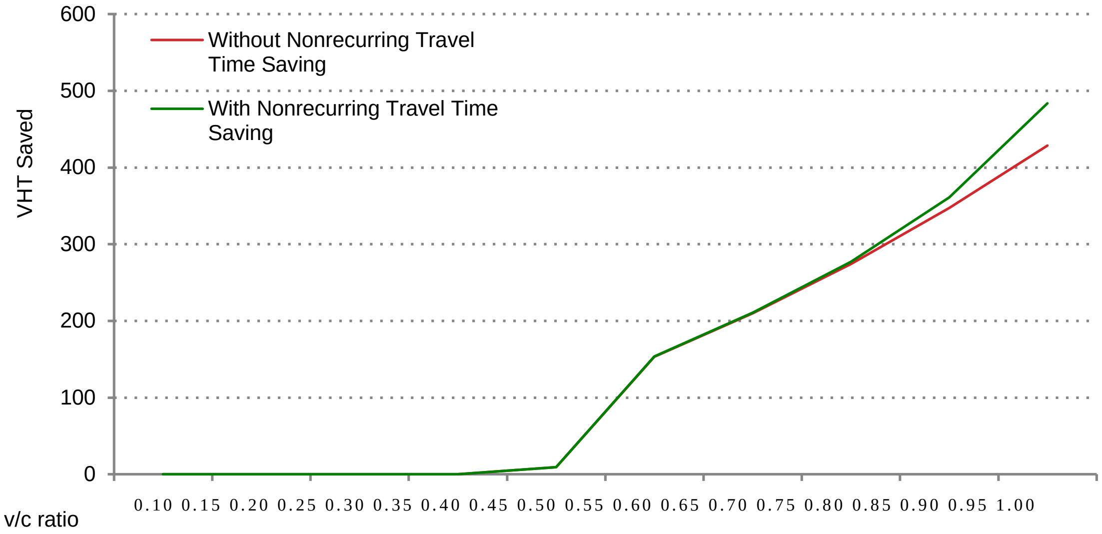

FIGURE 15: TRAVEL TIME SAVING ESTIMATION WITH AND WITHOUT CONSIDERING NONRECURRING TRAVEL TIME SAVINGS UNDER 12% LINK CAPACITY MULTIPLICATION FACTOR.

2.4.2.5 Travel Time Savings Benefits Valuation

After separating the vehicle types (passenger cars and trucks), determining the VOT and corresponding VOR for each vehicle type, and estimating the reliability ratio (RR), the equivalent travel time savings benefits of study segment after ATCS deployment can be quantified.

In the hypothetical case study, we assumed VOT as $12 for passenger cars and $24 for trucks, with a vehicle type distribution of 9 passenger cars to 1 truck (passenger cars to trucks: 9:1), and RR of 1, which implies equal importance of VOT and VOR. The annual benefits (255 workdays per year) for equivalent travel time savings during the peak hours (1 hour of peak time each during the morning and evening) due to anticipated ATCS implementation could be calculated as in Table 11. It is worth noting that since the sensitivity threshold is around 0.4; the benefits of travel time savings is not obvious under low traffic demand conditions.

TABLE 11: ANNUAL EQUIVALENT TRAVEL TIME SAVING BENEFITS DURING THE PEAK HOUR DUE TO ATCS DEPLOYMENT

v/c ratio	0.10	~	0.35	0.40	0.50	0.60	0.70	0.80	0.90	1.00
Annual Travel Time Benefit (USD) [12%]	$7.82	~	$481.35	$1,339.28	$63,614.84	$1,036,142.46	$1,420,464.01	$1,866,728.90	$2,432,036.58	$3,256,844.72
Annual Travel Time Benefit (USD) [11%]	$7.27	~	$451.52	$1,260.10	$63,025.47	$958,978.78	$1,313,862.49	$1,726,596.14	$2,249,456.99	$3,029,134.28
Annual Travel Time Benefit (USD) [10%]	$6.71	~	$420.28	$1,176.87	$62,337.13	$880,187.92	$1,205,313.00	$1,583,912.87	$2,063,556.58	$2,778,795.65
Annual Travel Time Benefit (USD) [09%]	$6.13	~	$387.52	$1,089.19	$61,518.61	$799,784.06	$1,094,762.89	$1,438,609.03	$1,874,243.98	$2,523,862.98
Annual Travel Time Benefit (USD) [08%]	$5.53	~	$353.13	$996.64	$60,524.07	$717,763.03	$982,157.42	$1,290,611.98	$1,681,424.47	$2,264,208.68
SENSITIVITY	INSENSITIVE			THRESHOLD	SENSITIVE					

Being consistent with the LCCA of average ATCS deployment, a service life of 20 years, and a discount rate of 7% is assumed for the life cycle travel time savings benefits.

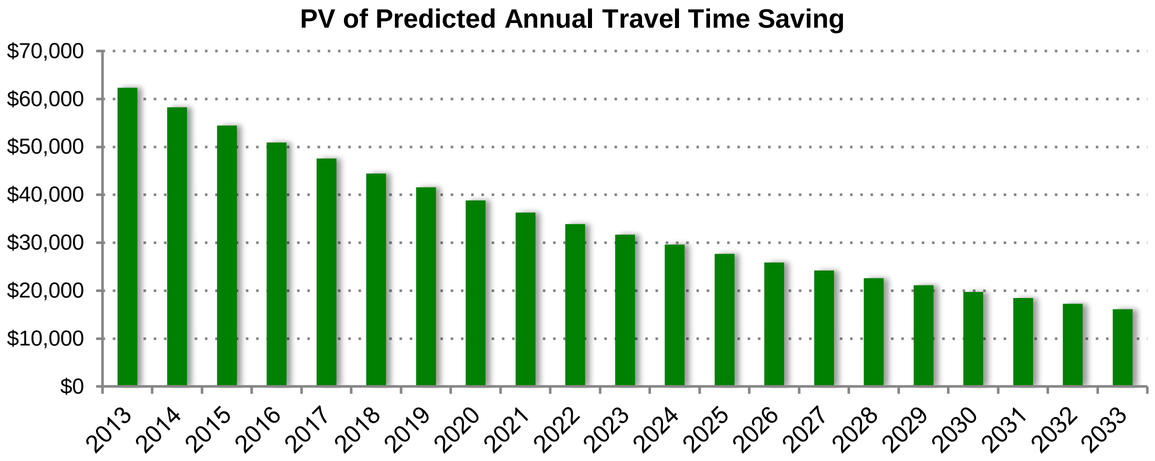

FIGURE 16: ANNUAL TRAVEL TIME SAVING BENEFITS (FOR ATCS) FLOW IN PV.

Figure 16 illustrates the present value of travel time savings benefits (assuming link capacity multiplication factor = 10%), under daily 2-hour traffic conditions with v/c=0.5 for the hypothetical case study for a period of 20 years. The total present value is calculated as $722,736. After comparing this value with the previously calculated life cycle cost of ATCS per intersection, a BCR 4.15:1 can be achieved. Figure 17 below presents the cash flow of costs and benefits for each year during the 20 year-span.

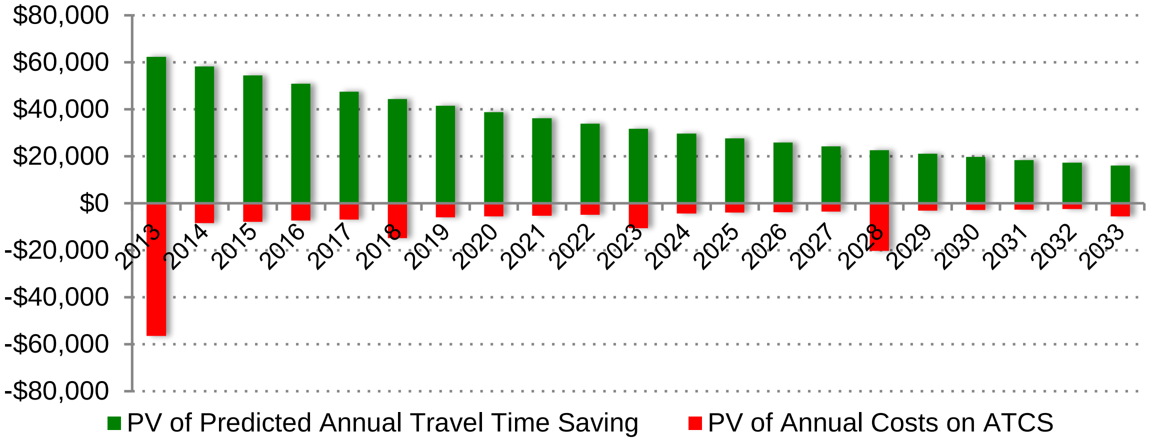

FIGURE 17: BENEFITS (TRAVEL TIME SAVINGS) AND COSTS FLOW FOR THE 20 YEARS' LIFE OF SERVICE FOR ATCS.

2.4.3 Energy Consumption Reduction Benefits of ATCS

The energy consumption reduction benefits analysis followed the methodology presented in the previous chapter. The on-the-road traffic flow fuel consumption was presented by vehicle type matrix, vehicle age distribution matrix, and fuel economy matrix. Dollar value was then assigned to the saved fuel consumption to calculate the monetized benefits. An LCA was introduced as an additional but important component for a comprehensive environmental impacts evaluation of a typical ATCS deployment in the United States. Similarly, A BCA was performed at the end to present the B/C scenario that considers the energy consumption reduction benefits only, and another scenario that considers both the travel time savings and energy consumption reduction benefits.

2.4.3.1 Hypothetical Case Study Overview

Following the previously defined methodology to conduct the estimation, prediction, and quantification of energy saving benefits, in this section, the same hypothetical case study is used to estimate the energy savings benefits for a highway segment after deployment of a typical ATCS. The basic infrastructure and traffic information are recalled as follows:

- *Length of analyzed segment: 1 mile*
- *Number of lanes: 2*
- *Free Flow Speed (FFS): 35 mph*

- *Link Capacity per lane: 2000 vph*
- *Traffic Demand (Volume): 2000 vph; v/c = 0.5*
- *Average daily passenger car to light duty truck ratio: 9:1*

Heavy-duty trucks and buses were ignored. For the consistency of the study, a life cycle of 20 years was used as the time span in the analysis.

2.4.3.2 Vehicle Type, Age, and Fuel Economy Distribution

Due to the absence of heavy-duty trucks and buses in the hypothetical case study, the number of rows in the vehicle type distribution matrix $[T]$, and age distribution matrix $[A]$ are reduced from 4 to 2. During a traffic condition with a demand of 2000 vph, (v/c = 0.5) the on-the-road vehicle type distribution according to these two matrices can be illustrated as the following:

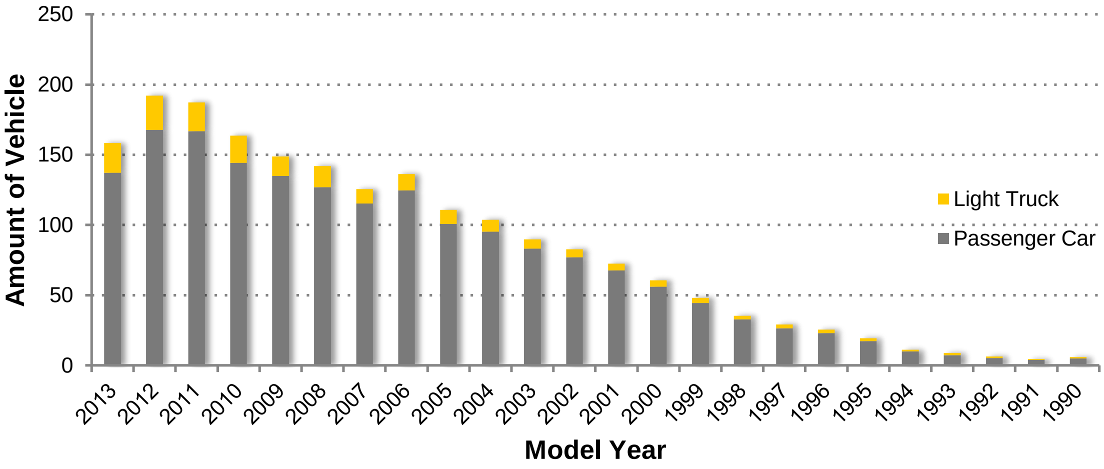

FIGURE 18: THE ON-THE-ROAD VEHICLE TYPE DISTRIBUTION.

Under traffic conditions with v/c = 0.5, the related flow speed dropped from FFS 35 mph down to approximately 25 mph using Akçelik speed-flow equation. The fuel economy matrix $[F]$ is then modified according to the fuel economy reduction factor α as 0.81. The modified vehicle economy matrix $[F]$ is presented in Figure 19 below:

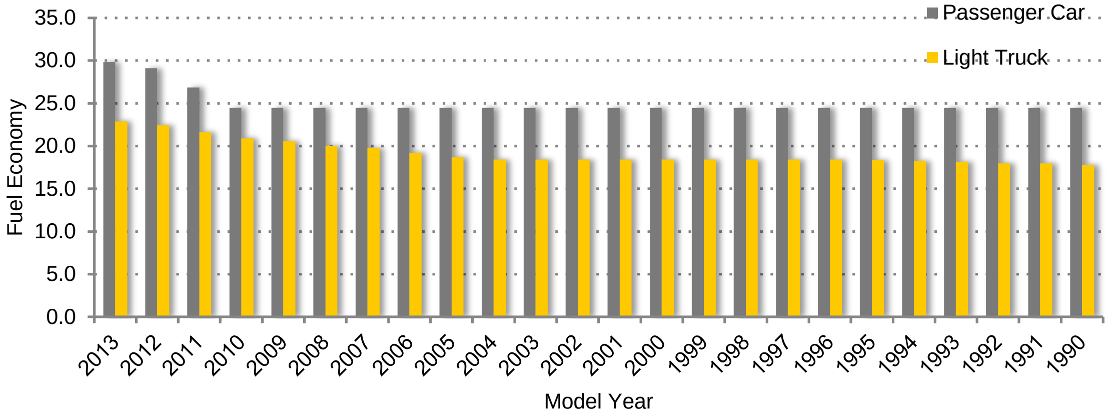

FIGURE 19: MODIFIED VEHICLE ECONOMY ACCORDING TO DIFFERENT MODEL YEARS.

