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# **SUSTAINABILITY ANALYSIS OF INTELLIGENT TRANSPORTATION SYSTEMS**

by

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A thesis submitted in partial fulfillment of the requirements  
for the degree of Master of Science  
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in the College of Engineering and Computer Science  
at the University of Central Florida  
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Major Professor: Omer Tatari

## **ABSTRACT**

Commuters in urban areas suffer from traffic congestion on a daily basis. The increasing number of vehicles and vehicle miles traveled (VMT) are exacerbating this congested roadway problem for society. Although literature contains numerous studies that strive to propose solutions to this congestion problem, the problem is still prevalent today. Traffic congestion problem affects society's quality of life socially, economically, and environmentally. In order to alleviate the unsustainable impacts of the congested roadway problem, Intelligent Transportation Systems (ITS) has been utilized to improve sustainable transportation systems in the world. The purpose of this thesis is to analyze the sustainable impacts and performance of the utilization of ITS in the United States.

This thesis advances the body of knowledge of sustainability impacts of ITS related congestion relief through a triple bottom line (TBL) evaluation in the United States. TBL impacts analyze from a holistic perspective, rather than considering only the direct economic benefits. A critical approach to this research was to include both the direct and the indirect environmental and socio-economic impacts associated with the chain of supply paths of traffic congestion relief. To accomplish this aim, net benefits of ITS implementations are analyzed in 101 cities in the United States. In addition to the state level results, seven metropolitan cities in Florida are investigated in detail among these 101 cities. For instance, the results of this study indicated that Florida saved 1.38 E+05 tons of greenhouse gas emissions (tons of carbon dioxide equivalent), \$420 million of annual delay reduction costs, and \$17.2 million of net fuel-based costs. Furthermore, to quantify the relative impact and sustainability performance of different ITS technologies, several ITS solutions are analyzed in terms of total costs (initial and operation & maintenance costs) and benefits (value of time, emissions, and safety). To account for the uncertainty in benefit and cost

analyses, a fuzzy-data envelopment analysis (DEA) methodology is utilized instead of the traditional DEA approach for sustainability performance analysis. The results using the fuzzy-DEA approach indicate that some of the ITS investments are not efficient compared to other investments where as all of them are highly effective investments in terms of the cost/benefit ratios approach. The TBL results of this study provide more comprehensive picture of socio-economic benefits which include the negative and indirect indicators and environmental benefits for ITS related congestion relief. In addition, sustainability performance comparisons and TBL analysis of ITS investments contained encouraging results to support decision makers to pursue ITS projects in the future.

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## **LIST OF ACRONYMS (or) ABBREVIATION**

AHS: Automated Highway System

ATIS: Advanced Traveler Information Systems

DEA: Data Envelopment Analysis

EIO-LCA: Economic Input Output – Life Cycle Assessment

ETC: Electronic Toll Collection

ISTEA: Intermodal Surface Transportation Efficiency Act

ITS: Intelligent Transportation Systems

QoL: Quality of Life

TBL: Triple Bottom Line

TTI: Texas Transportation Institute

UMR: Urban Mobility Report

VMT: Vehicle Miles Traveled

WHO: World Health Organization

# CHAPTER ONE: INTRODUCTION

## **1.1. Background Information**

### ***1.1.1. Traffic Congestion Problem in the U.S.***

Increase in population, number of vehicles, and vehicle miles traveled (VMT) are the leading causes of the roadway congestion problem in the United States. The vast amounts of studies that are published in literature in the last decade prove the importance of the congested roadway problem. For instance, annual VMT increased 8% after the 2008 financial crisis and reached 2.97 trillion miles in the U.S. in 2011 (Federal Highway Administration, 2013). Therefore, it clearly can be stated that traffic congestion has negative impacts on economy, environment, safety, and society. According to the Texas Transportation Institute's (TTI) Urban Mobility Report (UMR), in 2011 people in the U.S. traveled 5.5 billion more hours and purchased an extra 2.9 billion gallons for a congestion cost of \$121 billion. In other words, each commuter in the U.S. wasted 43 hours of time, \$922, and 20 gallons of fuel annually (Lomax, Schrank, & Eisele, 2011).

### ***1.1.2. Sustainable Transportation***

Numerous researchers, institutes, and government organizations are working on reducing traffic congestion and building sustainable transportation system all around the world. The common conclusion for this problem is that it is not feasible to continue to consume resources at current rates and the time is limited to take action. These conclusions lead to the idea of sustainable development implementations on transportation systems.

“Sustainable development” was defined by United Nations’ Report in 1987 as; *“generating a development which meets the needs of the present without compromising the ability of future generations to meet their own needs.”* This definition can be paraphrased for transportation systems as ensuring that future generations need for mobility and transport will not be compromised. Researchers, governors, decision makers etc. are still working on building a sustainable world, and sustainable transportation systems, however, the results of these efforts do not indicate significant improvements (Black, 2010).

The concept of sustainable development is not straightforward, since it has various indicators. For instance, transportation affects fossil fuel (petroleum) reserves, global atmosphere, local air quality, noise pollution, level of mobility, congestion rate, and mortality rates (fatalities and crashes).

The world has used approximately 1 trillion barrels of petroleum (Black, 2010). This fact could highlight the severity of this problem by itself. Due to the increasing rate of population growth and number of vehicles on the roads, the question arises as to whether or not the petroleum reserves will be able to meet the needs of future generations.

Congestion and level of mobility are directly affected by the increase of VMT and number of vehicles. Today in most urban areas, traffic congestion is one of the main concerns of residents. Even the local government agencies invest enormous amounts of money to expand roads and reduce congestion; however, the results of these investments do not indicate significant benefits since the existing roads cannot be expanded to the

infinity. In addition, congestion is the main reason for low air quality in urban areas, due to vehicle emissions.

Transportation is one of the main factors that affects air quality and greatly impacts the global atmosphere. Urban area air quality data is an example of the severity of transportation's impact on the environment. According to the U.S. Bureau of Transportation Statistics, transportation modes caused 3.7% of sulfur dioxide, 57% of nitrogen oxide, 68.4% of carbon monoxide, 2.9% of PM10 particulates and 11.8% of PM2.5 particulates, and 33.9% of volatile organic compounds emissions to the air in 2009 (U.S. Bureau of Transportation Statistics, 2009). Poor air quality does not only threaten human life, it also afflicts the life of all species on the planet. In addition, emissions and the global average temperature are increasing because vehicles are burning fossil fuels.

Finally, traffic crashes is another issue that should be included as a part of sustainable development. According to World Health Organization (WHO), crashes are responsible for almost 1 million fatalities each year and nearly 70 million of injuries (2001) (World Health Organization, 2004). Fortunately, per 100 million VMT mileage death rates are decreased from 2 to 1.25 in the last 10 years in the U.S. This decrease in crash rates can be explained by an increase in enforcement of traffic laws and new traffic regulations by the U.S. Government in last decade. Also, every crash costs a significant amount of money to society. For instance, moderate injury crash costs \$392,000 and where fatality crash costs \$4.2M in 2009 dollars [(Blincoe et al., 2002) (costs converted from year 2000 to year 2009 by consumer price index)].

As a result of these unsustainable aspects of transportation, there is a crucial need to develop new strategies to decelerate the current trend. Using the word “deceleration” is more accurate for current issue, because stopping or become sustainable cannot go beyond the point of utopia. The studies in this era include widespread point of view changes such as technological improvements, commuter behavior, alternative fuels etc. These changes may make interesting impacts on society in addition to the common concerns: economic and environmental. For instance, Frank et al.’s study (2004) states that the chance of becoming obese increases by 6% with every extra hour wasted in traffic (Frank, Andresen, & Schmid, 2004).

### ***1.1.3. Quality of Life***

According to World Health Organization’s (WHO) definition, quality of life (QoL) is an “*individual’s perception of their position in life in the context of the culture and value systems in which they live and in relation to their goals, expectations standards and concerns*”(World Health Organization, 1997). The twenty two indicators of QoL that are defined by Steg & Gifford’s (2005) study considers similar aspects as sustainable transportation does such as; energy and land use, waste, traffic safety, traffic noise, health consequences, accident costs, accessibility, and economic wealth indicators.

In Steg & Gifford’s study, the results of a study are evaluated to present how the unsustainable impacts of transportation systems affect QoL. The study ranks the QoL indicators in terms of the responders’ answers. Moreover, the researchers extend the study with investigating transportation policies’ impact on responders’ QoL. The study clearly



concludes that transportation policies and systems have influence on society's QoL indicators.

In conclusion, sustainable transportation ideas should be implemented in roadway design for metropolitan regions to improve the QoL of commuters. However, significant outcomes of sustainable transportation system designs can only be realized if travel behavior is also changed. Therefore, decision makers in government agencies should consider the indicators of QoL for future investments.

#### ***1.1.4. Part of the Solution: Intelligent Transportation Systems***

As is mentioned above, the sustainable transportation approach proposes some strategies to solve current problems, and Intelligent Transportation Systems (ITS) can assist with these strategies. ITS combine the implementation of technological improvements to a road system with improvements that increase the road system's efficiency. ITS are a solution which aims to enhance mobility, increase fuel efficiency, accessibility, operating efficiency, pollution, and safety. In other words, ITS aim to improve quality of life of society.

ITS helps mitigate problems such as traffic congestion, air quality, and safety without constructing additional roads (Bekiaris & Nakanishi, 2004). ITS are very broad and include several areas of technology and system improvements such as advanced traffic management system (e.g., freeway and incident management systems, electronic toll collection), advanced traveler information systems (e.g., dynamic message signs and in car

real time traffic information and navigations systems), advanced public transportation systems, and commercial vehicle operations among others (Bekiaris & Nakanishi, 2004).

Some researchers discovered the benefits of using communication technology on transportation systems in 1980s (Weiland R.J., Purser, 2000). University of California Berkeley led the U.S. with their unique experiments on ITS applications from the beginning such as Advanced Traveler Information Systems (ATIS). Finally, the Intermodal Surface Transportation Efficiency Act (ISTEA) launched the nationwide ITS program in the U.S. in 1991 (Bekiaris & Nakanishi, 2004). In that same year, the Intelligent Transportation Society of America (ITS America) was also established as a non-profit organization. These organizations enabled the growth of ITS in the U.S. since they established.

The European Union (EU), along with the American organizations, played a critical role in the development of Road Transport Telematics and ITS since 1988. The Directorate General for Information Society of the European Commission funded some successful research projects between 1994 and 1998 such as the Telematics Application Programme (Bekiaris & Nakanishi, 2004)..

In 2006, approximately \$1 billion was spent on ITS in the U.S. In detail, federal funding budgeted \$110 M and over \$850 M from local and state funding. Moreover, federal transportation agencies in the U.S. aim to increase the annual funding to \$2 billion for ITS projects by 2020 (Florida Department of Transportation Work Program Development Office, 2013).

## **1.2. Thesis Objectives**

As is stated in previous sections, traffic congestion has economic, environmental, and safety impacts on society. Operational treatments on roads, such as ITS, provide benefits to these societal impacts. The direct time or emissions savings are not the only impacts that should be studied, the benefits need to be studied in a holistic way by researchers in order to draw a comprehensive picture for decision makers and government agencies about widespread impacts, Therefore, the benefits can be plotted with their supply chain and life cycle results instead of conventional cost/benefit analysis. Furthermore, in order to consider socio-economic impacts, Economic Input Output-Life Cycle Assessment (EIO-LCA) or Hybrid-LCA approaches are not sufficient enough for this analysis. Thus, the Triple Bottom Line (TBL) approach was used because it allows researchers to investigate the impacts/benefits of systems while taking into consideration the indirect effects for socio-economic and environmental point of views.

ITS applications are generally effective investments in terms of their cost-benefit analysis; however these ratios do not provide adequate information for decision makers. Using a multi-criteria decision making tool is crucial to propose efficiency analysis of ITS applications. Data Envelopment Analysis (DEA) methodology is also not accurate enough to plot these results due to benefit and operation & maintenance analyses' unpredictable and assumption based structure. Hereby, fuzzy DEA methodology could be the best fit with its uncertainty levels to provide realistic decision making information for future ITS investments.