The annual fuel consumption for the existing study segment under daily 2-hour traffic condition with a demand of 2000 vph before ATCS deployment can be calculated using the equation discussed in the methodology section. The total annual 2-hour fuel consumption is calculated as around 5,500 gallons for light trucks, and around 39,500 gallons for passenger vehicles (45,000 gallons in total, 255 workdays assumed). A bar chart of accumulative annual peak hour fuel consumption for both light truck and passenger car is presented in Figure 20.

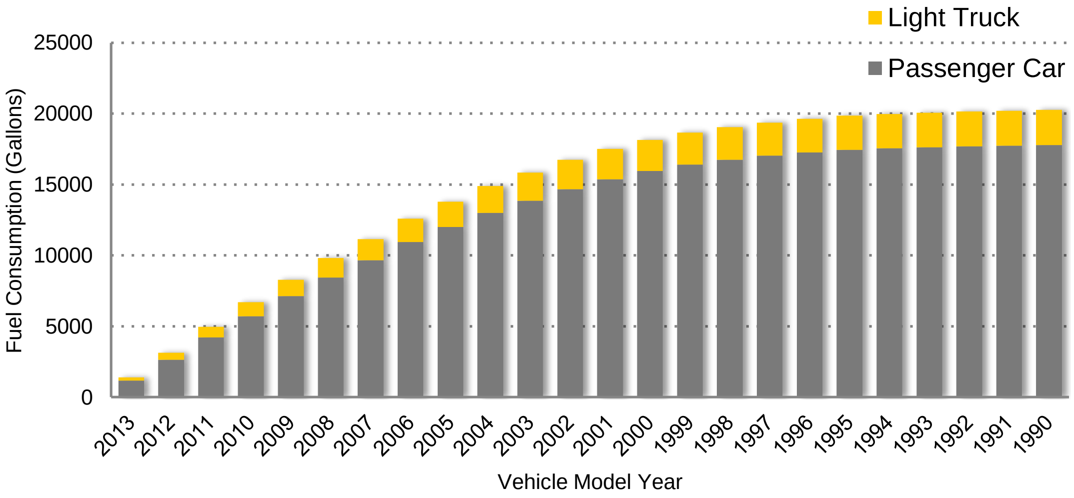

FIGURE 20: ACCUMULATIVE ANNUAL PEAK HOUR FUEL CONSUMPTION.

2.4.3.3 Energy Consumption Reduction Benefits Evaluation

Using the linear equation presented in the methodology section, a table of annual U.S average gasoline price prediction is concluded in Table 12.

TABLE 12: ANNUAL U.S. AVERAGE GASOLINE PRICE PREDICTION

Year	Gasoline Price ($/Gallon)
2014	$3.82
2015	$3.98
2016	$4.14
2017	$4.30
2018	$4.46
2019	$4.62
2020	$4.77
2021	$4.93
2022	$5.09
2023	$5.25
2024	$5.41
2025	$5.57
2026	$5.72
2027	$5.88
2028	$6.04
2029	$6.20
2030	$6.36
2031	$6.51
2032	$6.67
2033	$6.83

From the previous section, the total annual 2-hr fuel consumption is calculated as 45,000 gallons for the hypothetical case study. By assuming the next 20 years' gasoline prices, a 7% discount rate, and a **15% energy consumption reduction** due to ATCS deployment, the benefits in present value is calculated as shown in Figure 21. The total PV benefit is calculated to be approximately $380,000. Using the previously calculated total PV cost of $174,107 for the ATCS deployment, a BCR of 2.18:1 can be expected if only the peak-hour energy saving benefits are considered.

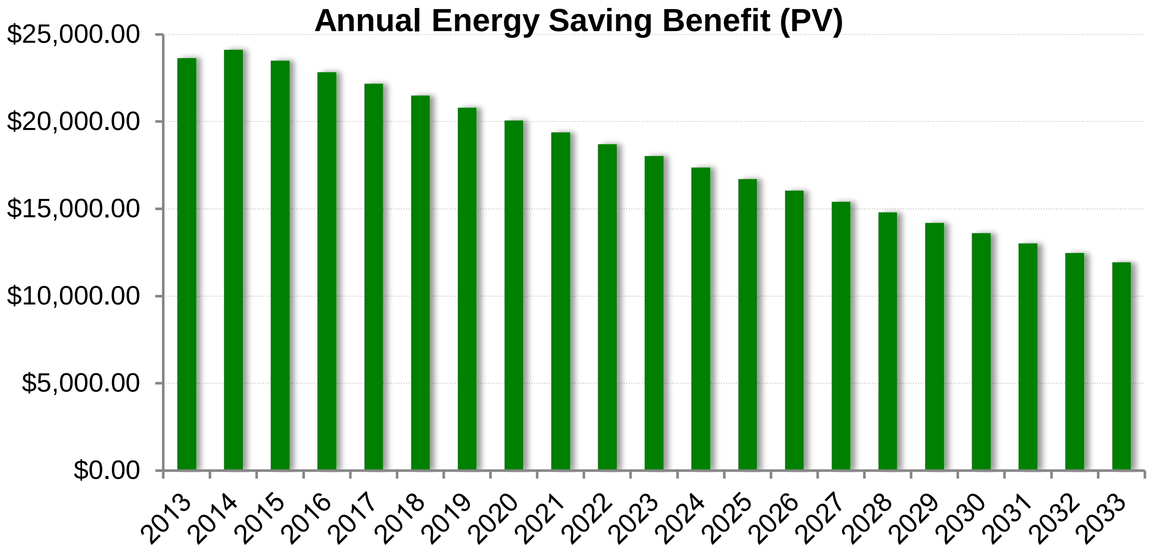

FIGURE 21: ANNUAL ENERGY SAVING BENEFITS IN PRESENT VALUE FOR ATCS.

If we add the total PV benefits of energy consumption reduction and travel time savings together into the life cycle benefit to cost analysis, the BCR can be expected as 6.34:1. Figure 22 illustrates the benefit/cost values during the next 20 years (2013 to 2033), considering both travel time savings benefits and energy savings benefits.

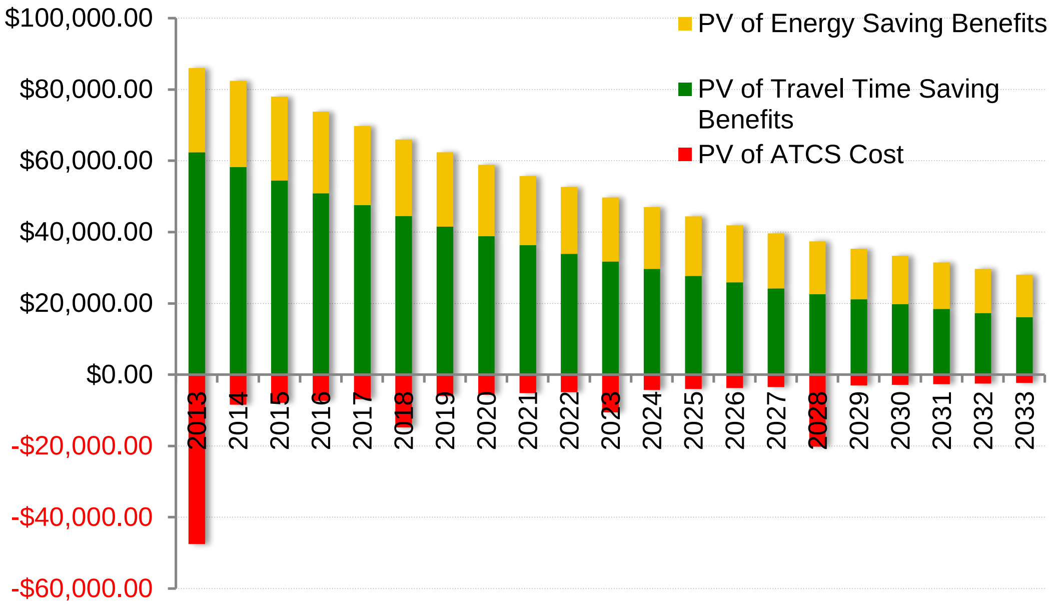

FIGURE 22: BENEFITS (TRAVEL TIME SAVINGS AND ENERGY SAVINGS) AND COSTS FLOW FOR ATCS DURING THE 20 YEARS' LIFE OF SERVICE.

2.4.3.4 LCA on Reduced Energy Consumption

From the previous section, the total annual 2-hr peak time fuel consumption was calculated as 45,000 gallons for the hypothetical case study. Given the next 20 years' gasoline prices, and 15% energy consumption reduction, an annual 6,750 gallons of gasoline savings can be expected. The result of the life cycle assessment shows an annual 61,290 kg ($6{,}150 gallon \times 9.08\ kg/gallon$) CO_2e emissions reduction due to fuel savings.

Following the carbon price prediction discussed in the methodology, the anticipated annual fuel savings benefit due to ATCS deployment during the next 20 years (2013 to 2033) can be calculated. The PV of the benefits for the hypothetical case study is presented (7% discount rate assumed) in Figure 23. A declining portion from 2013 to 2020 could be noticed from the graph, which is caused by the combined effect of steady carbon prices and the discounted benefits.

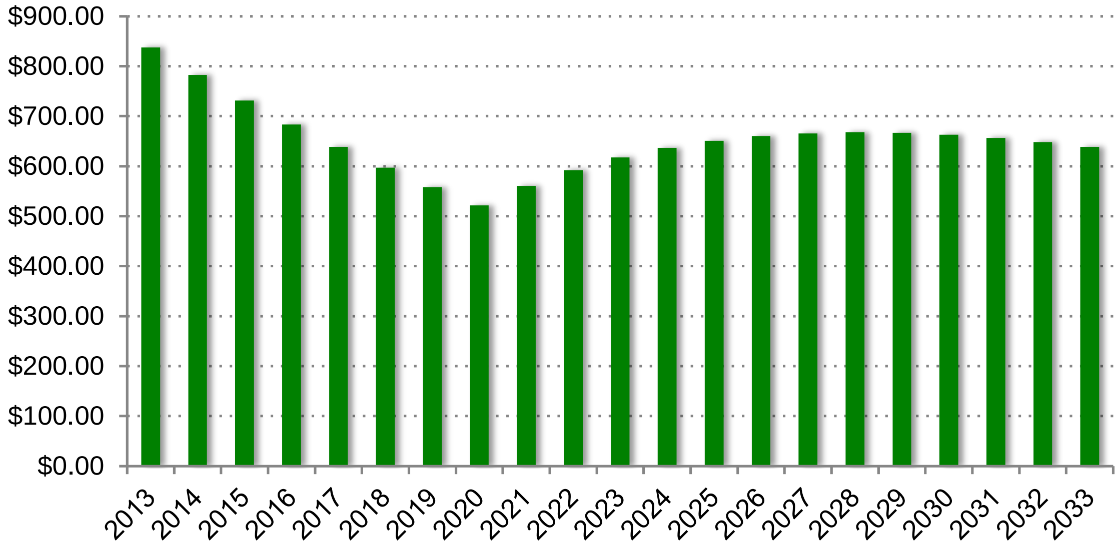

FIGURE 23: ANNUAL LIFE CYCLE ENVIRONMENTAL BENEFITS DUE TO REDUCED COMBUSTED GASOLINE IN PRESENT VALUE.

The total PV for the benefits due to reduced carbon emissions throughout a time span of 20 years as a result of deployment of ATCS is $14,600. Based on the total PV cost of $174,107 for the ATCS deployment, a BCR 0.34:1 can be expected.

2.4.4 Safety Benefits of ATCS

The safety benefits analysis was undertaken using the methodology presented in the previous chapter. The crash rates before and after the ATCS deployment 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.

2.4.4.1 Hypothetical Case Study Overview

The crash rate-v/c ratio relationship and monetary value per crash discussed in the methodology section were used to quantify the estimated safety benefits. In this section, the same hypothetical case study considered in the previous sections was used to estimate the safety benefits for a typical highway segment before and after ATCS deployment. The basic infrastructure and traffic information are recalled as follows:

- *Length of analyzed segment: 1 mile*
- *Traffic Location: Urban*
- *Number of lanes: 2*
- *Link Capacity per lane: 2000 vph*
- *Traffic Demand (Volume): 200 vph to 2000 vph, which implies the v/c ratio ranges from 0.05 to 0.50*
- *Link Capacity Multiplication Factor: 8% to 12%*

2.4.4.2 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 enhanced total crash rates before and after the ATCS deployment. The equation derived from the curve and adopted in this analysis is presented below:

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

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).

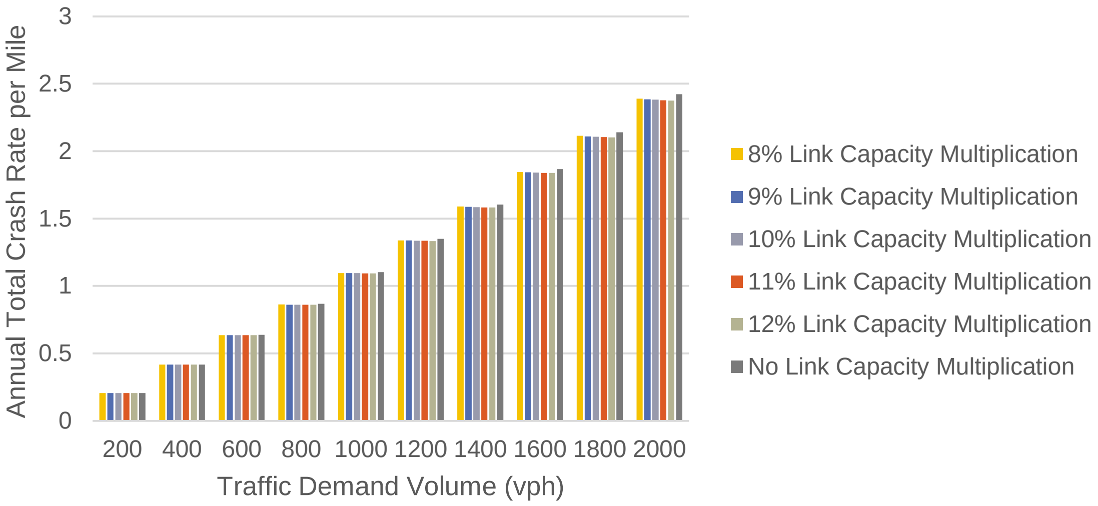

FIGURE 24: ANNUAL TOTAL CRASH RATE PER MILE TO TRAFFIC DEMAND RELATIONSHIP UNDER DIFFERENT LEVELS OF LINK CAPACITY MULTIPLICATION FACTORS.

Table 13 below presents the expected safety enhancement for link capacity multiplication factors ranging from 8% to 12% under different traffic demands ranging from 200 vph to 2000 vph. It is observed that the maximum safety benefit occurs when the demand equals 2000 vph. In the following safety benefits evaluation section, a safety enhancement of 1.67% under a v/c ratio of 0.5 was taken into consideration.

TABLE 13: 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%

2.4.4.3 Safety Benefits Evaluation

Figure 25 below exhibits the number of annual crashes under existing and enhanced (link capacity multiplication factor = 10%) traffic conditions for a demand of 2000 vph and a capacity of 4000 vph. Due to the ATCS deployment, under the same traffic demand, the traffic v/c ratio decreased as a result of the enlarged link capacity. Within the 1-mile segment that is analyzed, the total number of crashes drops from 2.42 per year to 2.38 per year.

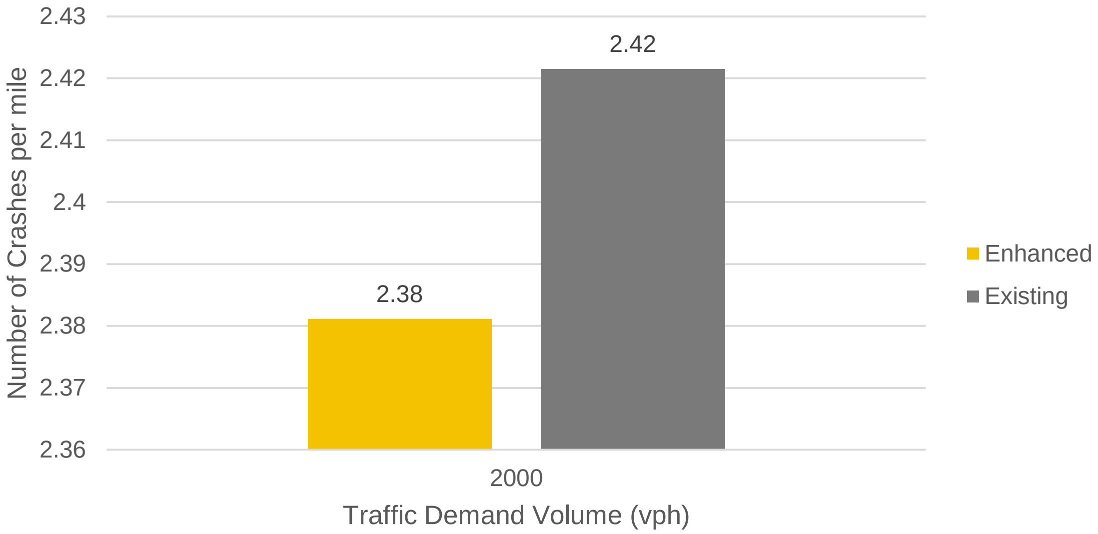

FIGURE 25: ANNUAL CRASHES UNDER EXISTING AND ENHANCED TRAFFIC CONDITIONS (V/C = 0.5).

As it was mentioned in the methodology section, for urban traffic conditions, 1% of total crashes are considered to result in fatalities. Considering the cost per crash involving a fatality as $7 million, the service life as 20 years, and fixed discount rate as 7%, the life cycle benefits of crash rate reduction due to ATCS deployment during the next 20 years is calculated in Figure 26:

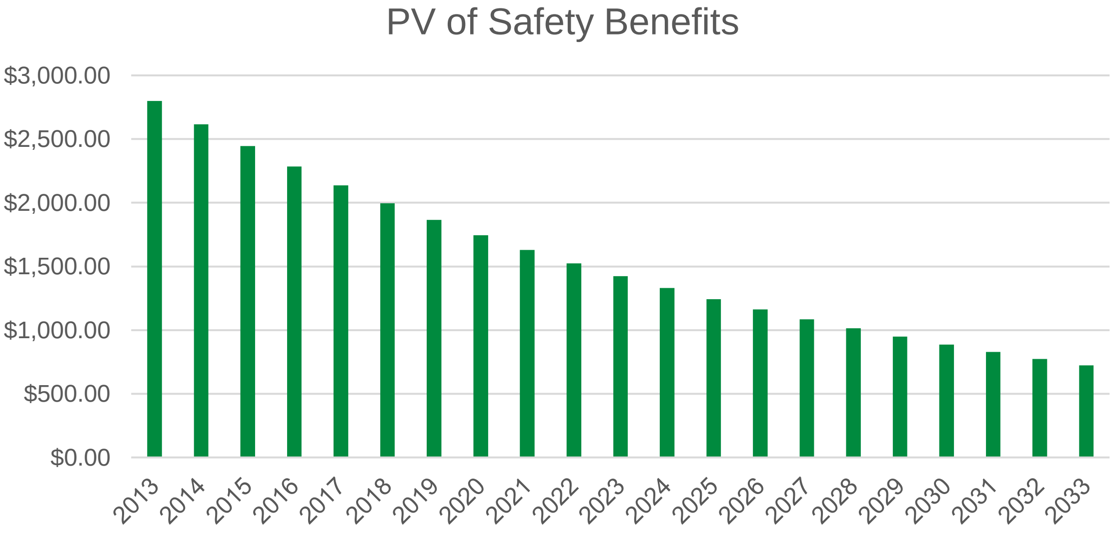

FIGURE 26: ANNUAL SAFETY BENEFITS FLOW IN PRESENT VALUE FOR ATCS.

The total PV of the benefits is approximately $32,463. Recalling the total PV cost per ATCS deployment as $174,000, a BCR of 0.19:1 can be expected if only the reduction in the rates of crashes that involve fatalities during the daily 2-hr peak times are considered.

If the total PV of the benefits obtained from safety benefits, energy consumption reduction and travel time savings are used in the life cycle BCA, the BCR is expected to be approximately 6.52:1. Figure 27 below illustrates the cost and benefit values during the next 20 years (2013 to 2033), considering all TBL benefits.

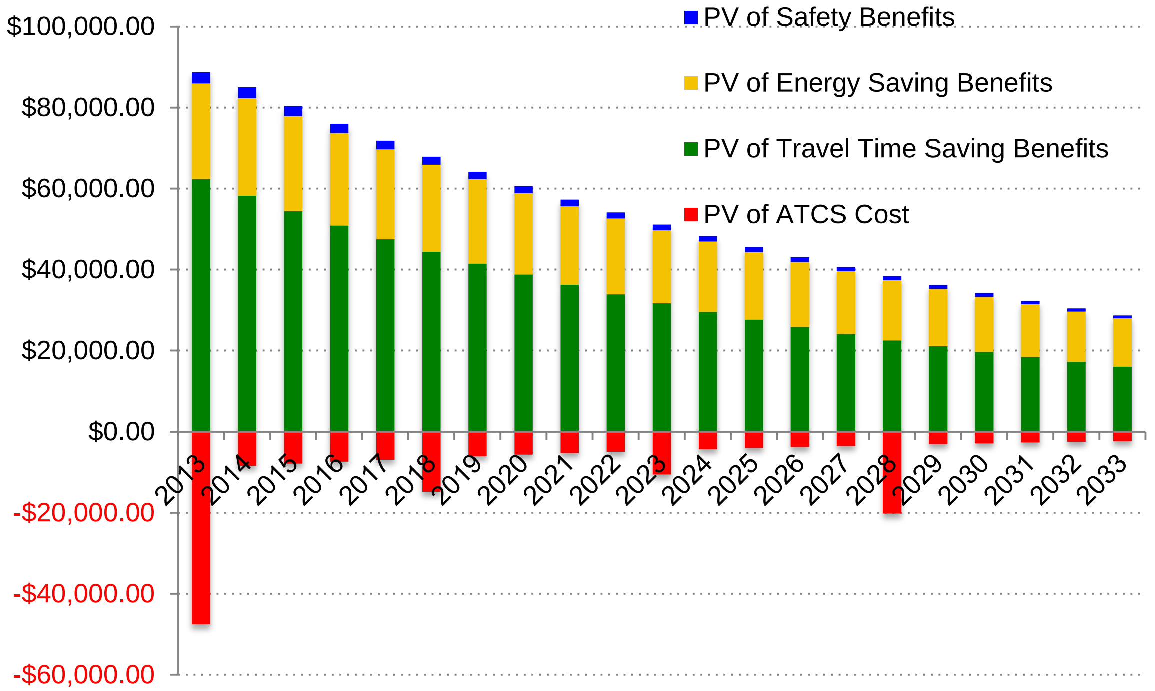

FIGURE 27: OVERALL LIFE CYCLE BENEFITS AND COSTS FLOW IN PRESENT VALUE FOR ATCS.

2.5 Summary

Based on *s2.4.1 Life Cycle Cost Analysis*, *s2.4.2: Travel Time Saving Benefits*, *s2.4.3: Energy Consumption Reduction Benefits*, and *s2.4.4 Safety Benefits*, 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. A life cycle benefit and cost flow is presented at the end of last section.

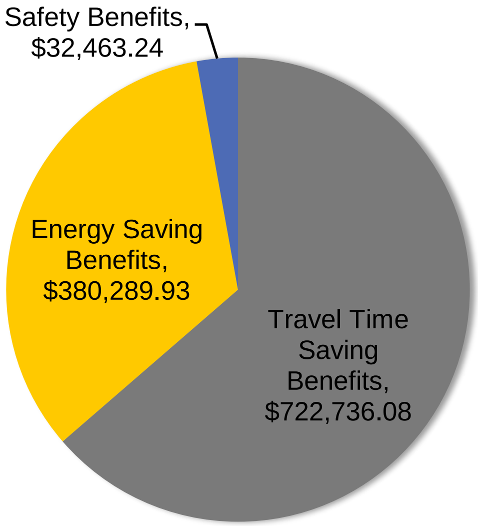

FIGURE 28: LIFE CYCLE BENEFITS DISTRIBUTION.

A life cycle benefits distribution pie chart is presented above in Figure 28. For a typical ATCS deployment in the US, during the analyzed service life, approximately $1,135,489 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 64%). For the remaining benefits, energy saving benefits, excluded LCA benefits accounts for 33%, and safety benefits due to reduced fatal crashes accounts for 3%. Table 14 below concludes the annual PV benefits flow for the analyzed period (from 2013 to 2033).

TABLE 14: ANNUAL BENEFITS FLOW BREAKDOWN IN PRESENT VALUE DURING THE 20 YEARS' LIFE OF SERVICE

Year	ATCS PV Costs	Travel Time Saving PV Benefits	Energy Saving PV Benefits	Safety PV Benefits	Net PV Benefit
2013	($47,475.00)	$62,337.00	$23,650.93	$2,800.00	$41,312.93
2014	($8,411.21)	$58,258.88	$24,124.57	$2,616.82	$76,589.06
2015	($7,860.95)	$54,447.55	$23,490.68	$2,445.63	$72,522.91
2016	($7,346.68)	$50,885.56	$22,836.48	$2,285.63	$68,660.99
2017	($6,866.06)	$47,556.60	$22,167.33	$2,136.11	$64,993.98
2018	($14,794.46)	$44,445.42	$21,488.01	$1,996.36	$53,135.33
2019	($5,997.08)	$41,537.78	$20,802.68	$1,865.76	$58,209.14
2020	($5,604.75)	$38,820.35	$20,072.99	$1,743.70	$55,032.29
2021	($5,238.08)	$36,280.70	$19,389.07	$1,629.63	$52,061.32
2022	($4,895.40)	$33,907.20	$18,708.71	$1,523.01	$49,243.52
2023	($10,548.25)	$31,688.97	$18,034.40	$1,423.38	$40,598.50
2024	($4,275.84)	$29,615.86	$17,368.24	$1,330.26	$44,038.52
2025	($3,996.11)	$27,678.37	$16,712.06	$1,243.23	$41,637.55
2026	($3,734.68)	$25,867.64	$16,039.36	$1,161.90	$39,334.22
2027	($3,490.36)	$24,175.36	$15,409.36	$1,085.89	$37,180.25
2028	($20,197.30)	$22,593.80	$14,793.14	$1,014.85	$18,204.49
2029	($3,048.61)	$21,115.70	$14,191.60	$948.46	$33,207.15
2030	($2,849.17)	$19,734.30	$13,605.45	$886.41	$31,376.99
2031	($2,662.78)	$18,443.27	$13,015.27	$828.42	$29,624.18
2032	($2,488.57)	$17,236.70	$12,462.76	$774.22	$27,985.11
2033	($2,326.00)	$16,109.07	$11,926.84	$723.57	$26,433.48

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.