Consequently, as a part of sustainable transportation, this thesis investigates how ITS improve the QoL for society. Therefore, congestion relief related ITS effects are studied for sustainability impacts and performances.

### **1.3. Aim of the Thesis**

This thesis aims to present sustainability impacts and performance of Intelligent Transportation System investments on the roads of the U.S. which consists of socio-economic, environmental and efficiency indicators. Therefore, this thesis will focus to propose following objectives:

- Quantify socio-economic and environmental impacts of ITS savings for a state,
- Quantify total socio-economic and environmental impacts of ITS savings in the U.S. for 4 years,
- Develop a common methodology to quantify costs and benefits of different ITS applications with the consideration of engineering economics, and
- Quantify efficiency scores of different ITS applications in terms of their costs and benefits in the U.S.

#### **1.4. Organization of the Study**

This thesis is organized into seven chapters. Following the detailed introductory chapter is a literature review of Intelligent Transportation Systems (ITS) analysis studies in different methodologies which is presented in chapter two. Traffic congestion savings, triple bottom line, and fuzzy-DEA methodologies are explained in detail with their formulations in chapter three.

Chapter four investigates in detail the socio-economic and environmental sustainability impacts of seven Florida metropolitans. Chapter five extends this analysis to the U.S. level which includes 101 cities. The results of sustainability indicators are presented on the U.S. map figures below, each result is 4 year total for the state. It is followed by the sustainability performance analysis which ranks the ITS investments in terms of their efficiency scores.

The final chapter (chapter seven) consists of overall findings of this thesis in terms of their socio-economic, environmental, and efficiency results. The conclusion section also aims to provide summaries of the implications of these studies for decision makers or researchers. Finally, it concluded with study limitations and recommendations for future studies in this field.

## **CHAPTER TWO: LITERATURE REVIEW**

### **2.1. Overview**

This chapter summarizes the researches that present the impacts of ITS in different aspects. Cost/benefit studies of ITS provide results for efficiency performances. It followed by LCA studies which investigates the direct and indirect impacts of ITS in addition to the costs & benefits. Finally, as a decision making tool, DEA studies evaluate ITS investments for their efficiency performances.

### **2.2. Cost-Benefit Studies of Intelligent Transportation Systems**

Avineri, et al.,'s (2000) study defines four different impact evaluation methods of transportation systems which are *profile and checklist*, *scoring*, *cost-benefit analysis*, and *mathematical programming*. This study follows the methodology of cost-benefit studies in order to provide data for multi-objective efficiency analysis. There are numerous cost-benefit evaluation studies about ITS, and Nas's (1996) book could be counted as the benchmark methodology of these studies.

In 2002, Cambridge Systematics, as part of a National Cooperative Highway Research Program (NCHRP) project, investigated the benefits of reducing congestion in terms of economic, environmental, social and safety point of views without considering indirect industry impacts (Cambridge Systematics, 2002). Another cost-benefit and economic impact focused study implemented on ITS projects was conducted by Texas

Transportation Institute (TTI) in 2003 (Stockton & Walton, 2003). This study neglected to consider the indirect economic and environmental impacts as well.

Bekiaris & Nakanishi's (2004) book lists the different methodologies that can be used in economic assessment of ITS. This book also includes cost/benefit case studies that are applied on different ITS applications such as; Brand, et al. (2004) on Commercial Vehicle Operation (CVO), Naniopoulos, et al. (2004) on information technology systems, Gillen, et al. (2001) on public transit. In addition, Thill, et al. (2004)'s study evaluated benefits and costs of ITS on a macro level.

U.S. Federal Highway Administration (FHWA) developed a decision making tool named *Surface Transportation Efficiency Analysis Model* (STEAM) that is used by federal and regional transportation agencies' to quantify infrastructure cost and benefits (U.S. Federal Highway Administration, 2013). In addition, U.S. Department of Transportation (DOT) prepared reports about ITS applications in the U.S. in terms of their cost, benefit, and lessons learned with numerous case studies (U.S. DOT Research and Innovative Technology Administration, 2008; U.S. DOT Research and Innovative Technology Administration, 2011) This cost-benefit database is also publicly available through U.S. DOT's website, which allows users to filter case studies in terms of their ITS type, state, cost, benefit etc. [<http://www.itsbenefits.its.dot.gov/> ].

### **2.3. Life Cycle Assessment Studies of Intelligent Transportation Systems**

Life Cycle Assessment (LCA) is a tool that was developed in early 1990s in order to investigate potential environmental impacts in system base. In other words, it is a powerful method which has been used widely in literature for providing the results of production or process's impacts from cradle to grave. This cradle to grave approach starts from raw material extraction and continues with production, transportation, use phases and finally concludes with end-of-life phase (Finnveden et al., 2009). The LCA methodology basically consists of goal and scope definition, life-cycle inventory analysis, life-cycle impact assessment, and interpretation sections (Graedel & Allenby, 2009).

Economic Input-Output (EIO) analysis proposed to build more powerful methodology with LCA approach to analyze the supply chain impacts including systems or products' economic and environmental impacts (Hendrickson, Lave, & Matthews, 2006). EIO-LCA tool was developed by Green Design Institute at Carnegie Mellon University (CMU 2013) and this publicly available tool has been widely used in literature (Carnegie Mellon University (CMU), 2002). The wide use of this tool in literature, which ranges from construction, transportation, health agricultural etc., indicates the power of it. In addition to EIO-LCA, the Center of Resilience at the Ohio State University built Ecologically-based LCA (Eco-LCA) to examine the role of the ecological goods and services which are used the industrial sectors (OSU 2013).

The Eco-LCA methodology was implemented on the construction industry by Kucukvar & Tatari, (2013). The researchers studied the resource consumption and



atmospheric emissions of the U.S construction sectors in terms of mass, energy and ecological exergy. Neither EIO-LCA nor Eco-LCA are able to identify the large economic, environmental and social impacts in one holistic picture, Triple Bottom Line (TBL) based LCA model could be proposed as an adequate methodology, since TBL merges economic and social indicators into EIO methodology with drawing environmental burdens at the same time.

The need to develop more holistic analysis about sustainability impacts brought the trend of integrating economic and social sustainability indicators into LCA framework. Moreover, this trend inspired the birth of Life Cycle Sustainable Assessment (LCSA) which is suggested by Kloepffer, 2008. The three main dimensions of sustainability such as environment, economy, and society (T. O. Wiedmann, Lenzen, & Barrett, 2009; T. Wiedmann & Lenzen, 2006) also generates the TBL concept and it achieved with implementing Life Cycle Cost (LCC) and Social Life Cycle Assessment (SLCA) methods (Zamagni, Guinée, Heijungs, Masoni, & Raggi, 2012).

Initial EIO based TBL model created by Foran et al. (2005) includes the industrial sectors of Australia's entire economy (Foran, Lenzen, & Dey, 2005). In this approach, the EIO tables of 135 sectors of Australia's economy integrated with three main sustainability metrics (environmental, economic, and social). Furthermore, this baseline TBL methodology led to the development of the *Balancing Act* software by researchers at the University of Sydney for the Australia, United Kingdom, and Japan economies. Foran et al. (2005) and Wiedmann et al. (2009)'s studies are some of the examples in the literature

that are accomplished with this TBL methodology (Foran, Lenzen, Dey, & Bilek, 2005; T. O. Wiedmann et al., 2009). The initial implementation of TBL methodology for the U.S. economy model is developed by Kucukvar & Tatari, (2013) with the study of presenting seven U.S. construction sectors' impacts. Moreover, this approach initially applied on ITS study is published by Ercan et al., in 2013 which indicates the direct and indirect socio-economic and environmental impacts in Florida.

#### **2.4. Data Envelopment Analysis (DEA) Studies of Intelligent Transportation**

##### **Systems**

Data Envelopment Analysis (DEA) was established by Farrell in 1957 and then conceived by Charnes, Cooper, & Rhodes (CCR) in 1978. It is a methodology to evaluate the relative efficiencies of a set of comparable entities, which are called Decision Making Units (DMU) by some specific mathematical programming models (Zhou, Poh, & Ang, 2007). As it is widely used for decision making in many disciplines such as operations research, management control systems, organization theory, strategic management, economics, accounting and finance, human resource management etc. (Rouse, 1997), it is also used widely in transportation systems' efficiency. DEA application examples vary in transportation problems (Ozbek, de la Garza, & Triantis, 2009; Cooper, Seiford, & Zhu, 2011) such as sustainability (Lee & Farzipoor Saen, 2012), safety (Egilmez & McAvoy, 2013), environment (Fried, Lovell, Schmidt, & Yaisawarng, 2002) etc. Nakanishi &

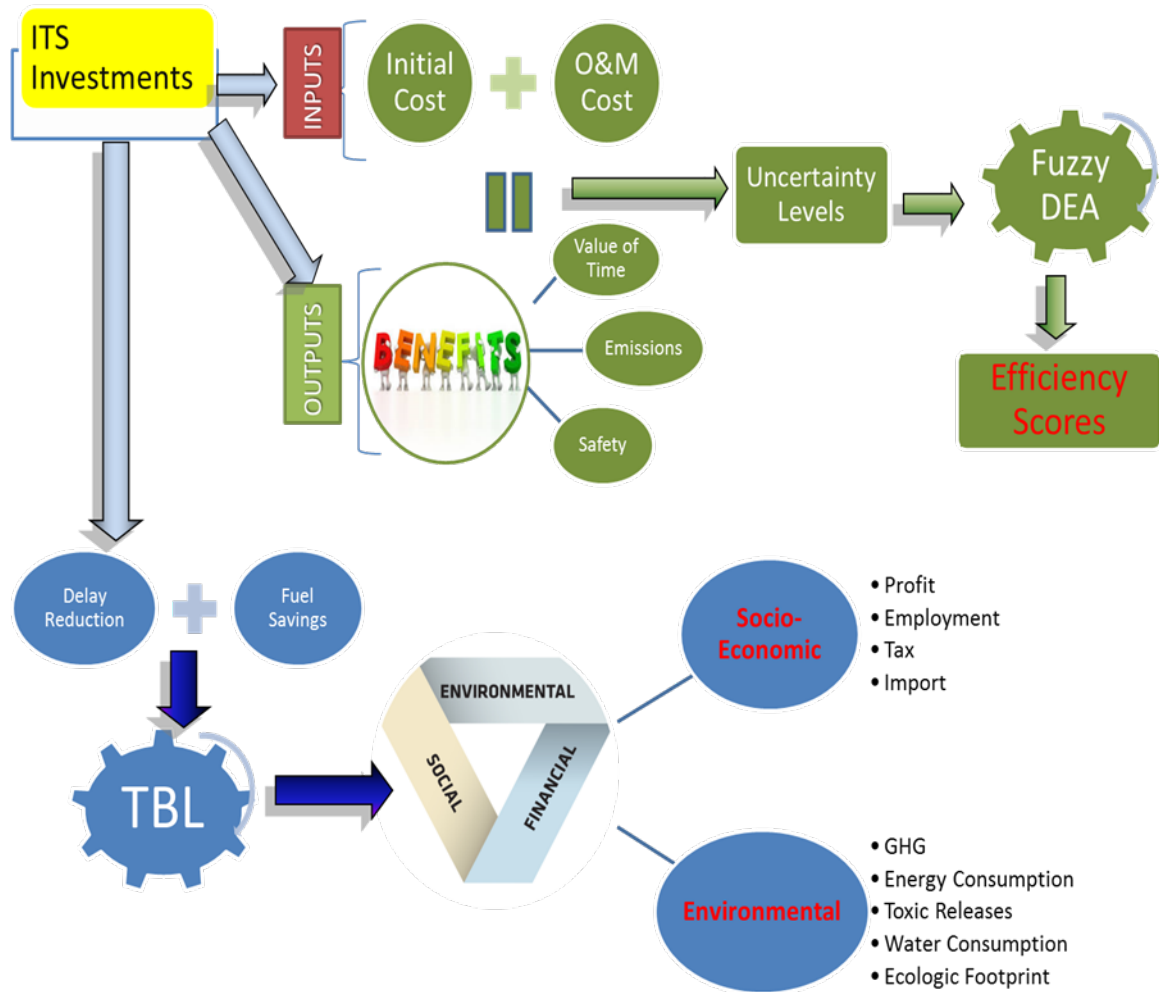
Falcochio (2004) examined the performance assessment of ITS and it also provide detail methodology information of using DEA on transportation problems.