The total BCR calculated for the hypothetical case study is approximately 6.52:1. 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 6.52:1 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 enhancement 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 6.52:1 to 13.04:1.

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 enhancement 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 (6.52:1 to 13.04:1) as the minimum, or “highly expected” BCR that can be expected for a typical ATCS deployment.

3 RAMP METERING SYSTEMS

3.1 Introduction

A ramp metering system 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 ramp metering systems 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 technology and regional disparities significantly influence the results of LCCA on current and potential ramp metering practices. The development of LCA allows the decision makers to evaluate the environmental impacts of ramp metering deployments from a more comprehensive perspective. The combination of LCCA and LCA will result in a BCA framework that covers the entire life cycle of the ramp metering deployment. The objectives of this chapter are to 1) assess the TBL benefits of typical ramp metering deployment applications, 2) setup a B/C framework to improve decision-making processes, and 3) perform the B/C analysis for current ramp metering practices.

3.1.1 Background Information

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 ramp metering systems 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 ramp metering is operated on fixed metering rates for pre-set metering periods (Abouaïssa, Dryankova, & Jolly, 2013). As the simplest form of ramp metering, 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 ramp metering is suitable for locations where the daily traffic flow is stable. Other than a pre-set fixed metering plan, a local responsive ramp metering system 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 ramp metering system, the local responsive ramp metering system can quickly respond to real-time traffic conditions and therefore increase the operational efficiency. System wide adaptive ramp metering is a ramp metering control system 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 ramp metering system.

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 ramp metering systems were deployed as of 2002, and this number increased dramatically in the last 10 years.

3.2 Literature Review

3.2.1 Ramp Metering Cost Database

Cost of ramp metering 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 ramp metering system 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 ramp metering system 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.

3.2.2 Ramp Metering Benefits Database

An interesting study that evaluated the benefits of ramp metering implementation was undertaken in 2001 in which Minnesota Department of Transportation (Mn/DOT) closed an extensive ramp metering system on Minneapolis-St. Paul area freeways for evaluation (Cambridge Systematics, Inc., 2001). During the 6-weeks 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 ATCS-ramp metering 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.

3.3 Methodology

3.3.1 Life Cycle Cost Analysis

Similar to the LCCA of ATCS deployment, the life cycle cost analysis of ramp metering deployment includes infrastructure costs, incremental costs, and O&M costs. A typical service life of 20 years is assumed for ramp meters in this analysis.

3.3.1.1 Infrastructure Costs

The infrastructure costs of ramp metering deployment include the principal cost for the infrastructure equipment, software installed, and labor cost for installing and operating the system. Due to the significant variations among different deployments under different conditions, and the rapid technological developments, it is difficult to estimate the infrastructure costs for the entire ramp metering systems deployed in the US. The built-in cost inventory obtained from TOPS-BC Tool was considered as an important reference material in the LCCA of ramp metering in this stage of study. The research team examined other recent studies on the costs of ramp metering deployment (Bhargava, Oware, Labi, & Sinha, 2006) (McDOT & KDOT, 2011) (USDOT, 2008) in determining the infrastructure costs. Based on review of literature, cost databases, and existing BCA tools, the average 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.

3.3.1.2 Incremental Costs

The incremental costs for a ramp metering deployment includes changing and updating of ramp meters, communication lines, loop detectors, etc., based on a fixed schedule. Some existing manuals and BCA tools established incremental cost databases. 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 ramp metering system. The costs for these components (ramp meter, loop detector, and communication line) are listed as \$88,000, \$11,000, and \$750, respectively. Currently, we use these costs in our life cycle 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.

3.3.1.3 Operation & Maintenance Costs

During the entire life cycle, O&M activities should be performed on both the initial set of equipment and on the equipment upgraded and changed with time. 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). 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.

3.3.2 Travel Time Savings Analysis

As in the travel time savings analysis methodology described in the previous chapter, the travel time savings estimation and evaluation followed a 2-cycle method:

- 1st Cycle - Measure Existing Travel Time (ETT) & Existing Travel Time Reliability (ETTR) (1st Cycle) before ramp metering deployment on a given freeway segment.
- 2nd Cycle - Estimate Anticipated Travel Time (ATT) & Anticipated Travel Time Reliability (ATTR) (2nd Cycle) after ramp metering deployment on a given freeway segment.

The recurring travel time savings is estimated based on traffic speed-flow rate relationship. Nonrecurring travel time savings is estimated using IDAS Travel Time Reliability Lookup Table. Since the methodology used in this part is similar to the methodology used in the analysis of ACTS, readers are encouraged to return to section 2.3.2 for more details.

3.3.3 Energy Consumption Reduction Analysis

Similar to the energy consumption reduction analysis methodology discussed in the previous chapter, the energy savings estimation and evaluation followed a microscopic scale top-down approach. The process is revisited below:

- 1st Step - Determine the boundary of study area.
- 2nd Step - Estimate existing traffic flow vehicle type distribution (Passenger Cars, Trucks).
- 3rd Step - For each vehicle type, estimate the age distribution.
- 4th Step - For each vehicle type, use fuel economy by model year to calculate the equivalent average fuel consumption for this vehicle type.
- 5th Step - Calculate the equivalent average fuel economy for the entire study freeway segment.
- 6th Step - Define the fuel consumption reduction factor for ramp metering deployment.
- 7th Step - Quantify and monetize the fuel consumption reduction benefits.
- 8th Step - Perform an LCA for calculated fuel consumption reduction.

Since the methodology used in this part is similar to the methodology used in the analysis of ACTS, readers are encouraged to return to section 2.3.3 for more details.

3.3.4 Life Cycle Assessment Analysis

As in the analysis of ATCS, Gabi 6 is used in LCA of saved combusted gasoline in the quantification of life cycle environmental impacts due to ramp metering deployment. Meanwhile, the carbon cost prediction method discussed in the previous chapter is used in this ramp metering study. Readers are encouraged to return to section 2.3.4 for more details.

3.3.5 Safety Analysis

The methodology used for estimating and evaluating the safety benefits of an ATCS deployment is also used in ramp metering analysis. The process is presented below:

- 1st Step - Classify crashes according to the level of severity.
- 2nd Step - Calculate the v/c ratios before and after ramp metering 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 a monetary value to each level of crash, and calculate the annual safety benefit.

Readers are encouraged to return to section 2.3.5 for more details.

3.4 Analysis Results

3.4.1 Life Cycle Cost Analysis

With the information collected as discussed in the LCCA methodology section, the PV (throughout a life cycle of 20 years) of the life cycle costs of a ramp metering system deployed at an intersection is estimated and summarized in Figure 29 and Table 15. In this LCCA, the infrastructure cost in the initial year (2013) is assumed to be $130,000 per deployment with 5 years' of service life (FHWA, 2012), and incremental costs in the following 20 years are assumed as follows:

- Ramp meter: $88,000 (over 20 years)
- Loop detectors: $11,000 (over 20 years)
- Communication lines: $750 (over 20 years)
- Annual O&M cost is assumed to be $25,000.

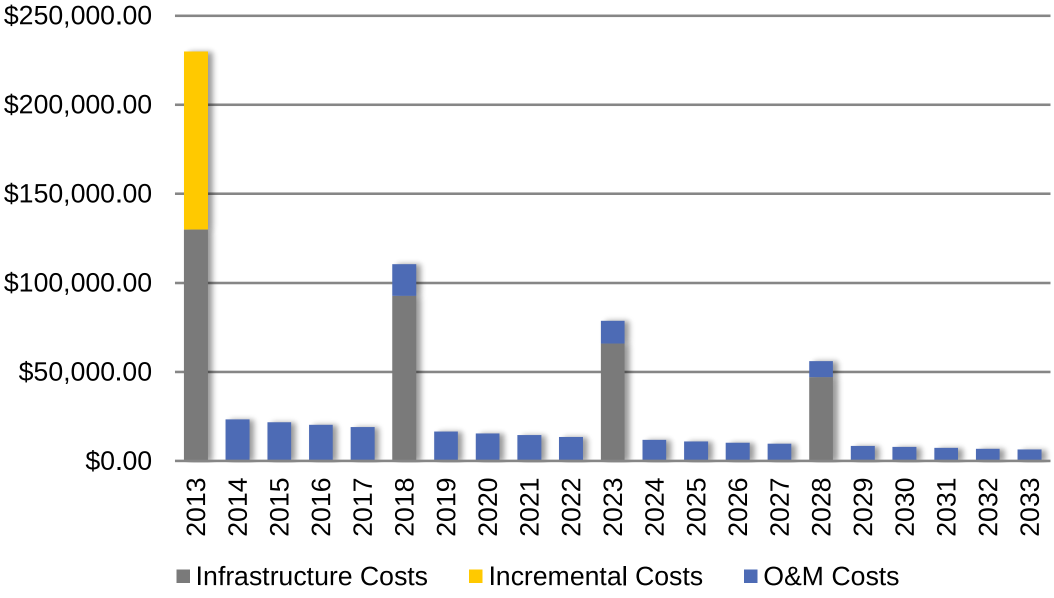

FIGURE 29: ANNUAL COST FLOW DURING THE 20 YEARS' LIFE OF SERVICE IN PRESENT VALUE.

TABLE 15: ANNUAL COST BREAKDOWN DURING THE 20 YEARS' LIFE OF SERVICE

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	$130,000.00	$130,000.00	$99,750.00	$0.00*	$0.00	$229,750.00	$229,750.00
2014	$0.00	$0.00	$0.00	$25,000.00	$23,364.49	$25,000.00	$23,364.49
2015	$0.00	$0.00	$0.00	$25,000.00	$21,835.97	$25,000.00	$21,835.97
2016	$0.00	$0.00	$0.00	$25,000.00	$20,407.45	$25,000.00	$20,407.45
2017	$0.00	$0.00	$0.00	$25,000.00	$19,072.38	$25,000.00	$19,072.38
2018	$130,000.00	$92,688.20	$0.00	$25,000.00	$17,824.65	$155,000.00	$110,512.86
2019	$0.00	$0.00	$0.00	$25,000.00	$16,658.56	$25,000.00	$16,658.56
2020	$0.00	$0.00	$0.00	$25,000.00	$15,568.74	$25,000.00	$15,568.74
2021	$0.00	$0.00	$0.00	$25,000.00	$14,550.23	$25,000.00	$14,550.23
2022	$0.00	$0.00	$0.00	$25,000.00	$13,598.34	$25,000.00	$13,598.34
2023	$130,000.00	$66,085.41	$0.00	$25,000.00	$12,708.73	$155,000.00	$78,794.14
2024	$0.00	$0.00	$0.00	$25,000.00	$11,877.32	$25,000.00	$11,877.32
2025	$0.00	$0.00	$0.00	$25,000.00	$11,100.30	$25,000.00	$11,100.30
2026	$0.00	$0.00	$0.00	$25,000.00	$10,374.11	$25,000.00	$10,374.11
2027	$0.00	$0.00	$0.00	$25,000.00	$9,695.43	$25,000.00	$9,695.43
2028	$130,000.00	$47,117.98	$0.00	$25,000.00	$9,061.15	$155,000.00	$56,179.13
2029	$0.00	$0.00	$0.00	$25,000.00	$8,468.36	$25,000.00	$8,468.36
2030	$0.00	$0.00	$0.00	$25,000.00	$7,914.36	$25,000.00	$7,914.36
2031	$0.00	$0.00	$0.00	$25,000.00	$7,396.60	$25,000.00	$7,396.60
2032	$0.00	$0.00	$0.00	$25,000.00	$6,912.71	$25,000.00	$6,912.71
2033	$0.00**	$0.00	$0.00	$25,000.00	$6,460.48	$25,000.00	$6,460.48
TOTAL PV					$700,491.96		

It could be found from Figure 29 and Table 15 that the total PV for life cycle cost of a typical ramp metering deployment in United States is around $700,000. This number will be used as the baseline for the BCA in the following sections.

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

**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.

3.4.2 Travel Time Savings Benefits

The travel time savings benefits analysis was conducted using the methodology described in the previous chapter. The recurring and nonrecurring travel time savings were calculated separately and combined at the end. Unlike the analysis undertaken for the ATCS deployment, in the ramp metering study, we considered both travel time savings on the freeway segment, and the travel time changes on the ramp segment. A monetary value was assigned to the saved travel time per hour per vehicle. BCA was performed at the end to present the B/C under the scenario in which only the travel time savings benefits are considered.