Due to the difficulty of defining real world's problems' imprecision and vagueness, the fuzzy set theory developed by Zadeh, (1965). His study identified the importance of having linguistic variables in uncertain environments. DEA methodology uses some specific numerical data that may consist of imprecise or vague information. In 1992, Sengupta (1992) initially introduced fuzzy set theory in DEA model with uncertainty levels. Fuzzy set theory in DEA defined in four different categories such as *the tolerance approach*, *the  $\alpha$ -level based approach*, *the fuzzy ranking approach*, and *the possibility approach*. The  $\alpha$ -level approach is one of the most popular model owing to the number of studies that are published which use the model (Hatami-Marbini, Emrouznejad, & Tavana, 2011). Kao and Liu (2000) developed the key algorithm in  $\alpha$ -level based fuzzy DEA approach. Their approach converts fuzzy data to crisp model in BCC-DEA (BCC is due to Banker, Charnes, & Cooper (1984)) in order to measure efficiency of Decision Making Unit (DMU)'s. In other words, it determines the fuzzy efficiency score of a specific  $\alpha$ -level for lower and upper boundaries. Some of the examples of this approach are; Hatami-Marbini, et al., (2009), Saneifard, et al., (2007) and Triantis, (2003) etc. Recently, Angiz L, et al., (2012) developed a local  $\alpha$ -cut level based fuzzy DEA model which is also followed by this study to propose efficiency scores of DMU's.

## **CHAPTER THREE: METHODOLOGY**

### **3.1. Overview**

This thesis consists of multi disciplinary methodologies to determine impacts of ITS investments and their efficiency scores. First, the ITS related traffic congestion relief savings need to be determined for further Triple Bottom Line (TBL) calculations. The Florida based and U.S. based ITS related traffic impacts are determined with TTI's 2011 UMR methodology. In order to compare different ITS in same fraction unit in terms of their cost and benefit (Value of time, emissions, and safety) values, the methodology of TTI's 2011 UMR were modified based on the calculations of reference studies. The general summary of methodologies can be seen on Figure-1, below. Thesis utilizes the ITS related benefits and costs to run TBL or fuzzy-DEA engines for sustainability impact and performance analyses.



**Figure 1:** The summary of methodologies in use to determine sustainability and efficiency impacts of ITS

### 3.2. ITS Related Traffic Congestion Relief Saving Calculations

#### *3.2.1. Traffic congestion relief saving calculations for TBL methodology*

This thesis gathers the traffic information from TTI's 2011 Urban Mobility Report (UMR) (Lomax et al., 2011). UMR consist of congestion related wasted time, fuel values and operational treatment (ITS) related time and fuel savings for 101 metropolitan areas in

the U.S. The report creates a “what if” scenario of how the traffic will be affected if there is not ITS on the roads in congested areas of metropolitan cities compared to the congestion that is relieved with the use of ITS on the road system. The difference in congestion for the road with ITS versus the road without ITS is the congestions savings. Total congestion cost is a summation of annual delay hour and fuel wasted costs (see Eq. #1). This equation leads to the basics of calculating the fuel based consumption savings and time savings.

$$\text{Annual Congestion Cost} = \text{Annual Passenger Vehicle Delay Cost} + \text{Annual Passenger Vehicle Fuel Cost} + \text{Annual Commercial Vehicle Delay Cost} + \text{Annual Commercial Vehicle Fuel Cost} \quad (1)$$

Each component of the equation #1 has its own basic formula inside. For the fuel related components the content is generated by; average passenger and commercial vehicle percentages on the roads, the cost of the average fuel or diesel, the annual amount of fuel saved or wasted. Moreover, the time related calculations are based on following parameters such as average passenger and commercial vehicle percentages on the roads, annual congestion related time wasted or saved, vehicle occupancy of passenger or commercial vehicles, the value of time for passenger or commercial vehicles. As it can be seen from the parameters, the cost of the congestion or the cost savings of ITS can be calculated from the same method.

The next step for these calculations is followed by the TBL methodology which is explained later in this chapter to gather the environmental indirect benefits of ITS deployment.

### ***3.2.2. Traffic congestion relief saving and cost calculations for Fuzzy-DEA methodology***

The case study of efficiency analysis of ITS includes different case studies of ITS which aim to present benefits and costs of those systems. In order to provide adequate efficiency analysis results from this study, each case study was converted to the same fraction units in terms of their cost and benefit calculations. Because, each case study used its own coefficient values for cost and benefit calculations. Hereby, this thesis used same inflation rate for converting cost data to year 2013 dollars and same value of time, emission cost, and accident cost for benefit calculations. It can be seen from the reference case studies that each uses different vehicle occupancy rates, vehicle percentage or value of time data for their calculations. These baseline cost and coefficient values can be seen on data description section of this efficiency analysis study.

Since all of the reference case studies prepared in different years it is crucial to adjust these cost data to same year values. Engineering economics methods were used to adjust the cost values to year 2013 based on consumer price index' inflation rate (Bureau of Labor Statistics, 2013). In addition to the initial cost of ITS projects, there is operational & maintenance (O&M) cost which will generate the life cycle cost of the project together.

The sustainability performance analysis of ITS consider the three components of traffic related congestion relief benefits, which are value of time, emissions, and safety. Value of time represents the dollar value of the time that is saved with ITS investments for people on the roads. In regards to consumer price index, every hour that is spend in traffic worth \$17.46 (2013 dollars) to the commuter. This value dramatically increases for commercial vehicles. Every extra hour that is spent for a commercial vehicle in traffic congestion costs \$94.40 to society (Lomax et al., Appendix B, 2011). Since these dollar values are in person hour (person-hr) fraction, they have to be multiplied with vehicle occupancy. Based on the assumption from UMR (2011) average vehicle occupancy is 1.25 person for passenger vehicles and 1.05 for commercial vehicles. Finally, these components need to be multiplied actual time saving that is made in a year. Traffic analysis studies consider only the working days of the year for annual results. However, some studies considers 260 working days in a year where some of them consider 250. As it mentioned before, in order to have all of the benefits in same fraction, the annual time saving data from reference studies are converted to daily savings to multiply with 250 working days. In conclusion, following formula sums all of the components of value of time calculation. The following formula is based on the methodology that is used in TTI UMR studies for total congestion cost calculations (Lomax et al., 2011).



$$\text{Value of Time Benefits (\$)} = [\text{Congestion relief related time savings (person hr)} * \text{Value of each person hour for commuters} * \text{Vehicle occupancy of passenger vehicles}] + [\text{Congestion relief related time savings (person hr)} * \text{Value of each person hour for commercial vehicles} * \text{Vehicle occupancy of commercial vehicles}] \quad (2)$$

Emission savings are also related to the time savings on traffic congestion but not limited to them because emission rates are also related with the number of acceleration/deceleration. Reducing congestion not only means less time consumed on traffic but also means fewer stop-goes for vehicles. Same as with the time savings methodology, the reference studies used simulation models to capture emission savings related to congestion relief. This study only considers three major components of vehicle related emissions such as HC, CO, and VOC. However, there are 30 more different minor toxic emissions that are released into the air continuously from vehicles on the roads, according to Environmental Protection Agency (EPA)'s Motor Vehicle Emission Simulator (MOVES) (U.S. Environmental Protection Agency, 2010). Key studies have quantified the value of emissions from vehicles. These studies have determined that there is an economic benefit to emission savings. In other words, each kilogram of emission from vehicles cost money to the society. These coefficient values for emission calculations are presented in data collection section of efficiency analysis study of ITS. The total emissions saving calculations are summarized with following formula (See Eq. #3).

$$\text{Value of Emission Savings} = [\text{Amount of HC savings} * \text{Cost of HC emission (per kg)}] + [\text{Amount of CO savings} * \text{Cost of CO emission (per kg)}] + [\text{Amount of NO}_x \text{ savings} * \text{Cost of NO}_x \text{ emission (per kg)}] \quad (3)$$

Safety benefits are based on the number of accidents on the corridor where ITS were implemented by agencies. Any reduction or increase on number of the accidents on certain corridors presents the impacts of ITS treatments. The case studies in this research use before-after study or simulation models to estimate the safety impacts. As a result of safety researches are unpredictable and dependable on many parameters content, ITS may not be beneficial for all cases. In other words, a captured benefit from before/after study of safety impacts of ITS on a corridor might result in the opposite way following years. After the number of accident portion is calculated, it is multiplied with the average accident cost for 2013. Blincoe et al., (2002) states the accidents costs for fatality, serious injury, and property damage for 2000. The reference studies does not provide any information for the number of accidents' type, so in this thesis the researchers use an average accident cost to determine value of safety benefits in 2013 dollars. Total safety impact calculations are summarized with following formula (See Eq. #4).

$$\text{Value of Safety Savings} = \text{Amount of crash reduction} * \text{the average cost of an accident} \quad (4)$$

### **3.3. Triple Bottom Line (TBL) Methodology**

The methodology TBL-LCA approach of this thesis is developed by Kucukvar & Tatari (2013). Same as the EIO-LCA, TBL approach considers all relations of economic activities between 428 sectors of the U.S. which are associated with the direct activity (U.S. Bureau of Economic Analysis, 2002). TBL approach improves this methodology with implementing socio-economic indicators. In the following formula,  $A$  presents the matrix of sector level direct requirements. This matrix includes the dollar value of inputs required from other sectors to produce one dollar of output. A sector's total output could be represented in this economic model with  $f$  (final demand) (Miller & Blair, 2009).

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1} \mathbf{f} \quad (5)$$

where  $\mathbf{x}$  is the total outputs of sectors,  $\mathbf{I}$  represent the diagonal identity matrix, and  $\mathbf{f}$  refers to the final demand vector representing the change in a final demand of desired sector. After providing per dollar of output economic values on matrix, the total environmental impacts can be determined by multiplying it with its environmental parameter. A vector of environmental outputs can be expressed as (Miller & Blair, 2009):

$$\mathbf{r}_i = \mathbf{E}_i \mathbf{x} = \mathbf{E}_i (\mathbf{I} - \mathbf{A})^{-1} \mathbf{f} \quad (6)$$

where  $\mathbf{r}_i$  is the total environmental outputs vector for the environmental impact category of  $i$ , and  $\mathbf{E}_i$  represents a diagonal matrix, which consists primarily of the environmental impacts per dollar of output for each industrial sector.

### ***3.3.1. Socio-Economic Indicators***

The following socio-economic indicators were utilized:

- Business Profit:

As a positive indicator, business profit is represented by Gross Operating Surplus (GOS). Since the GOS represents the capital available to corporations, which grant them to pay taxes and to fund their investments. The data source for GOS values by each industrial sector is the U.S. input-output tables (U.S. Bureau of Economic Analysis, 2002).

- Import:

Imports are the purchased goods and services from foreign countries to sell or produce domestic commodities. Each industrial sector's import values are determined from the U.S. input-output tables. The unit function of these values is presented in million dollars (U.S. Bureau of Economic Analysis, 2002).

- Tax:

This is the collected taxes by the government on production and imports. Government funds national civil infrastructures with taxes. So, tax is considered as a sustainability indicator. On the other hand, congestion relief means less fuel consumption and less tax. The values for taxes generated by each sector are obtained from the U.S. input-output tables (U.S. Bureau of Economic Analysis, 2002).

- Income:

Income is another important indicator which is the recompense of employees, containing wages and salaries. The data source for income generated by each industrial sector is the U.S. input output tables (U.S. Bureau of Economic Analysis, 2002). Total employment hours stands for the full time-equivalent employment for each U.S. sector in the units of hours per year.

### ***3.3.2. Environmental and Ecologic Indicators***

The diagonal environmental impact matrixes, including the value of these environmental impacts categories per dollar output of each industrial sector is obtained from the EIO-LCA model. Thus, the following environmental and ecologic indicators were utilized:

- GHG Emissions:

Fossil fuel combustion (coal, natural gas, petroleum etc.) causes carbon dioxide (CO<sub>2</sub>), nitrogen oxides (NO<sub>x</sub>) and methane gas emissions. Moreover, the general name for these gases is GHG emissions. The total GHG emission savings are expressed in terms of CO<sub>2</sub>-eqv in this study. This environmental indicator accounts for the direct and indirect contribution of one sector to GHG emissions.

- Energy Consumption:

The total energy consumption savings for each sector is the summation of the amount of energy capacity of various fossil fuels and electricity from non-fossil sources. The values of major fuel consumption by industrial sectors are estimated by the U.S. input-

output tables. Numbers of fuel consumptions (in terms of TJ) are based on the average producer price of each fuel types (Carnegie Mellon University (CMU), 2002).

- Toxic Releases to Air:

EIO-LCA tool is used to determine the amount of toxic release to the atmosphere [10, 28]. The toxic chemical emission coefficients for each sector used in this model is based on U.S. EPA's toxic releases inventory database (Environmental Protection Agency, 2013).

- Water Withdrawals:

There are various categories in the United States Geological Survey data that are used by the EIO-LCA model in order to estimate direct water withdrawals. These categories are power generation, irrigation, industrial, livestock and aquaculture, mining, public supply, and domestic water use. Based on their water consumption rates some of these categories are then allocated to different U.S. sectors. Blackhurst et al. (2010) used the same method where the total amounts of water withdrawals were categorized and allocated for each industrial sector (Blackhurst, Hendrickson, & Vidal, 2010).

- Ecological Footprint:

In this indicator, the CO<sub>2</sub> uptake land is calculated and the amount of forestland saved to absorb the carbon emissions is estimated. The U.S Energy Information Administration is the data source for the total CO<sub>2</sub> emissions due to fuel consumptions (Energy Information Administration; U.S. Department of Energy, 2013).

### **3.4. Fuzzy DEA Methodology**

Fuzzy-DEA methodology that is used in this thesis is developed by Egilmez et. al. (2013) in University of Central Florida. Fuzzy-DEA model, presented by Kao and Liu, (2000) is used to evaluate and rank different ITS deployments in different states of the U.S. based on cost and benefit results. Some notations that are employed in Kao&Liu's (2000) fuzzy-DEA model are presented below. Here,  $X_{ij}$  and  $Y_{ik}$  show  $i^{th}$  DMU's  $j^{th}$  input and  $i^{th}$  DMU's  $k^{th}$  output, respectively ( $j=1,2,\dots,s$  ;  $i=1,2,\dots,n$ ,  $k=1,2,\dots,t$ ).  $\varepsilon$  is designated to a small non-Archimedean number. The weight of  $j^{th}$  input that is assigned by algorithm is  $v_j$  and the weight of  $k^{th}$  output that is assigned by algorithm is  $v_k$ .  $E_r$  is  $r^{th}$  DMU's relative efficiency which has lower and upper efficiency score based on  $\alpha$ -cut sets. Especially,  $X_{ij}$  and  $Y_{ik}$ , input and output values, have uncertainty or incomplete information. Therefore,  $X_{ij}$  and  $Y_{ik}$  are addressed by convex fuzzy numbers. Also, their fuzzy membership functions is showed  $\mu_{X_{ij}}$  and  $\mu_{Y_{ik}}$ , respectively.

$\alpha$ -cuts of  $X_{ij}$  and  $Y_{ik}$  are described as an interval and defined as follows;  $(X_{ij})_\alpha = [(X_{ij})_\alpha^L, (X_{ij})_\alpha^U]$  and  $(Y_{ik})_\alpha = [(Y_{ik})_\alpha^L, (Y_{ik})_\alpha^U]$ , respectively. DEA models can be thought as a transformation of input and output variables. Therefore,  $\mu_{\tilde{E}_r}(z)$  can be described in Eq.7 which is come from Zadeh's extension principle (L A Zadeh, 1978);

$$\mu_{\tilde{E}_r}(z) = \text{Sup}_{x,y} \min \left\{ \mu_{X_{ij}}(x_{ij}), \mu_{Y_{ik}}(y_{ik}), \forall i, j, k \mid z = E_r(x, y) \right\} \quad (7)$$

To establish the membership functions of  $\mu_{\tilde{E}_r}(z)$ , the lower and upper bounds of  $\tilde{E}_r$  at different  $\alpha$  level should be derived. According to the Eq.7, minimum values of  $\mu_{X_{ij}}(x_{ij})$  and  $\mu_{Y_{ik}}(y_{ik})$  determine the value of  $\mu_{\tilde{E}_r}(z)$ ,  $\forall i, j, k$ . We need at least one  $\mu_{X_{ij}}(x_{ij})$  or  $\mu_{Y_{ik}}(y_{ik})$  equal to  $\alpha$ , and  $\mu_{X_{ij}}(x_{ij}) \geq \alpha$ ,  $\mu_{Y_{ik}}(y_{ik}) \geq \alpha$ , such that  $\mu_{\tilde{E}_r}(z) = \alpha$ ,  $\forall i, j, k$ . At the same time, the formed nested structure based on  $\alpha$ -cuts is represented as follows:  $[(X_{ij})_{\alpha_2}^L, (X_{ij})_{\alpha_2}^U] \subseteq [(X_{ij})_{\alpha_1}^L, (X_{ij})_{\alpha_1}^U]$ ,  $[(Y_{ik})_{\alpha_2}^L, (Y_{ik})_{\alpha_2}^U] \subseteq [(Y_{ik})_{\alpha_1}^L, (Y_{ik})_{\alpha_1}^U]$ , for  $0 < \alpha_1 \leq \alpha_2 \leq 1$ . Therefore,  $\{x_{ij} \in S(\tilde{X}_{ij}) \mid \mu_{\tilde{X}_{ij}}(x_{ij}) \geq \alpha\}$ ,  $\{x_{ij} \in S(\tilde{X}_{ij}) \mid \mu_{\tilde{X}_{ij}}(x_{ij}) = \alpha\}$ ,  $\{y_{ik} \in S(\tilde{Y}_{ik}) \mid \mu_{\tilde{Y}_{ik}}(y_{ik}) \geq \alpha\}$ , and  $\{y_{ik} \in S(\tilde{Y}_{ik}) \mid \mu_{\tilde{Y}_{ik}}(y_{ik}) = \alpha\}$  have same maximum and minimum elements, respectively. The lower bound  $E_r^L$  and upper bound  $E_r^U$  of the fuzzy efficiency score for a specific  $\alpha$ -level are calculated with two-level mathematical models which are presented by Kao & Liu (2000) as follows;

$$(E_r)_\alpha^L = \min_{\substack{(X_{ij})_\alpha^L \leq x_{ij} \leq (X_{ij})_\alpha^U \\ (Y_{ik})_\alpha^L \leq y_{ik} \leq (Y_{ik})_\alpha^U \\ \forall i, j, k}} = \begin{cases} E_r = \max \sum_{k=1}^t u_k y_{rk} + u_0 \\ s.t. \sum_{j=1}^s v_j x_{rj} = 1 \\ \sum_{k=1}^t u_k y_{ik} - \sum_{j=1}^s v_j x_{ij} + u_0 \leq 0, \forall j \\ u_k, v_j \geq 0, \forall k, j \end{cases} \quad (8)$$



$$(E_r)_\alpha^U = \max_{\substack{(x_{ij})_\alpha^L \leq x_{ij} \leq (x_{ij})_\alpha^U \\ (y_{ik})_\alpha^L \leq y_{ik} \leq (y_{ik})_\alpha^U \\ \forall i, j, k}} = \begin{cases} E_r = \max \sum_{k=1}^t u_k y_{rk} + u_0 \\ s.t. \sum_{j=1}^s v_j x_{rj} = 1 \\ \sum_{k=1}^t u_k y_{ik} - \sum_{j=1}^s v_j x_{ij} + u_0 \leq 0, \forall j \\ u_k, v_j \geq 0, \forall k, j \end{cases} \quad (9)$$

*Proposition 1.* At the specific  $\alpha$  level, smallest efficiency score for  $r^{th}$  DMU is calculated by adjusting its fuzzy inputs as the upper bounds and the fuzzy outputs at the lower bounds; meanwhile; the fuzzy inputs of all other DMUs at their corresponding lowest level and the fuzzy outputs at their highest level (Liu, 2008)

In fuzzy-DEA model, basically, different efficiency scores are found based upon various  $\alpha$ -level. Therefore, we need to find composite efficiency score for ranking and comparing them. Researchers have introduced valuable ranking methods in the literature (Chen & Klein, 1997; Guo & Tanaka, 2008; Guo, 2009; Hatami-Marbini, Saati, & Makui, 2010; Jahanshahloo et al., 2009; Juan, 2009; Lertworasirikul, 2002; Lotfi, Firozja, & Erfani, 2009). Some of these methods need the membership functions of fuzzy numbers; some of these do not need that. However, the results of efficiency scores are found to be as an interval valued in our problem. Thus, Chen and Klein's ranking method, which does not need the exact membership functions of the fuzzy numbers, is employed in this thesis;

$$I(\tilde{E}_r) = \frac{\sum_{i=0}^{n-1} ((E_r)_{\alpha_i}^U - c)}{\left[ \sum_{i=0}^{n-1} ((E_r)_{\alpha_i}^U - c) - \sum_{i=0}^{n-1} ((E_r)_{\alpha_i}^L - d) \right]}, \quad n \rightarrow \infty \quad (10)$$

where  $c = \min_{i,j} \{(E_r)_{\alpha_i}^L\}$ ,  $d = \max_{i,j} \{(E_r)_{\alpha_i}^U\}$  and  $n$  is the number of  $\alpha$ -cuts.  $I(\tilde{E}_r)$  is the ranking index of  $r^{\text{th}}$  DMU. Descending order of  $I(\tilde{E}_r)$  determines the place of DMUs in the list. Theoretically, infinite  $\alpha$ -cut partitions can be generated. However, Chen and Klein (1997) suggest that 3 to 4  $\alpha$ -cut intervals are enough to determine the differences. Therefore, based on the cost and benefit results of 7 different ITS deployments in different states of the U.S., three  $\alpha$ -cut sets are determined and calculated their fuzzy efficiency scores.

## **CHAPTER FOUR: SUSTAINABILITY IMPACTS OF INTELLIGENT TRANSPORTATION SYSTEMS IN FLORIDA**

### **4.1. Background Information**

This chapter summarizes the sustainability impacts of seven metropolitans of Florida with comprehensive TBL methodology. The results of this chapter is published in Transportation Research Board (TRB) journal as “*Congestion Relief Based on Intelligent Transportation Systems in Florida; Analysis of Triple Bottom Line Sustainability Impact*” in 2013 (Ercan, Kucukvar, et al., 2013)

It is important to present the impacts of ITS investments in states of U.S. in order to encourage policy makers for new projects. This chapter focuses on the state of Florida, which has the fourth largest population in the U.S. with 18.8 million citizens and 84% of this population living in urbanized areas in 2010 (U.S. Department of Commerce Bureau of Census, 2011). In addition, 82.6 million tourists visited Florida in 2010, which exacerbated congestion. Florida also has the third highest rate of VMT with 195,755 (in millions) in the U.S. (Federal Highway Administration, 2013). According to Texas Transportation Institute’s 2011 Urban Mobility report, the economic and environmental impacts of congestion are enormous: people in Florida wasted 274 million person-hours, 216 million gallons of excess fuel, and 6.4 billion dollars on roads (Lomax et al., 2011).

Existing ITS in Florida include freeway ramp metering, freeway incident management, arterial signal coordination, arterial access management, and High Occupancy Toll (HOT) lanes. Based on Florida DOT’s 2010 annual report, VMT

increased by 30% since 2000 while registered vehicles in Florida increased 24%. Fortunately, the death rate decreased from 2 to 1.25 in 10 years per 100 million VMT (Florida Department of Transportation; Transportation Statistics Office, 2011).