3.4.2.1 Hypothetical Case Study Overview

As in the analysis for ATCS, the time savings estimation for ramp metering 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 before and 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.

- *Length of Analyzed Freeway Segment: 10 mile*
- *Length of Analyzed Ramp Segment: 0.2 mile*
- *Number of Lanes: 2*
- *Number of Metered Ramps: 1*
- *Free Flow Speed (FFS): 55 mph*
- *Average Ramp Free Flow Speed (RFFS): 35 mph*
- *Freeway Link Capacity per lane: 2000 vph*
- *Ramp Link Capacity: 2000 vph*
- *Traffic Demand (Volume): 400 vph to 4000 vph, which implies the v/c ratio ranges from 10% to 100%*
- *Link Capacity Multiplication Factor: 8% to 12%*
- *Ramp Capacity Multiplication Factor: -12%*

The hypothetical case presented above was used to conduct the entire travel time savings benefits estimation in this section, the energy consumption reduction estimation, and crash rate reduction estimation in the following sections.

3.4.2.2 Recurring Travel Time Savings Estimation

Unlike the travel time estimation methodology presented in the ATCS analysis, two segments need to be taken into consideration in ramp metering analysis: 1) freeway segment, and 2) ramp segment. Calculations of both segments follow the same methodology discussed in previous sections. However, it should be noted that the capacity multiplication factor for the ramp segment is negative since the metered ramp limits the on-the-ramp throughput. In the following sections, the freeway segment and ramp segment are analyzed separately.

3.4.2.2.1 Travel Time Savings on the Freeway Segment

The link capacity enhancement is considered in the travel time savings estimation on the freeway segment of ramp metering deployment. Table 16 below summarizes the results of recurring travel time savings for various link capacity multiplication factors for the 10-mile freeway segment.

TABLE 16: RECURRING TRAVEL TIME SAVINGS ON FREEWAY SEGMENT UNDER VARIOUS LINK CAPACITY MULTIPLICATION FACTORS

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**	**0.90**	**0.95**	**1.00**
Travel Time Saving (hr) [12%]	0.00	~	0.60	1.40	4.70	92.6	10679.0	1534.3	1808.0	2098.7	2409.9	2742.4	3096.1	3471.2	3867.7	4285.7
Travel Time Saving (hr) [11%]	0.00	~	0.60	1.30	4.60	91.9	10464.0	1420.0	1672.4	1941.2	2229.0	2536.5	2863.7	3210.6	3577.4	3963.9
Travel Time Saving (hr) [10%]	0.00	~	0.50	1.30	4.40	91.0	10071.0	1303.3	1534.3	1780.8	2044.8	2326.9	2627.0	2945.3	3281.7	3636.3
Travel Time Saving (hr) [09%]	0.00	~	0.50	1.20	4.10	89.9	944.3	1184.3	1393.7	1617.5	1857.3	2113.4	2386.0	2675.1	2980.7	3302.7
Travel Time Saving (hr) [08%]	0.00	~	0.40	1.10	3.90	88.6	862.5	1062.8	1250.4	1451.1	1666.2	1896.0	2140.6	2399.9	2674.0	2962.9
SENSITIVITY	**INSENSITIVE**			**THRESHOLD**		**SENSITIVE**										

3.4.2.2.2 Travel Time Changes on Ramp Segment

Due to the ramp metering deployment, the capacity of ramp segment is decreased. Table 17 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 17: THE RECURRING TRAVEL TIME SAVINGS ON RAMP SEGMENT WITH -12% CAPACITY MULTIPLICATION FACTOR

Traffic Demand (vph)	200	400	600	800	1000	1200	1400	1600	1800	2000
VHT Differential (hr)	0.00	0.00	0.00	-0.01	-0.03	-0.08	-1.64	-22.97	-51.38	-83.81
Traffic Demand (vph)	2200	2400	2600	2800	3000	3200	3400	3600	3800	4000
VHT Differential (hr)	-103.56	-123.37	-144.83	-167.98	-192.85	-219.42	-247.71	-277.72	-309.43	-342.87

3.4.2.2.3 Travel Time Differential on Entire Ramp Metered Segments

The total equivalent 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 18 (for v/c ratio ranging from 0.5 to 1.0, the differentials in low traffic demand conditions have been ignored):

TABLE 18: TOTAL EQUIVALENT TRAVEL TIME SAVINGS CONSIDERING BOTH THE FREEWAY AND RAMP SEGMENTS

v/c ratio	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Travel Time Saving (hr) [12%]	8.8	964.3	1410.9	1663.2	1930.7	2217.1	2523.0	2848.4	3193.5	3558.3	3942.8
Travel Time Saving (hr) [11%]	8.1	942.8	1296.6	1527.6	1773.2	2036.2	2317.1	2616.0	2932.9	3268.0	3621.0
Travel Time Saving (hr) [10%]	7.2	903.5	1179.9	1389.5	1612.8	1852.0	2107.5	2379.3	2667.6	2972.3	3293.4
Travel Time Saving (hr) [09%]	6.1	840.7	1060.9	1248.9	1449.5	1664.5	1894.0	2138.3	2397.4	2671.3	2959.8
Travel Time Saving (hr) [08%]	4.8	758.9	939.4	1105.6	1283.1	1473.4	1676.6	1892.9	2122.2	2364.6	2620.0

3.4.2.3 Nonrecurring Travel Time Savings Estimation

In this section, we use the same hypothetical case described as in *section 3.4.2.2: Recurring Travel Time Savings Estimation* to predict the nonrecurring travel time savings, then calculate the total equivalent travel time savings which combines both recurring and nonrecurring (incident) travel time savings. The nonrecurring travel time savings value is only considered on the freeway segment, rather than on both freeway and ramp segments.

As in the nonrecurring travel time savings analysis for ATCS, the IDAS Travel Time Reliability Lookup Tables (IDAS User's Manual, Appendix B.2.15) is adopted in this section. The v/c ratio is then interpolated to determine the related nonrecurring (incident) traffic delay for the 10-mile freeway segment. Table 19 below summarizes the nonrecurring (incident) travel time savings with different link capacity multiplication factors under different traffic demands.

TABLE 19: NONRECURRING TRAVEL TIME SAVINGS WITH DIFFERENT LINK CAPACITY MULTIPLICATION FACTORS UNDER DIFFERENT TRAFFIC DEMANDS

Traffic Demand Volume (vph) (/2000 vph)	**400**	**800**	**1200**	**1600**	**2000**	**2400**	**2800**	**3200**	**3600**	**4000**
Incident Travel Time Saving (hr) [12%]	0.00	0.00	0.10	0.60	1.90	4.90	11.40	30.60	141.40	552.20
Incident Travel Time Saving (hr) [11%]	0.00	0.00	0.10	0.50	1.70	4.50	10.50	28.30	130.80	535.70
Incident Travel Time Saving (hr) [10%]	0.00	0.00	0.10	0.50	1.60	4.10	9.60	25.90	120.00	491.40
Incident Travel Time Saving (hr) [09%]	0.00	0.00	0.10	0.40	1.50	3.80	8.80	23.50	109.00	446.30
Incident Travel Time Saving (hr) [08%]	0.00	0.00	0.10	0.40	1.30	3.40	7.90	21.10	97.80	400.40

3.4.2.4 Total Equivalent Travel Time Savings Estimation

By combining the results from s*3.4.2.2: Recurring Travel Time Saving Estimation*, and *s3.4.2.3: Nonrecurring Travel Time Saving Estimation*, the total equivalent travel time savings is calculated and presented in Table 20:

TABLE 20: THE TOTAL EQUIVALENT TRAVEL TIME SAVINGS

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	1.4	10.7	1415.8	1942.1	2553.6	3334.9	4495.0
Equivalent Travel Time Saving (hr) [11%]	0	~	0.6	1.3	9.8	1301.1	1783.7	2345.4	3063.7	4156.7
Equivalent Travel Time Saving (hr) [10%]	0	~	0.5	1.3	8.8	1184.0	1622.4	2133.4	2787.6	3784.8
Equivalent Travel Time Saving (hr) [09%]	0	~	0.5	1.2	7.6	1064.7	1458.3	1917.5	2506.4	3406.1
Equivalent Travel Time Saving (hr) [08%]	0	~	0.4	1.1	6.1	942.8	1291.0	1697.7	2220.0	3020.4
SENSITIVITY	**INSENSITIVE**			**THRESHOLD**		**SENSITIVE**				

In comparison with the equivalent travel time savings for ATCS deployment, it is worth noting that the sensitivity threshold is raised from a v/c value of 0.4 to 0.5. The amount of VHT saved during high traffic demand conditions (with v/c > 0.5) increases dramatically with the level of traffic saturation. Figure 30 below presents the travel time savings estimation with and without considering nonrecurring travel time savings (12% link capacity multiplication factor assumed) over the 10-mile freeway segment and 0.2-mile metered ramp. Nonrecurring travel time changing was not calculated for the ramp due to the short length of the ramp segment and the uncertainties in calculation.

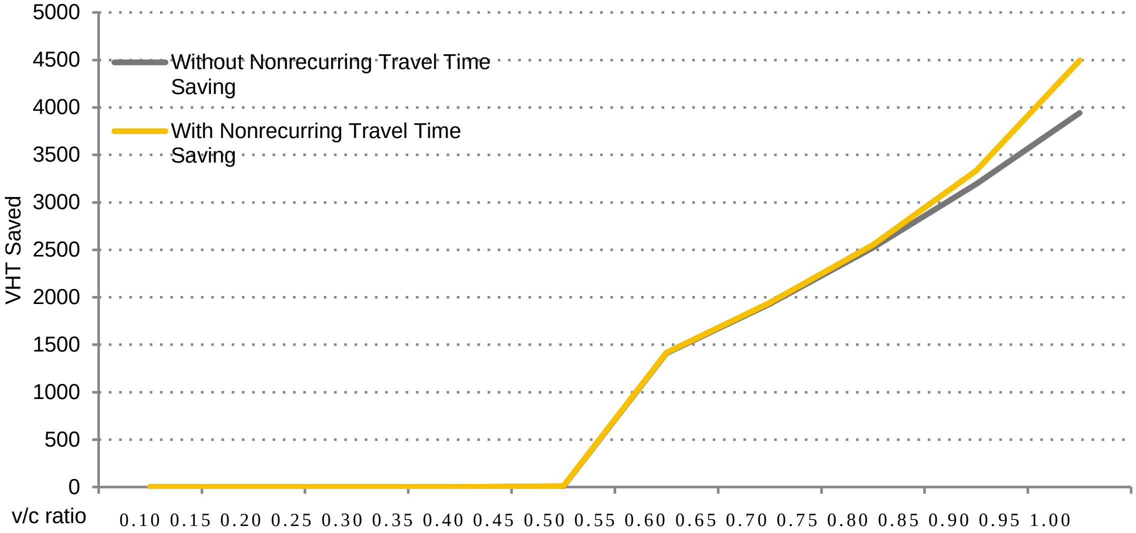

FIGURE 30: TRAVEL TIME SAVINGS ESTIMATION WITH AND WITHOUT CONSIDERING NONRECURRING TRAVEL TIME SAVINGS FOR RAMP METERING.

3.4.2.5 Travel Time Savings Benefits Evaluation

In the hypothetical case, we assumed VOT as $12 for passenger cars and $24 for trucks, with a vehicle type distribution of 9 passenger cars for each truck, and a reliability ratio (RR) of 1 (implying equal importance of VOT and VOR). The annual benefits (255 workdays per year) for equivalent travel time savings during the peak hours (1 hour peak in the morning and 1 hour peak in the evening) due to anticipated ramp metering implementation could be calculated as in Table 21. It is worth noting that since the sensitivity threshold is around 0.4 to 0.5, the travel time savings benefits are not considerably high under low traffic demand conditions.

TABLE 21: ANNUAL EQUIVALENT TRAVEL TIME SAVING BENEFITS DURING THE PEAK HOUR

v/c ratio	0.10	~	0.35	0.40	0.50	0.60	0.70	0.80	0.90	1.00
Annual Travel Time Benefit (USD) [12%]	$0.00	~	$4,039.20	$9,424.80	$71,969.00	$9,531,386.09	$13,074,337.95	$17,190,670.07	$22,450,429.31	$30,260,575.21
Annual Travel Time Benefit (USD) [11%]	$0.00	~	$4,039.20	$8,751.60	$65,910.20	$8,759,225.69	$12,007,989.15	$15,789,067.67	$20,624,710.91	$27,983,139.61
Annual Travel Time Benefit (USD) [10%]	$0.00	~	$3,366.00	$8,751.60	$59,178.20	$7,970,908.49	$10,922,117.55	$14,361,883.67	$18,766,005.71	$25,479,508.81
Annual Travel Time Benefit (USD) [09%]	$0.00	~	$3,366.00	$8,078.40	$51,099.80	$7,167,780.89	$9,817,396.35	$12,908,444.87	$16,872,967.31	$22,930,100.41
Annual Travel Time Benefit (USD) [08%]	$0.00	~	$2,692.80	$7,405.20	$41,001.80	$6,347,150.09	$8,691,132.75	$11,428,751.27	$14,944,922.51	$20,333,568.01
SENSITIVITY	INSENSITIVE			THRESHOLD		SENSITIVE				

To be consistent with the LCCA of average ramp metering deployment, a service life of 20 years, and a discount rate of 7% is assumed for the life cycle travel time savings benefits.