The aforementioned facts about Florida clearly indicate the need for transportation investments. Florida Department of Transportation (FDOT) budgeted 975 million dollars to be used for ITS in 2011 (Florida Department of Transportation Work Program Development Office, 2013; Florida Department of Transportation, State Traffic Engineering and Operations Office, 2011). There are numerous studies about cost-benefit analysis of new investments in transportation. The decision is a contentious whether to build new roads, expand existing ones (or both), or instead to develop and enhance existing roads through innovative ITS technology projects.

#### **4.2. Data Description**

TTI's 2011 Urban Mobility Report was utilized to collect traffic information data. In the UMR, data were collected related to the following seven urbanized areas: Orlando, Miami, Cape Coral, Jacksonville, Pensacola, Tampa-St. Petersburg, and Sarasota-Bradenton (Lomax et al., 2011). The report consists of annual delay hours and fuel wasted in traffic congestions, and the savings achieved that were related to ITS investments in these seven cities (Table 1). The total congestion cost and annual saving data are based on the formula that is proposed in methodology section (*Section 3.1.1*).

In order to calculate the delay hour cost, consumer price index values for 2010 were used; \$16.30 per person hour and \$88.12 per commercial vehicle hour. According to the U.S. DOT's Highway Performance Monitoring System dataset for Florida's urbanized areas, passenger cars constituted 90% of the traffic while commercial vehicles made up 6.5% (Department of Transportation Federal Highway Administration; Office of Highway Policy Information (HPPI), 2013). These percentages were also used to multiply fuel cost with the average prices of gasoline and diesel in 2010. As can be seen on Table 1, total congestion cost for Florida's urbanized areas was 5.6 billion dollars.

The saving values are based on the scenario of disconnecting all of the existing ITS deployments in Florida. Hence, owing to Urban Mobility Report, delay reduction hours and fuel savings on roads values are used for TBL impact analysis. Right columns of Table 1 present the time, fuel, and money savings due to ITS in Florida in 2010. After estimating delay reduction and fuel reduction related ITS, annual congestion cost savings were calculated. Table 1 indicates that ITS obtained \$M 420.3 savings in 2010 in urbanized areas of Florida.

These values are only the savings that Florida accrued through operations. It is necessary to calculate the whole impact to the economy and society at large scale as a result of these savings. There is a need to calculate the whole impact to the economy and society at large due to these savings. Although ITS lead to savings in fuel imports, it also drops the profit, employment and taxable incomes for petroleum refineries and government. Economic input-output model was used for this purpose.

**Table 1:** Texas Transportation Institute 2011 Urban Mobility Report Summary for Florida

**ADH:** Annual Delay Hours, **AEFW:** Annual Excess Fuel Wasted, **TCC:** Total Congestion

Regions	Congestion Data			ITS Savings				
	ADH (10 <sup>3</sup> person- hrs)	AEFW (10 <sup>3</sup> gal)	TCC ( \$M)	ADR (10 <sup>3</sup> hrs)	FS (10 <sup>3</sup> gal)	ACC S (\$M)	DRCS (\$M)	FRCS (\$M)
Orlando	38,260	11,883	811	2,254	692	47.8	45.98	1.84
Miami	139,764	66,104	2,906	12,065	5,386	250.9	235.4 7	14.16
Cape Coral	7,600	1,366	158	382	77	8	7.79	0.20
Jacksonville	18,005	5,461	371	1,055	324	21.8	21.52	0.86
Pensacola	4,699	888	93	74	21	1.5	1.51	0.06
Tampa-St. Petersburg	53,047	28,488	1,097	3,873	1,899	80.1	75.59	4.99
Sarasota	8,015	2,240	161	509	130	10.2	10.38	0.35
Total for Florida	269,390	116,430	5,597	20,212	8,529	420.3	398.2 4	22.46

**Cost, ADR:** Annual Delay Reduction, **FS:** Fuel Savings, **ACCS:** Annual Congestion Cost Savings, **DRCS:** Delay Reduction Cost Savings, **FRCS:** Fuel Reduction Cost Savings

[Source: (Lomax et al., 2011)]

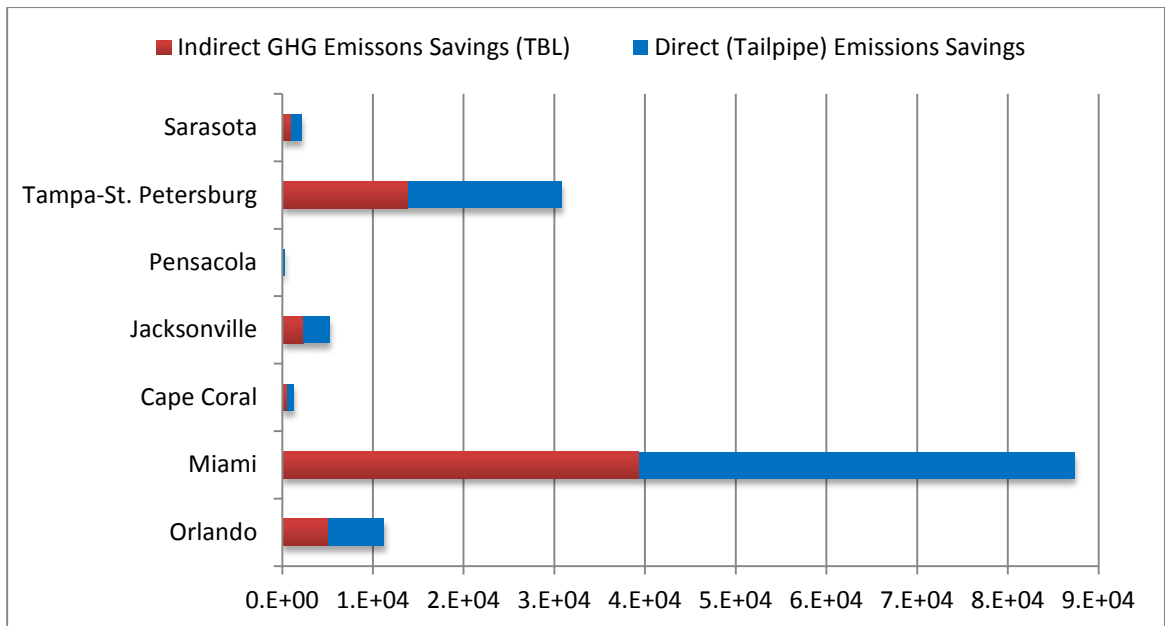
### **4.3. Results**

#### ***4.3.1. Direct and Indirect Environmental Savings***

The figures presented below indicates the direct savings (i.e. operational related savings) and indirect savings (i.e. total impacts of TBL`s direct and indirect savings). In other words, TBL methodology provides the data for the fuel consumption sector related direct and its related sector`s indirect savings under the figure headings for indirect savings.

Some environmental concerns, such as water consumption, do not include any operational (i.e. direct) savings.

Figure 2 presents the total GHG emissions for seven urbanized areas in Florida. In addition to the TBL’s direct and indirect emission values for per million dollars fuel consumption savings, direct impacts (i.e. tailpipe emissions) are calculated with Environmental Protection Agency’s (EPA) per gallon fuel use emissions rate (EPA (Environmental Protection Agency), 2013). As a result of the total tailpipe emission savings and indirect emission savings, Florida saved 1.38 E+05 tone carbon dioxide equivalent (CO<sub>2</sub>-eqv) in 2010. In addition, tailpipe GHG emissions dominate the total saving values with almost doubled the indirect savings values.

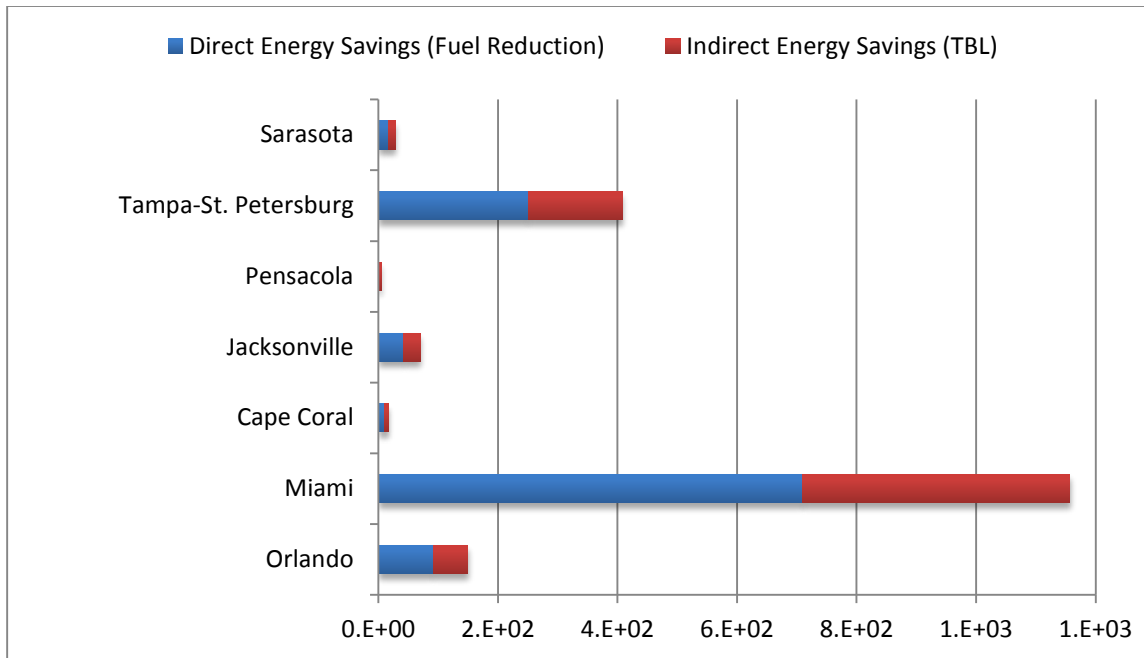


**Figure 2:** Greenhouse gases (GHG) emission savings in Florida's metropolitans (metric t CO<sub>2</sub> eqv.)

*Energy savings* are depicted in Figure 3. Fuel cost savings generated the direct and indirect energy savings for petroleum refineries and also generated the fossil fuel savings. Miami provided 709.6 TJ direct fuel savings related energy consumption savings to the environment and 446.8 TJ total indirect savings with the highest population ratio. These indirect savings consist of petroleum refinery industries direct and its related sectors impacts. Therefore, the total energy consumption savings for Miami were 1.16 E+03 TJ in 2010. Pensacola, the least populated area, provided the least savings with total 4.5 TJ.

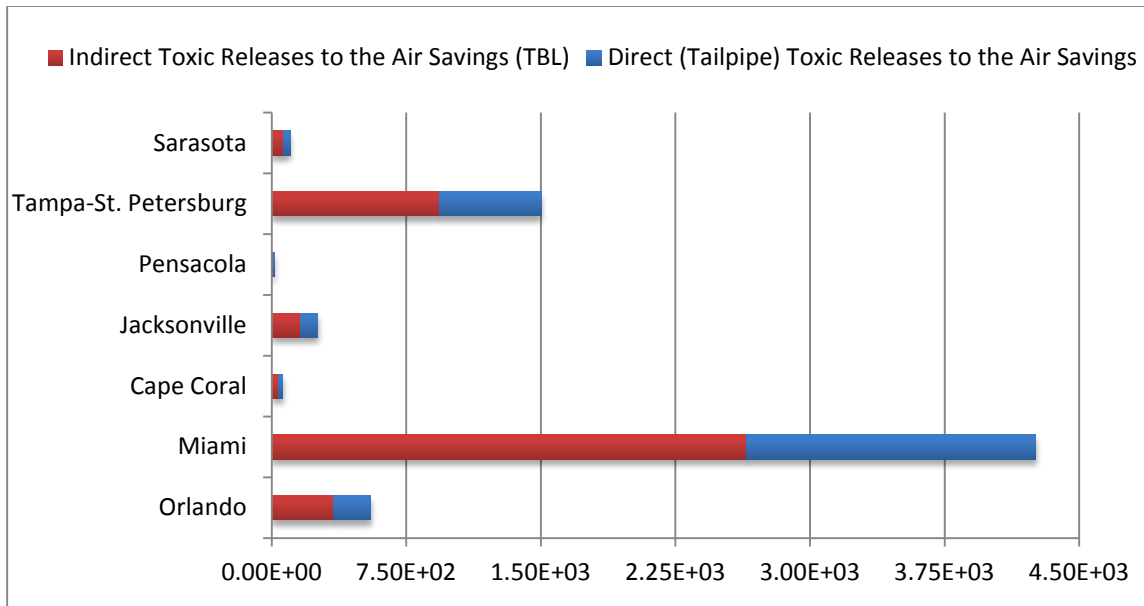
Florida amassed 1.83 E+03 TJ energy consumption savings in 2010. It is also important to highlight that indirect energy consumption savings generates the 708.7 TJ of those total savings. Moreover, the half of those indirect savings stemmed from drops in petroleum refineries activity and the other half is generated by drops in related supply chain industries.