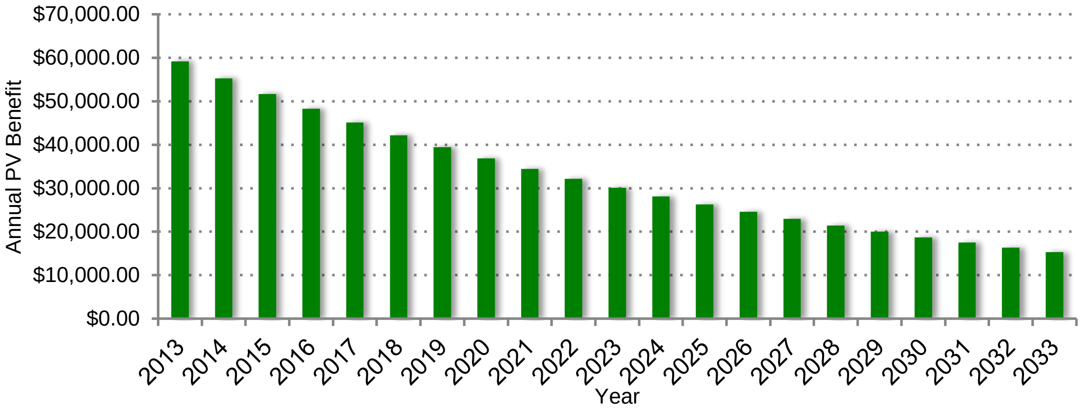

FIGURE 31: TRAVEL TIME SAVING BENEFITS IN PRESENT VALUE DURING A 20 YEARS' LIFE OF SERVICE FOR RAMP METERING.

Figure 31 illustrates the present value of the travel time savings benefits for the hypothetical case study throughout a time span of 20 years, under daily 2-hour peak (v/c ratio = 0.5; link capacity multiplication factor = 10%) traffic conditions. The total present value is calculated as $686,112. In comparison with the previously calculated life cycle cost of ramp metering deployment ($700,000), a BCR of approximately 0.98:1 can be achieved. Figure 32 below exhibits the cash flow of costs and benefits for each year during the 20 year life span of the deployment.

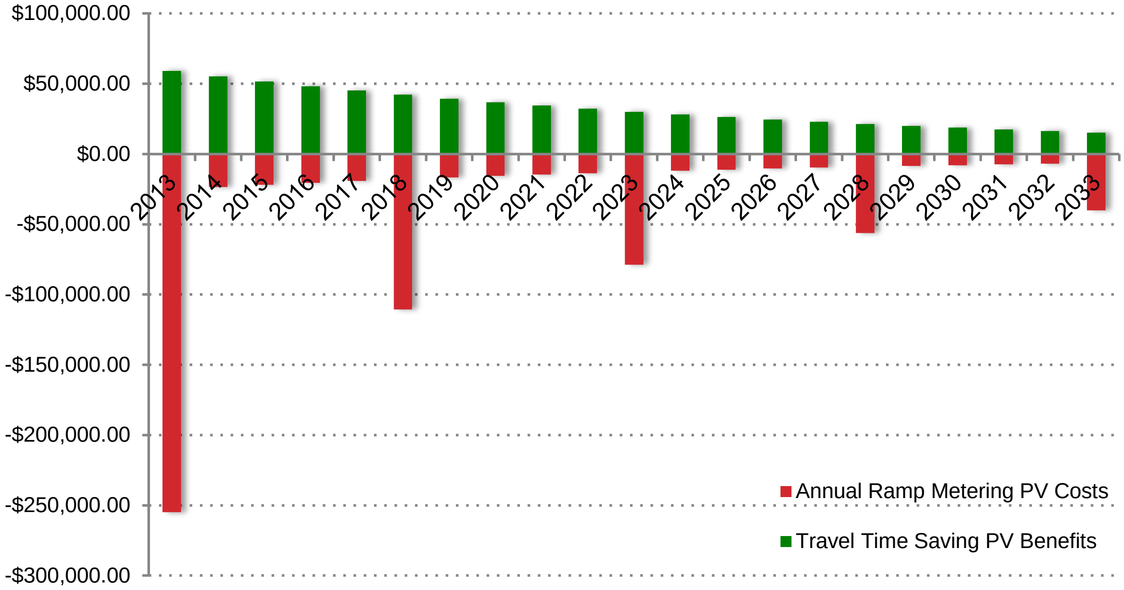

FIGURE 32: ANNUAL BENEFITS (TRAVEL TIME SAVINGS) AND COSTS FLOW DURING THE 20 YEARS' LIFE OF SERVICE FOR RAMP METERING.

3.4.3 Energy Consumption Reduction Benefits

The energy consumption reduction benefits analysis was undertaken following the methodology described in the previous chapter. The on-the-road traffic flow fuel consumption was presented by vehicle type matrix, vehicle age distribution matrix, and fuel economy matrix. A monetary value was then applied to the saved fuel consumption to calculate the monetized benefits. An LCA was introduced as an additional component for a comprehensive evaluation of the environmental impacts of typical ramp metering deployments in the United States. Similarly, BCA was performed at the end to present the B/C values under scenarios that only consider the energy consumption reduction benefit, and both the travel time savings and energy consumption reduction benefits.

3.4.3.1 Hypothetical Case Study Overview

The microscopic scale top-down approach discussed previously in the methodology section is used to estimate the energy savings benefits. In this section, the same hypothetical case study described in the previous section is used to estimate the energy savings benefits for a typical ramp metering deployment. The basic infrastructure and traffic information are re-visited below:

- *Length of Analyzed Freeway Segment: 10 mile*
- *Length of Analyzed Ramp Segment: 0.2 mile*
- *Number of Lanes: 2*
- *Number of Metered Ramps: 1*
- *Free Flow Speed (FFS): 55 mph*
- *Average Ramp Free Flow Speed (RFFS): 35 mph*
- *Freeway Link Capacity per lane: 2000 vph*
- *Ramp Link Capacity: 2000 vph*
- *Traffic Demand (Volume): 2000 vph; v/c = 0.5.*
- *Ramp Capacity Multiplication Factor: -12%*

In addition to the assumptions above, the average daily passenger car to light duty truck ratio was assumed as 9:1, and heavy-duty trucks and buses were ignored. For consistency, a life cycle of 20 years is used as the analysis period.

3.4.3.2 Energy Consumption Reduction Estimation

Due to the similarity in traffic conditions, the vehicle type distribution matrix $[T]$, and age distribution matrix $[A]$ for ramp metering case study are identical to the ATCS analysis. The resultant on-the-road vehicle distribution according to these two matrices is revisited below in Figure 33 (2000 vph assumed):

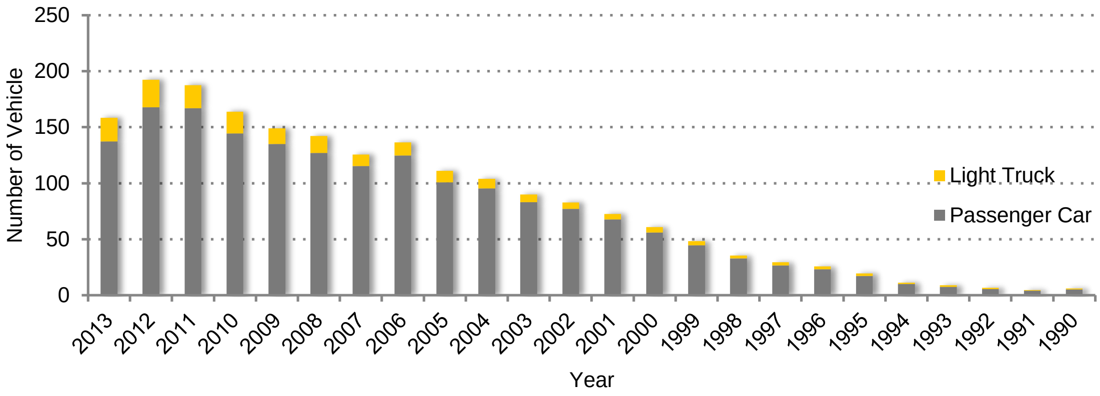

FIGURE 33: ON-THE-ROAD VEHICLE TYPE DISTRIBUTION.

Under saturated traffic conditions, using Akçelik speed-flow equation it was found that the freeway segment free flow speed dropped from 55 mph to approximately 43 mph. The fuel economy matrix $[F]$ is then modified according to the fuel economy reduction factor value (α) of 0.89. On the other hand, the ramp segment flow speed dropped from 35 mph to approximately 28 mph. The fuel economy matrix $[F]$ is then modified according to the fuel economy reduction factor value (α) of 0.75. The modified vehicle economy values $[F]$, for both freeway and ramp segments are presented in Figure 34 below:

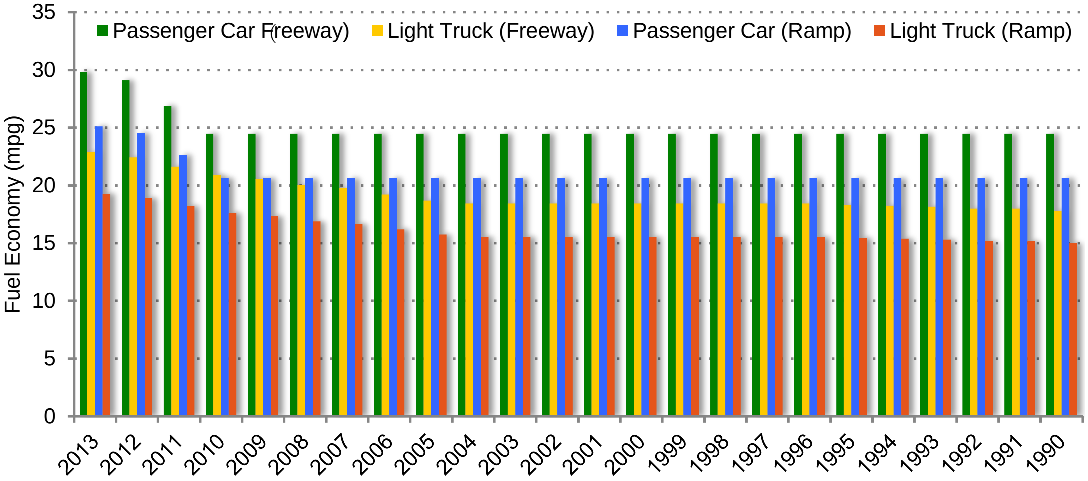

FIGURE 34: MODIFIED FUEL ECONOMY VALUES FOR DIFFERENT VEHICLE TYPES ACCORDING TO DIFFERENT VEHICLE MODEL YEAR.

The annual fuel consumption for the 10-mile freeway segment before ramp metering deployment (under daily 2-hour traffic conditions with a demand of 2000 vph) was calculated using the equation discussed in s2.3.3.4. The total annual 2-hr peak time fuel consumption is calculated as approximately 49,000 gallons for light trucks, and 356,000 gallons for passenger vehicles (405,000 gallons in total, 255 workdays assumed). The resultant value is almost ten times the resultant value for ATCS deployment. The reason is that the analyzed length for freeway segment in ramp metering analysis is 10 miles whereas it was 1 mile in the ATCS analysis.

Similarly, the annual fuel consumption for the 0.2-mile ramp segment before ramp metering deployment under daily 2-hour traffic conditions with a demand of 2000 vph is calculated using the equation discussed in s2.3.3.4. The total annual 2-hr peak time fuel consumption is approximately 1,200 gallons for light trucks, and 8,500 gallons for passenger vehicles (9,700 gallons in total, 255 workdays assumed).

The total annual energy consumption on the analyzed 10-mile freeway segment and 0.2-mile ramp without ramp metering deployment is calculated as 414,700 gallons.

3.4.3.3 Energy Consumption Reduction Benefits Evaluation

From the previous section, the total annual 2-hr peak time fuel consumption is calculated as 414,700 gallons for the hypothetical case study. Based on the assumptions on the next 20 years' gasoline prices, a discount rate of 7%, and **an assumed energy consumption reduction rate of 15%** due to ramp metering deployment, the present value of the benefits are calculated and presented in Figure 35 below.

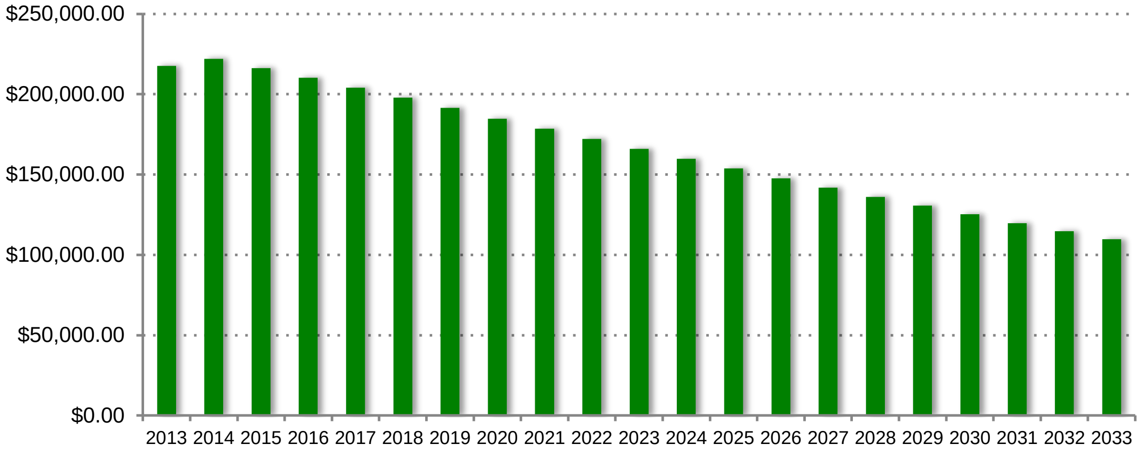

FIGURE 35: ANNUAL ENERGY CONSUMPTION REDUCTION BENEFITS FLOW IN PRESENT VALUE FOR RAMP METERING.