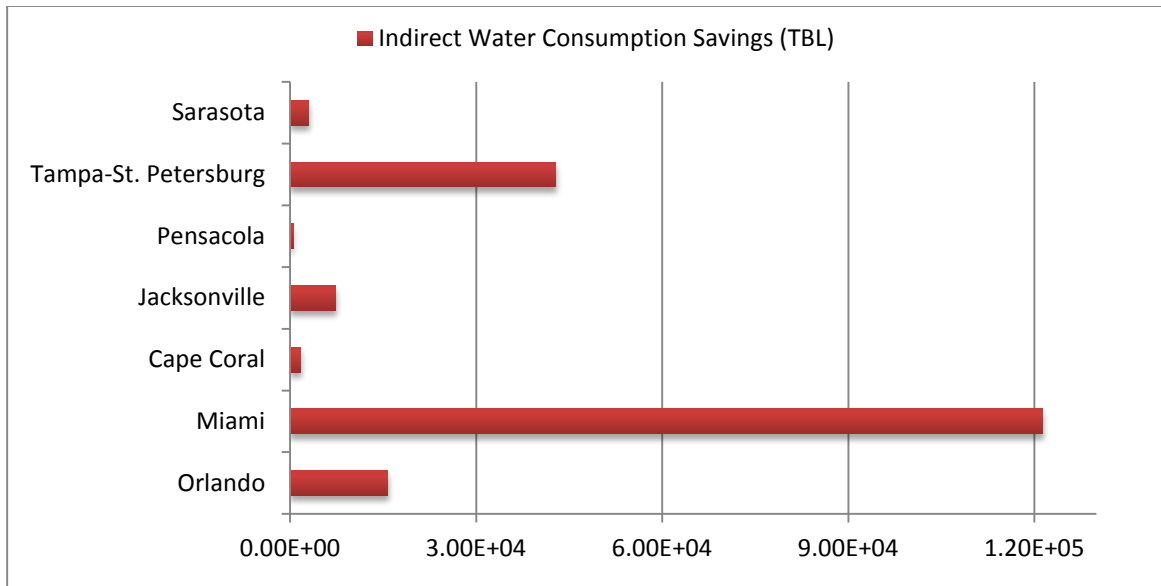
**Figure 3:** Energy Consumption savings in Florida's metropolitans (TJ)

Process related toxin can be released to air, water or land. This study focused on savings in toxic releases to the air. Figure 4 presents the values of *toxic release savings* accrued in Florida. ITS investments provided  $6.75 \text{ E}+03 \text{ t}$  total toxic release savings to the air in 2010. It is important to highlight that, indirect toxic release savings are significantly higher than tailpipe emissions. For instance, in Miami, indirect toxic release savings were  $2.64 \text{ E}+03$ , whereas tailpipe emission savings were  $1.61 \text{ E}+03$ . Tailpipe (direct) toxic emissions rates are determined with Bureau of Transportation Statistics' *National Transportation Statistics* vehicle emissions data.



**Figure 4:** Toxic releases to the air savings in Florida's metropolitans (t)

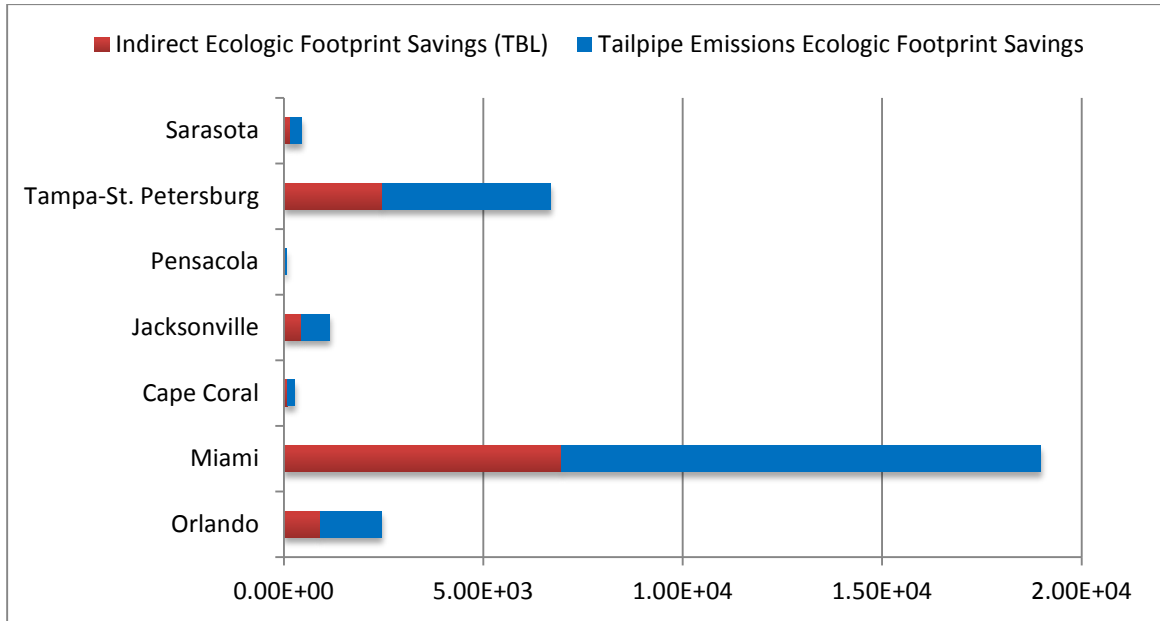
ITS related *water consumption savings* are presented in Figure 5. The production of less fuel at petroleum refineries consumes less water, which results in environmental and fuel savings, but does not have direct impacts on water consumption savings. As a result,  $1.92 \text{ E}+05$  (kgal) water consumption savings were realized in Florida. In Orlando, for instance, indirect water consumption savings were  $1.58 \text{ E}+04$  (kgal) in 2010.



**Figure 5:** Water Consumption Savings in Florida’s metropolitans [kGal]

Finally, the ecologic footprint was calculated. Tailpipe emissions also dominated the total savings similar to GHG emission savings. Figure 6 presents *CO<sub>2</sub> uptake land savings* related to the fuel savings on roads of Florida’s urbanized areas. The total savings generated in 2010 were 3.00 E+04 global hectares (gha).

It is obvious that the environmental savings rely on savings in fuel consumption, in turn rely on the population rate of a given area. Therefore, the figure shapes are most likely to be the same for environmental concerns. As can be seen on Table 1, Miami has almost 2.8 times the fuel savings accrues in Tampa-St. Petersburg region. This difference is what distinguished the two regions the most.



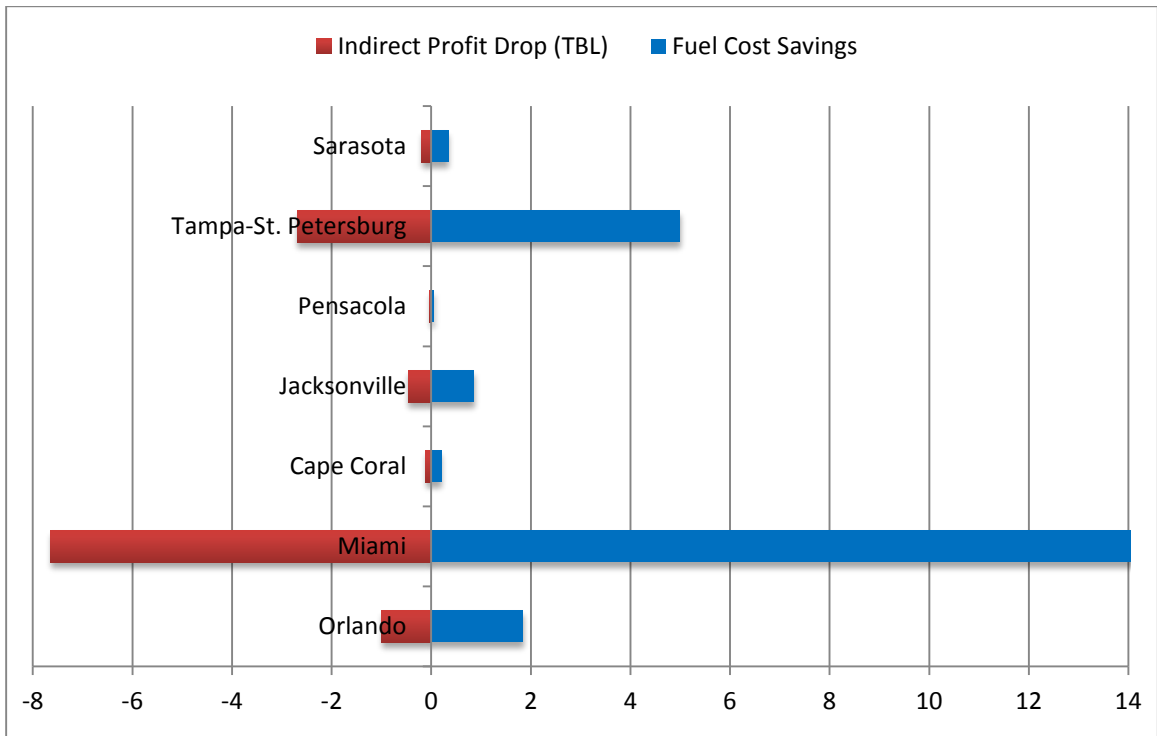
**Figure 6:** Ecologic footprint savings in Florida's metropolians [gha]

#### 4.3.2. Direct and Indirect Socio-Economic Savings

The most significant impact of congestion relief through ITS stemmed from a reduction in annual, since, these hours were underemployment hours for industries in the past. Although cost savings accrued as a result of reduced person and commercial vehicle hours, fuel savings reduced the profit and employment of some industries, especially petroleum refineries. Taxes that are paid with per gallon fuel purchases and its production related (i.e. indirect) impacts reduced the government revenue. On the other hand, consuming less fuel means fewer fuel imports to the U.S. which is an important positive outcome for the national economy. Hence, there is a need to analyze these indicators in

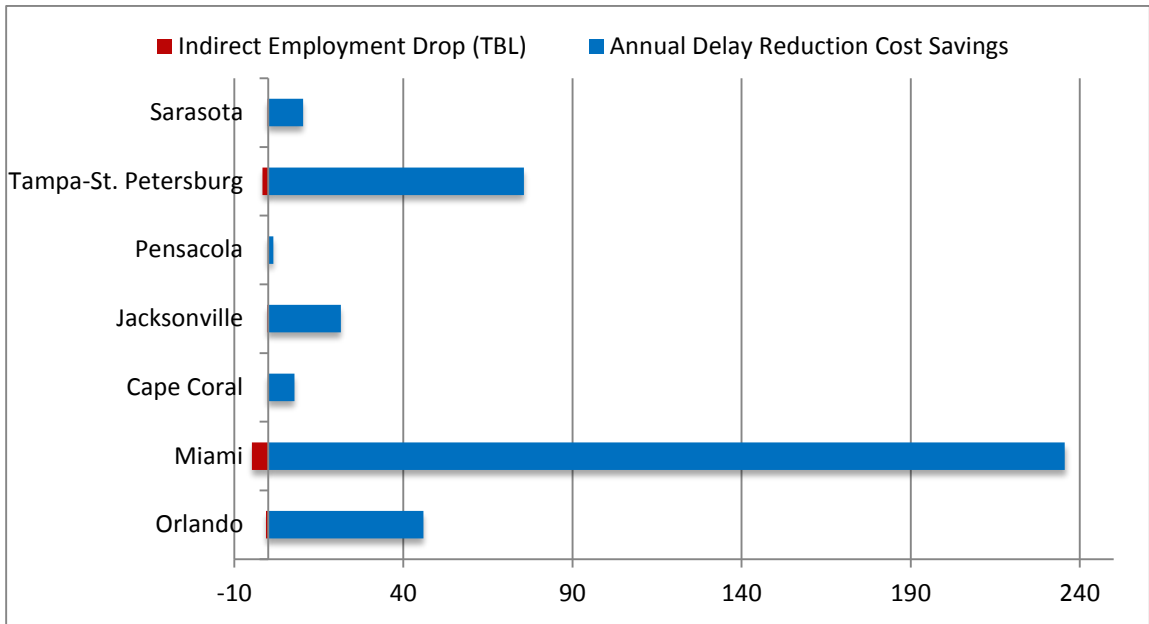
the TBL model. It is also crucial to highlight that TBL results presented as indirect impacts, however, they include direct impacts related to the primary sector and supply chain sectors activities.