The total PV of the benefits is approximately $3,500,000. Recalling the PV of the total cost for ramp metering as $700,000, a BCR of 5:1 can be expected if only the peak-hour energy savings benefits are considered.

If we add the total PV of the benefits of energy consumption reduction and travel time savings together and incorporate them into the life cycle BCA, the expected value of BCR is 5.98:1. Figure 36 below illustrates the B/C flows during the next 20 years (2013 to 2033), considering both travel time savings benefits and energy savings benefits.

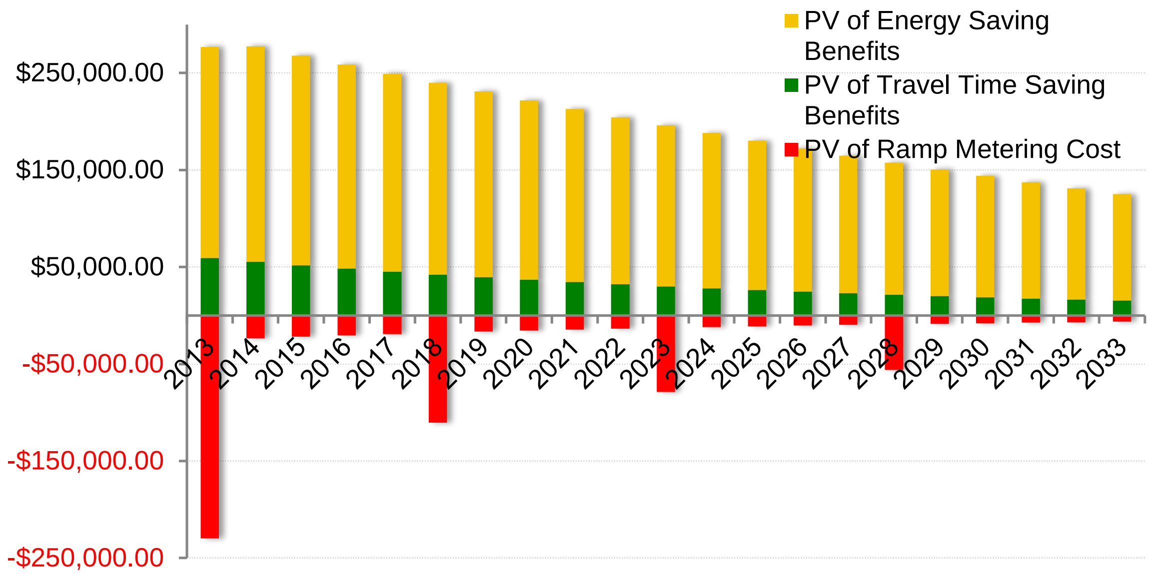

FIGURE 36: ANNUAL BENEFITS (TRAVEL TIME SAVINGS AND ENERGY SAVINGS) AND COSTS FLOW FOR RAMP METERING IN PRESENT VALUE DURING THE 20 YEARS LIFE OF SERVICE.

3.4.3.4 Life Cycle Assessment on Energy Consumption Reduction

In the previous section, the total annual 2-hr peak time fuel consumption was calculated as 414,000 gallons for the hypothetical case study. Based on an assumed energy consumption reduction of 15%, 62,100 gallons of gasoline can be expected to be saved on an annual basis. Based on these values, the result of the life cycle assessment shows an annual CO_2e emission reduction of 564,000 kg ($62{,}100 gallon \times 9.08\ kg/gallon$) due to this amount of gasoline savings.

Following the carbon price prediction method discussed in the methodology section (s2.3.5.2), the anticipated annual gasoline savings benefits due to ramp metering deployment during the next 20 years (2013 to 2033) can be calculated. The present value flow of the benefits for the hypothetical case study is presented (7% discount rate assumed) below in Figure 37.

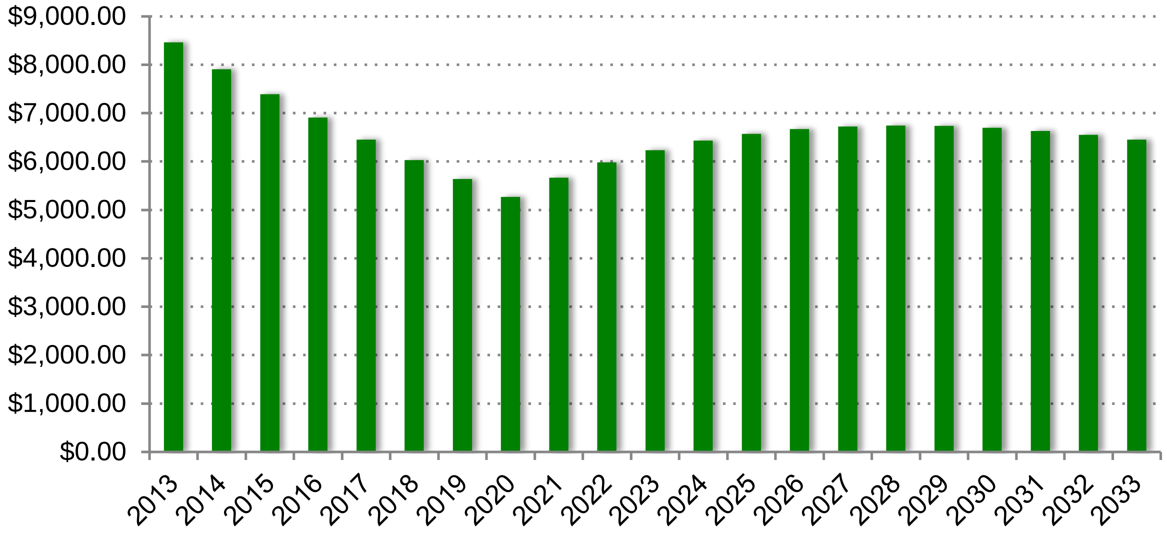

FIGURE 37: ANNUAL LIFE CYCLE ENVIRONMENTAL BENEFITS FOR RAMP METERING DUE TO REDUCED COMBUSTED GASOLINE DURING THE 20 YEARS' LIFE OF SERVICE.

The total PV of the carbon costs saved for the 20 years as a result of ramp metering deployment is $138,000. Recalling that the PV of total costs as $700,000 for the ramp metering deployment, a benefit cost ratio of 0.2:1 can be expected.

3.4.4 Safety Benefits

The safety benefits analysis is undertaken following the methodology discussed in the previous chapter. The crash rates before and after the ramp metering deployment were estimated separately. A monetary value was assigned to the reduced number of accidents. BCA was performed at the end to present the B/C results for the scenarios that consider only the safety benefit, and all the TBL benefits.

3.4.4.1 Hypothetical Case Study Overview

The crash rate – v/c ratio relationship and monetary value per crash concepts discussed previously in the methodology section (s2.3.5) are used to estimate the safety benefits. In this section, the same hypothetical case study assumed in previous sections is used to estimate the safety benefits for a typical freeway segment before and after ramp metering deployment. The basic infrastructure and traffic information are revisited below:

- *Length of Analyzed Freeway Segment: 10 miles*
- *Length of Analyzed Ramp Segment: 0.2 miles*

- *Number of Lanes: 2*
- *Number of Metered Ramps: 1*
- *Free Flow Speed (FFS): 55 mph*
- *Average Ramp Free Flow Speed (RFFS): 35 mph*
- *Freeway Link Capacity per lane: 2000 vph*
- *Traffic Demand (Volume): 200 vph to 2000 vph, which implies the v/c ratio ranges from 0.05 to 0.50.*
- *Link Capacity Multiplication Factor: 8% to 12%*

3.4.4.2 Crash Rate Estimation

The equation derived from Lord, Manar, and Vizioli's crash rate – v/c ratio curve (Lord, Manar, & Vizioli, 2005) is used in this study. The equation is presented below:

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

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 hypothetical case study, L is 16,1 kilometers (10 miles) for the freeway segment, V ranges from 200 vph to 2000 vph, implying that x ranges from 0.05 to 0.5. Due to its relatively small contribution to the final result, the crash rate occurring on the 0.2-mile ramp is ignored in this study. Figure 38 summarizes the annual number of crashers per mile on the freeway segment under various link capacity improvement factors.

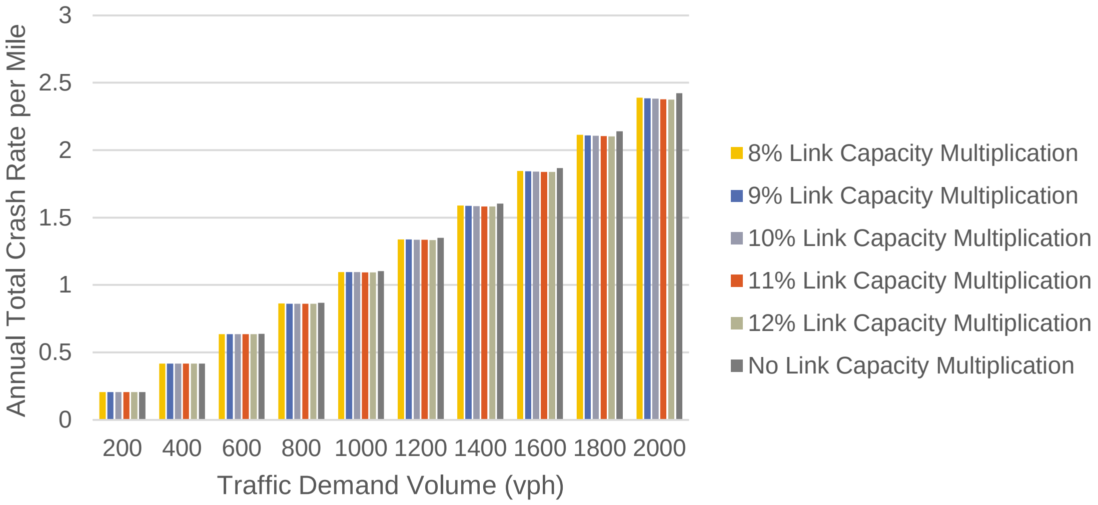

FIGURE 38: ANNUAL CRASH RATE PER MILE TO TRAFFIC DEMAND VOLUME RELATIONSHIP UNDER DIFFERENT LINK CAPACITY MULTIPLICATION FACTORS.

Table 22 below presents safety enhancements under 8% to 12% link capacity enhancements under different traffic demands. In order to ensure consistency and compatibility of the results a v/c ratio of 0.5 is assumed in the next steps. Therefore, in monetary evaluation of safety benefits, a safety enhancement of 1.67% is taken into account.

TABLE 22: SAFETY ENHANCEMENTS UNDER 0% TO 12% LINK CAPACITY ENHANCEMENTS UNDER DIFFERENT TRAFFIC DEMANDS

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%**

3.4.4.3 Safety Benefits Evaluation

Due to the ramp metering deployment, under the same traffic demand, the v/c ratio on the freeway segment decreased as the link capacity increased. Within the 10-mile long freeway segment, the total number of crashes drops approximately 0.4 crashes per year for link capacity enhancement of 10%. The methodology used in this analysis is identical to the one used in the ATCS safety benefits evaluation.

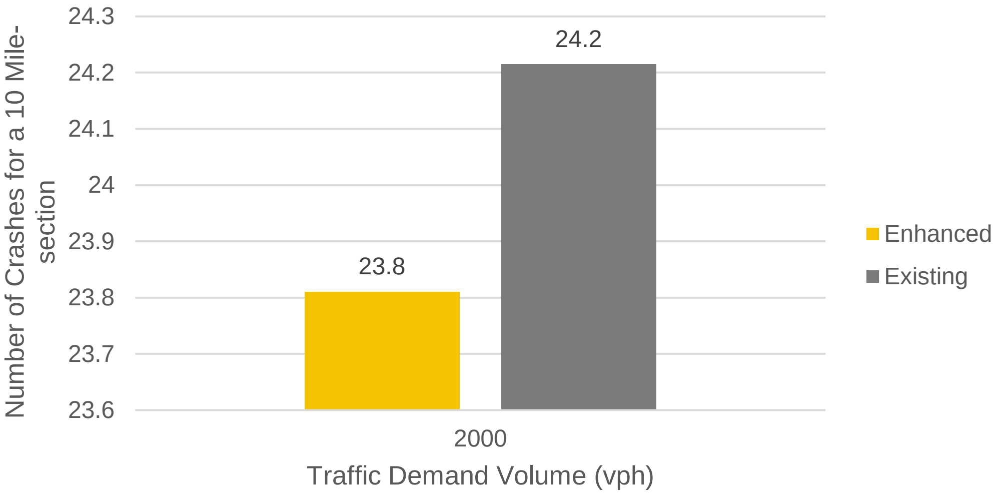

FIGURE 39: NUMBER OF CRASH PER MILE PER YEAR UNDER SATURATED EXISTING AND ENHANCED TRAFFIC CONDITION.