Figure 7 indicates indirect revenue decrement in negative values and positive values present in the fuel cost savings (direct). Fuel savings in Florida caused \$M 12.1 drop, where total fuel cost savings were \$M 22.4. Indirect profit revenue drop includes the petroleum refineries profit cut as direct impact of TBL. As a result, the net revenue for Florida was a positive \$M 10.3 in 2010.



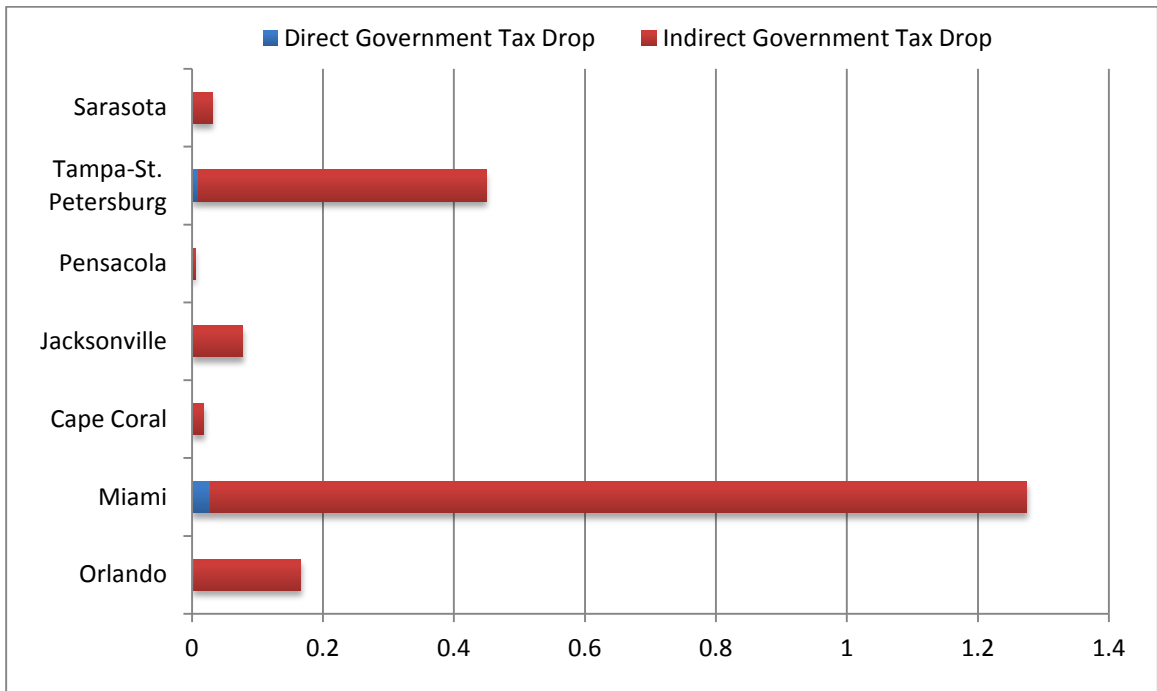
**Figure 7:** Profit drop in industries with fuel cost savings in Florida's metropolitans (\$M)

In addition, the decrease of fuel consumption caused employment to drop in some industries. Figure 8 presents the employment values on a negative scale and the annual delay reduction cost savings on positive scale. It explicitly indicates that employment decreases are negligible values as compared with annual delay reduction and cost savings associated with this delay reduction. Fuel savings caused \$M 7.6 drop for employment in 2010, when the cost savings in annual delay reduction are \$M 398. These drops reflect the strong dependence of the U.S. economy on the oil industry. In turn, a shift in the economic structure may result in a stronger economy and more employment opportunities in other sectors.



**Figure 8:** Employment drop in industries with fuel savings and annual delay reduction cost in Florida's metropolitans (\$M)

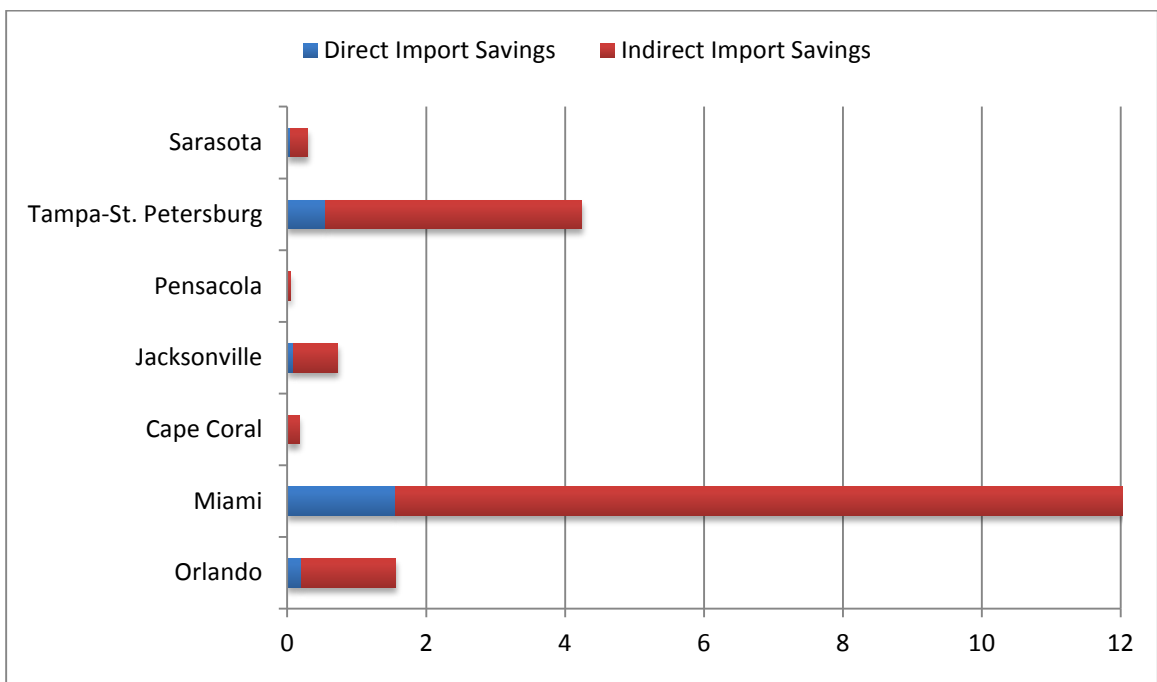
Tax revenue that government could make without fuel savings is presented in Figure 9. Per gallon fuel consumption savings caused government tax revenue to drop to only \$M 2 for Florida in 2010. The direct tax drop calculated by the rates in 2010 in Florida including state and county (area) taxes. The per gallon tax rate was \$0.30 in 2010. It is important to state that majority of that tax revenue consisted of indirect tax values. Since, drop on the business profit for fuel production related industries generates the indirect tax drop.



**Figure 9:** Government tax drop in Florida's metropolitans (\$M)

Finally, Figure 10 presents the import savings produced by fuel savings in 2010. Consumption of less fuel leads to fewer fuel imports as well as other imports to the U.S.

Petroleum refineries imported less oil from other countries, which represents the direct import savings. Gasoline and diesel production related supply chain industry's imports also decreased, which is shown as indirect imports savings on the Figure 10. Furthermore, Florida saved \$M 19.1 total import savings in 2010. Indirect import savings dominates the total import savings value.



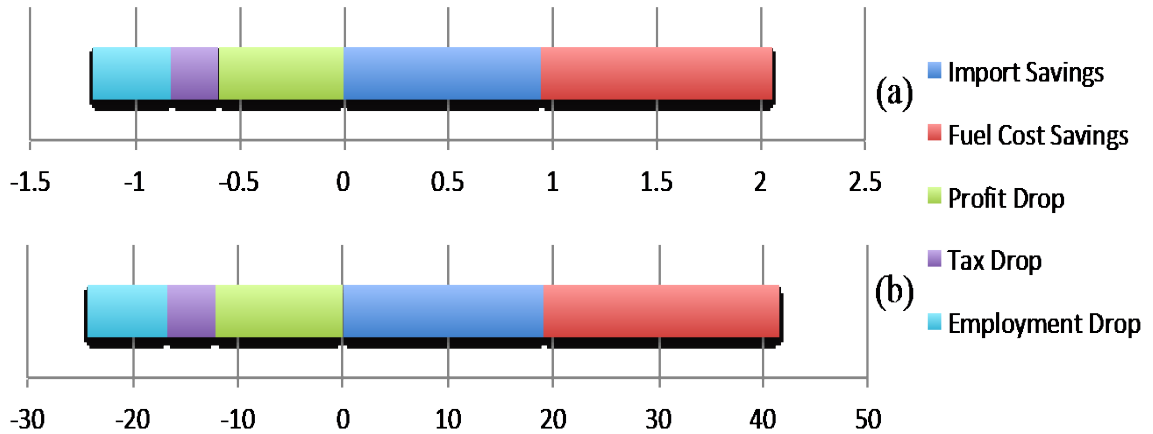
**Figure 10:** Import savings with fuel cost savings in Florida's metropolitans (\$M)

#### 4.3.3. Summary of Results

In conclusion, this study fills an important gap through analyzing of widespread (and in-depth) impacts of new ITS investments on transportation. It truly paints the full picture of ITS project implementation impacts. As mentioned in the previous section, some economic indicators had negative impacts on net economic savings. Figure 11a depicts the



positive and negative values of total economic impact per traffic delay hours. The net finding of that figure is 0.85 dollar/person-hrs savings per delay hour reduction. Figure 11b presents the fuel-based net economic savings. Net fuel profits and import savings worth \$M 41.55, whereas negative values such as government tax revenue and employment total is only \$M 24.34. Therefore, the net fuel-based economic savings are \$M 17.2 in Florida in 2010.



**Figure 11: (a)** Fuel savings related drops and savings for per-delay reduction hour [\$/hrs]  
**(b)** Fuel savings related drops and savings in profit [\$M]

## **CHAPTER FIVE: SUSTAINABILITY IMPACTS OF INTELLIGENT TRANSPORTATION SYSTEMS IN THE U.S.**

### **5.1. Background Information**

This chapter expands the results of previous chapter's Florida cities impacts to states for total 4 years. Similar to the Chapter 4, this chapter also utilizes TTI UMR (2011) for ITS related congestion relief sustainability impacts. Besides, the results of this chapter are also a working paper of Ercan, et al. (2013) at University of Central Florida.

The infrastructure expansion and extension could not be indefinite due to limited economic and natural resources. Thus, in order to guarantee the future generations' needs, efficiency of the existing transportation system should be improved. Intelligent transportation systems (ITS) are one approach that could assist to reach that efficiency point. Today, ITS have widespread applications on the U.S. transportation system. Moreover, regarding the technological improvements of today, ITS deployment and developments also grow every day.

Due to the aforementioned significant traffic congestion results on society and the operational treatments that are proposed as a solution for this problem should be analyzed in holistic point of view. In the literature, the impact analyses of ITS present mostly focus on direct cost related benefits. The uniqueness of this study is that it uses Triple Bottom Line (TBL) point of view in order to analyze the direct and indirect impacts of three sustainability indicators. These sustainability indicators are; socio-economic and environmental. Herewith, in order to fill the gap of this era about presenting whole impact

analysis for decision makers could be done with TBL instead of considering only direct economic benefits of treatments. This point is also important to exhibit the future generations' needs in a complete picture.