As it was mentioned in the methodology section (s2.3.5.2), for urban traffic conditions, 1% of total crashes are considered to involve fatalities. Considering the cost per fatality level crash as $7 million, the service life as 20 years, and fixed discount rate as 7%, the life cycle benefits of crash rate reduction due to ramp metering deployment during the next 20 years can be calculated as follows in Figure 40:

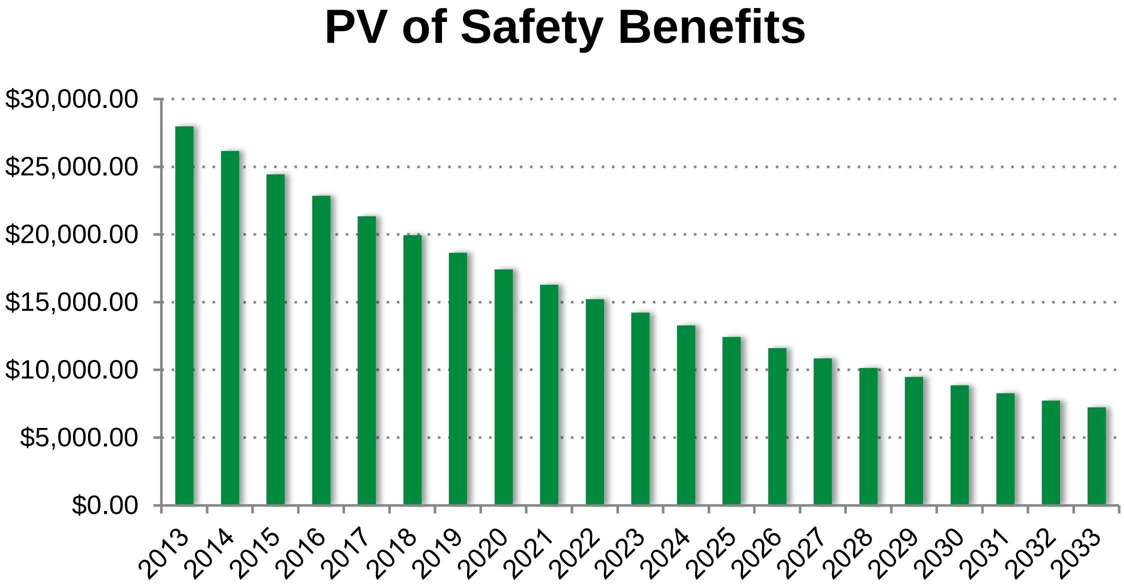

FIGURE 40: LIFE CYCLE CRASH RATE REDUCTION BENEFITS IN PRESENT VALUE FOR RAMP METERING.

The total PV of the benefits is determined to be approximately $324,632. Recalling that the total PV of the costs was $700,000 for a ramp metering deployment, a BCR 0.46:1 can be expected if only the fatality level crash rate reduction is considered during the daily 2-hr peak times (where v/c = 0.5).

If the total PV of benefits due to safety enhancements, energy consumption reduction and travel time savings are combined and introduced into the life cycle BCA, a BCR of 6.44:1 can be expected. Figure 41 below illustrates the B/C flow during the next 20 years (2013 to 2033), considering safety, travel time savings and energy savings benefits.

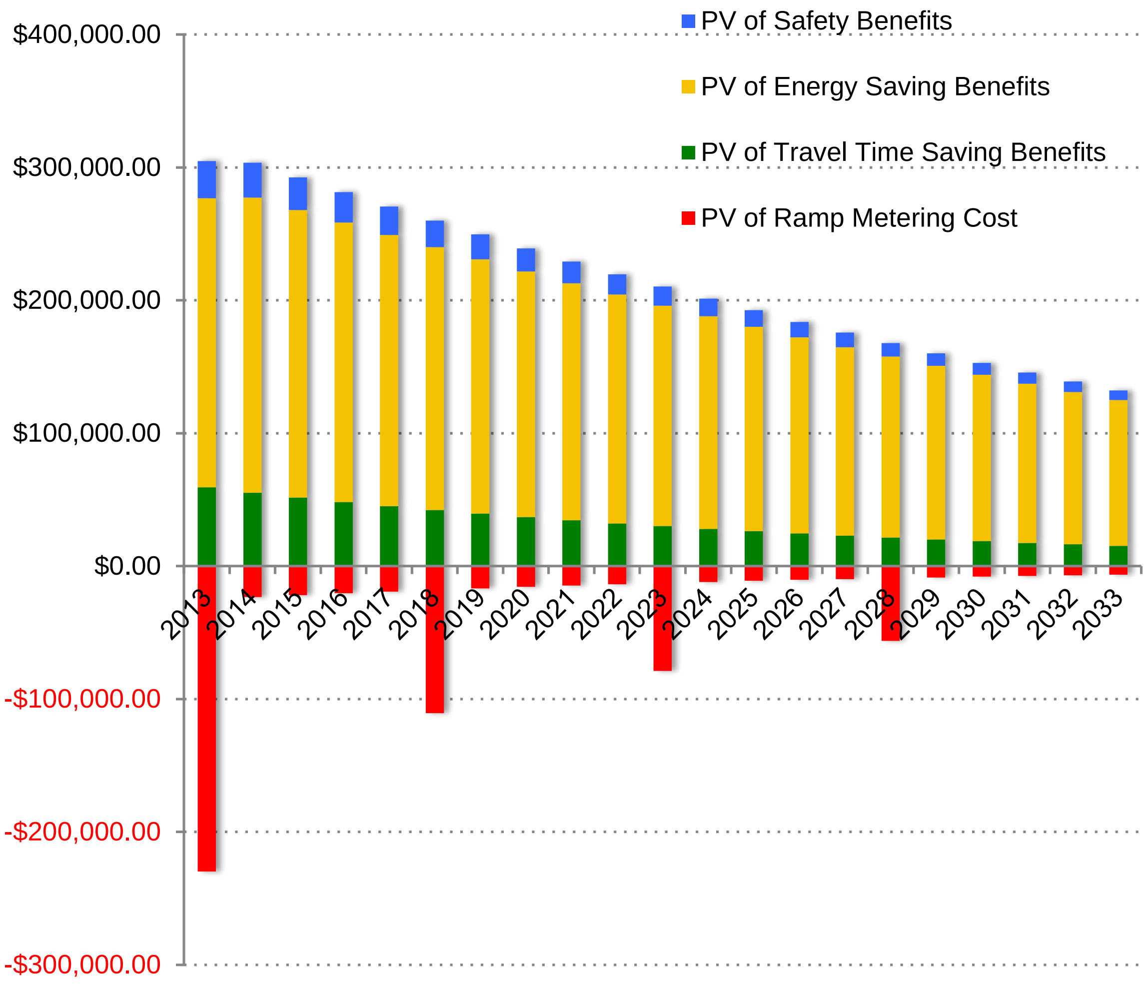

FIGURE 41: LIFE CYCLE ANNUAL BENEFITS AND COSTS FLOW FOR RAMP METERING IN PRESENT VALUE.

3.5 Summary

Based on previous benefits analysis (s*3.4.1 Life Cycle Cost Analysis*, *s3.4.2: Travel Time Saving Benefits*, *s3.4.3: Energy Consumption Reduction Benefits*, and *s3.4.4 Safety Benefits)*, the overall benefit/cost analysis for a typical ramp metering deployment is completed. 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. Life cycle benefit-cost flows are presented at the end of s3.4.4.3.

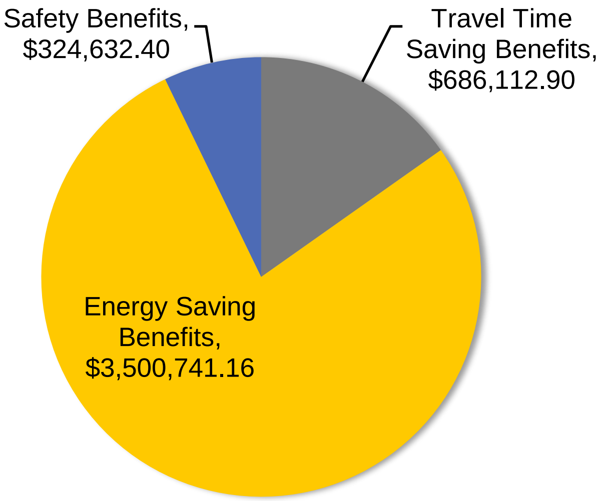

FIGURE 42: LIFE CYCLE BENEFITS DISTRIBUTION.

Figure 42 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 $4,511,486. Energy savings benefits (LCA benefits excluded) due to gasoline consumption reduction account for the most part in the total life cycle benefits with an approximate share of 78%. For the remaining benefits, travel time savings benefits consisting of recurring and nonrecurring travel time savings account for 15%, and safety benefits due to crash rate drop accounts for rest (7%). Table 23 below concludes the annual PV benefits flow for the analyzed time period (2013 to 2033).

TABLE 23: ANNUAL BENEFITS AND COSTS BREAKDOWN IN PRESENT VALUE

Year	Ramp Metering PV Costs	Travel Time Saving PV Benefits	Energy Saving PV Benefits	Safety PV Benefits	Net PV Benefit
2013	($229,750.00)	$59,178.20	$217,717.50	$28,000.00	$75,145.70
2014	($23,364.49)	$55,306.73	$222,077.66	$26,168.22	$280,188.12
2015	($21,835.97)	$51,688.53	$216,242.38	$24,456.28	$270,551.22
2016	($20,407.45)	$48,307.04	$210,220.13	$22,856.34	$260,976.06
2017	($19,072.38)	$45,146.77	$204,060.36	$21,361.07	$251,495.82
2018	($110,512.86)	$42,193.24	$197,806.82	$19,963.61	$149,450.81
2019	($16,658.56)	$39,432.93	$191,498.16	$18,657.58	$232,930.11
2020	($15,568.74)	$36,853.21	$184,780.96	$17,436.99	$223,502.42
2021	($14,550.23)	$34,442.25	$178,485.11	$16,296.25	$214,673.38
2022	($13,598.34)	$32,189.02	$172,222.18	$15,230.14	$206,043.00
2023	($78,794.14)	$30,083.20	$166,014.81	$14,233.78	$131,537.65
2024	($11,877.32)	$28,115.14	$159,882.53	$13,302.60	$189,422.95
2025	($11,100.30)	$26,275.83	$153,842.09	$12,432.33	$181,449.95
2026	($10,374.11)	$24,556.85	$147,649.58	$11,619.00	$173,451.32
2027	($9,695.43)	$22,950.33	$141,850.13	$10,858.88	$165,963.91
2028	($56,179.13)	$21,448.90	$136,177.57	$10,148.49	$111,595.83
2029	($8,468.36)	$20,045.70	$130,640.11	$9,484.57	$151,702.02
2030	($7,914.36)	$18,734.30	$125,244.36	$8,864.08	$144,928.38
2031	($7,396.60)	$17,508.69	$119,811.44	$8,284.19	$138,207.72
2032	($6,912.71)	$16,363.27	$114,725.34	$7,742.23	$131,918.13
2033	($6,460.48)	$15,292.77	$109,791.94	$7,235.73	$125,859.96

It is also worth noting that life cycle environmental impact benefits due to reduced CO_2e 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 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.

The total BCR calculated for the hypothetical case study is approximately 6.44:1. 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, in comparison to the ATCS case study, the share of travel time savings benefits dropped from 64% to 15%. The reasons are: 1) the metered ramp limits the throughput on the ramp, which offsets the VHT saved on the freeway segment. The total travel time savings on both freeway and ramp segments are not obvious under undersaturated to saturated traffic conditions. 2) 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.

4 CONCLUSIONS

In this study, the research team developed 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:

1. Life Cycle Cost Analysis,
2. Analysis of Benefits through Travel Time Savings,
3. Analysis of Benefits through Reductions in Energy Consumption,
4. 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 deployment. As a result of our hypothetical case studies, the BCR (considering only the benefits obtained through time savings) is calculated as 4.15:1.

In comparison to the BCR for an ATCS deployment when only the benefits obtained through time savings are considered (4.15:1), the BCR for ramp metering (0.98:1) is considerably low. The reasons may include: 1) the comparatively high infrastructural costs for ramp metering deployment, and 2) the limited throughput on-the-ramp due to the ramp metering deployment. Negative travel time differential before and after the ramp metering deployment offsets the travel time savings on the freeway segment, especially for the saturated traffic conditions.

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 a linear 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 single largest percentage in the total life cycle benefits of ramp metering deployment and the second largest percentage of ATCS deployment. The life cycle benefits for the 2-hr peak time fuel consumption reduction can be approximately 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.

Introduction of LCA provides a comprehensive method to evaluate the environmental impacts of energy consumption reduction from a broader perspective. However, due to its relatively small contribution in 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 CO_2e/intersection were achieved annually due to ATCS deployment. For ramp metering deployments, savings of 564,000 kg CO_2e 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.

Analysis of benefits through safety enhancements 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 is worth noting 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 (6.52:1 to 13.04:1) 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.

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APPENDIX

Publications / Presentations that resulted from this project:

As the preparation of this final report is being finalized, the research team is planning to prepare and submit manuscripts to various journals to disseminate the research efforts and results in appropriate mediums. So far, the following publication / presentation resulted from this project:

- Salem, O., Chen, X., Salman, B., and Abdel-Rahim, A. (2014). "Life-Cycle Benefits & Cost Analysis Framework of Adaptive Traffic Control System Deployment." *International Conference on Architecture and Civil Engineering*. Dubai, UAE.