## **5.2. Data Description**

Utilizing ITS related congestion relief savings for 101 cities of the U.S. in a comprehensive methodology and its data collection were the challenge of this study. Metropolitan cities of the U.S. related ITS' traffic congestion relief data determined with the methodology that is proposed in the *Section 3.1.1*. The indirect impacts of savings are calculated with the methodology of TBL approach (*Section 3.2*).

In addition to the indirect analysis (TBL), some environmental indicators also require direct (tailpipe) savings analysis. GHG emission savings are calculated based in EPA's per gasoline-diesel consumption emission rates (EPA (Environmental Protection Agency), 2013). Ecologic footprint calculation is also based on the same parameters. Toxic releases to the air rates for tailpipe savings analysis are gathered from National Transportation Statistics (U.S. Department of Transportation Research and Innovative Technology Administration Bureau of Transportation Statistics, 2011).

In order to calculate the delay hourly cost, consumer price index values for 2010 were used; \$16.30 per person hour and \$88.12 per commercial vehicle hour. According to DOT's highway performance monitoring system dataset for the U.S.'s urbanized areas, passenger cars are 91% of the traffic while commercial vehicles are 7% (Department of

Transportation Federal Highway Administration; Office of Highway Policy Information (HPPI), 2013). These percentages are also used to multiply fuel cost with the average prices of gasoline and diesel for each state in 2007 through 2010. According to each indicator that is mentioned above, the annual congestion cost can be calculated with the following equation (See *Eq. #1* in *Section 3.1.1.*). Similarly to this formula, the cost savings of congestion relief related annual fuel savings can be determined.

Table 2 presents the average values for 101 U.S. cities congestion and ITS savings which also constitute the database of this thesis. The following information provides better understanding about the average traffic congestion impacts in the U.S. for each year. Traffic congestion is linearly affects the congestion cost and ITS related savings which was dramatically decreased due to less vehicle usage in 2008 which was the consequences of 2008's economic crisis. However, in 2010, it started its usual increasing trend similar to years before 2008. Obviously, the results of the ITS savings are not significant enough to reduce congestion results. However, from an optimistic point of view, the proportion of annual congestion cost and ITS related cost savings provide approximately 8% savings. The methodology of this paper used the ITS saving values for analysis which is indicated on Table 2.

**Table 2:** Average congestion impacts and ITS investment savings of 101 cities in the U.S.

		<b>2007</b>	<b>2008</b>	<b>2009</b>	<b>2010</b>
Congestion Impacts	<b>Annual Delay Hours (10<sup>3</sup> hrs)</b>	45,878	40,471	41,807	42,461
	<b>Annual Excess Fuel Wasted (10<sup>3</sup> gallons)</b>	20,259	17,334	17,678	18,172
	<b>Total Congestion Cost (\$M)</b>	922	841	866	890
ITS Savings	<b>Annual Delay Reduction (10<sup>3</sup> hrs)</b>	3,438	2,939	3,023	3,079
	<b>Wasted Fuel Reduction (10<sup>3</sup> gallons)</b>	1,540	1,330	1,268	1,313
	<b>Congestion Cost Savings (\$M)</b>	79.7	71.7	71.5	64.5

[Source: (Lomax et al., 2011)]

### **5.3. Results**

The study aims to fill a gap on ITS impact analysis in a holistic point of view. Aforementioned socio-economic values are not positive for all cases of ITS. For instance, fuel industry' employment, tax and profit indicators will be dropped due to the fuel savings. Therefore, providing net benefits of ITS is crucial for decision makers and governmental associations. On the other hand, regarding the benefits of operational treatments on roads, the net results are expected to be positive. In environmental point of view, the results will stand only for positive (beneficial) impacts.

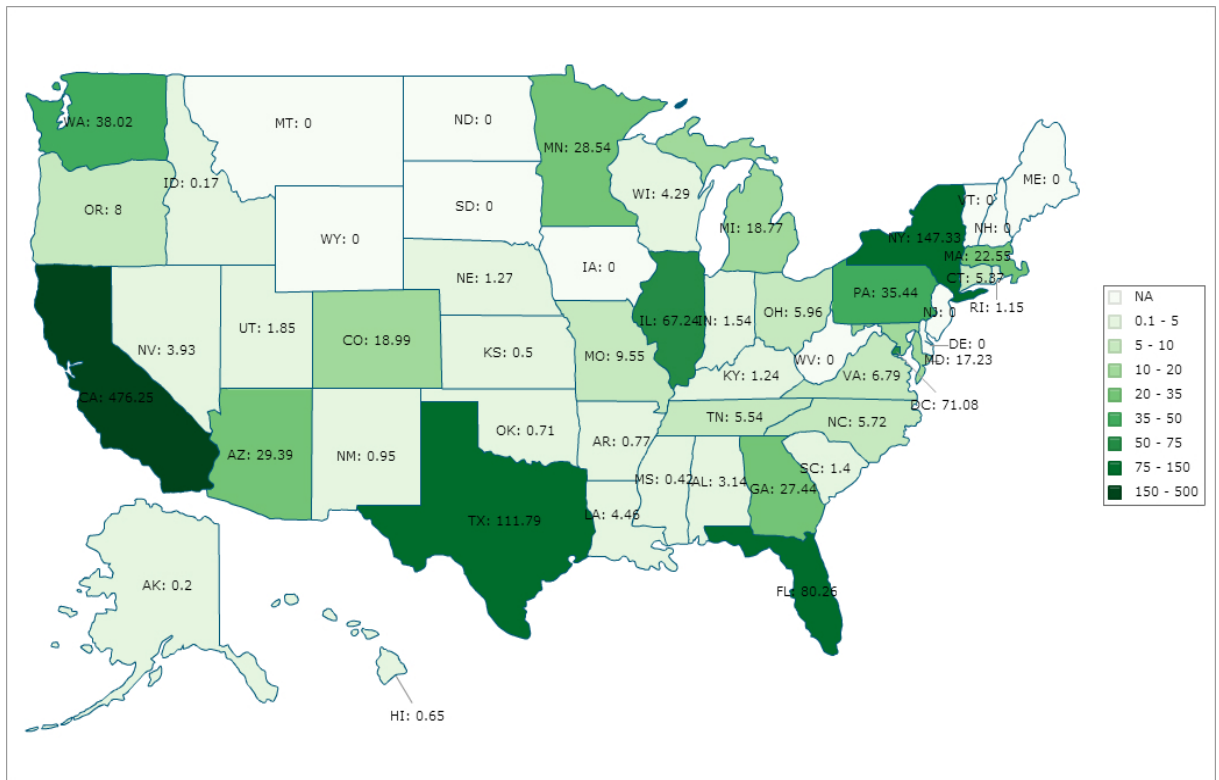
The net results for each indicator are shown on the U.S. map figures with various color ranges. The figures present the total – net values for 2007, 2008, 2009 and 2010 years for each state. Some states consist of one city data while some include 10 different cities total operational treatment savings. Besides, in the UMR study some states' cities are not considered due to their low population and traffic congestion values. Therefore, these states' ITS related saving data are neglected.

### ***5.3.1. Socio-Economic Impacts***

The highest impact of congestion relief with ITS was due to annual delay reduction, since, these hours were underemployment hours for industries before. However, while making cost savings due to reduced person and commercial vehicle hours, making fuel savings reduced the profit and employment of some industries, especially petroleum refineries. Government revenue is reduced by fuel tax that is paid for per gallon fuel purchase and tax of fuel production's supply chain industries. On the other hand, consuming less fuel means less fuel import to U.S. which is an important positive outcome for the national economy. Overall, it is crucial to highlight that TBL related primary sector impacts and supply chain sectors activities are presented as indirect impacts where the value of less fuel purchase is presented as direct impact.

The Figure 12 presents the import savings regarding to less fuel consumption. As it is explained in the methodology section, import value is crucial for national economic indicators. Moreover, fuel import is on the top list of national imports list with its significant value. Therefore, it is important to reduce import rates for better socio-economy.

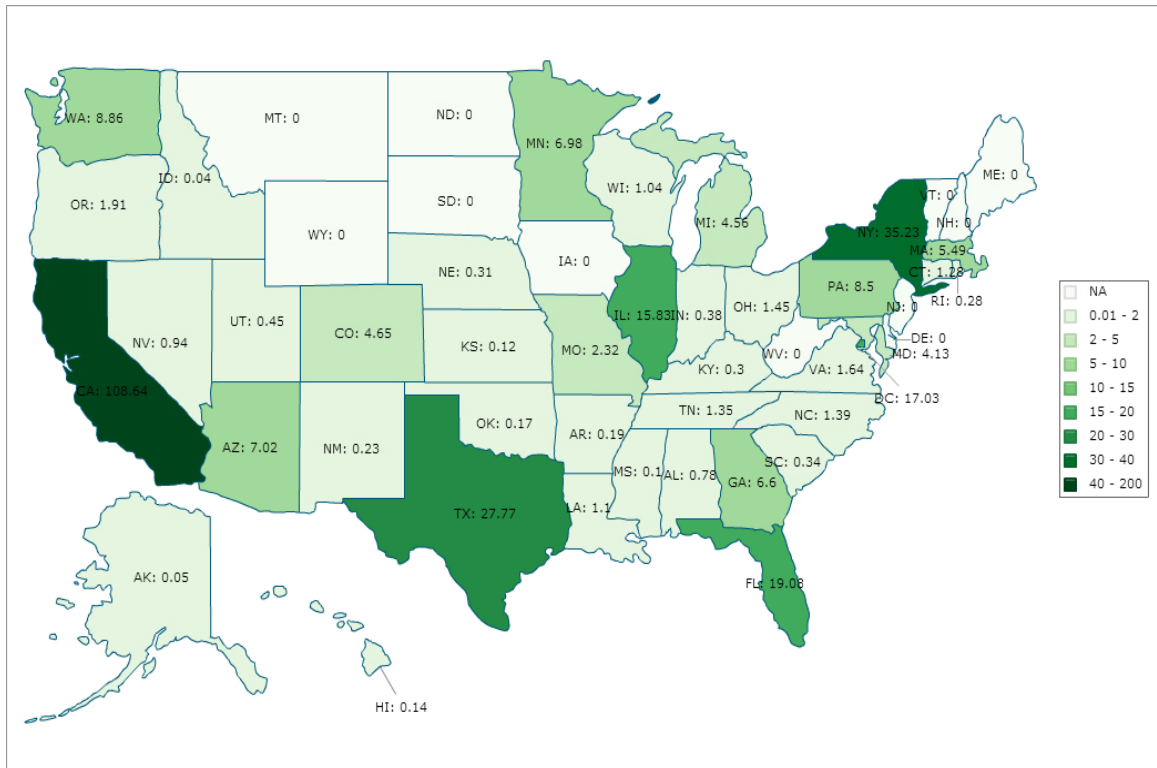
Following values consist of direct import drop from fuel sales and indirect drop in terms of fuel production and its supply chain sectors. As can be seen from colored scale, the states, with the largest cities have the largest savings such as California (CA), New York (NY), Texas (TX), Florida (FL), Washington DC and Illinois (IL).



**Figure 12: Total Direct - Indirect Savings (\$M)**

Figure 13 presents the first example of negative impacts of ITS investments which affects government. Basically, less fuel sales mean less tax earned for the government. Direct tax drop is generated by fuel sale taxes reduction. On the other hand, indirect tax

drop consists of whole supply chain and fuel production tax reduction which dominates the total negative value.



**Figure 13: Total Direct - Indirect Tax Drop (\$M)**

Profit savings are important to highlight, because they represents the net value of savings. The term “net” indicates the summation of where direct profit is positive and indirect profit is negative. Indeed, direct profit generates the value of driver’s fuel expenses which is named savings. Moreover, indirect profit states the value of fuel producers’ and its supply chain’s profit drop due to less fuel sales. Therefore, the results present the net





significantly higher than fuel based savings. Therefore, the net impacts of employment indicator are positive as it is shown on Figure 15.

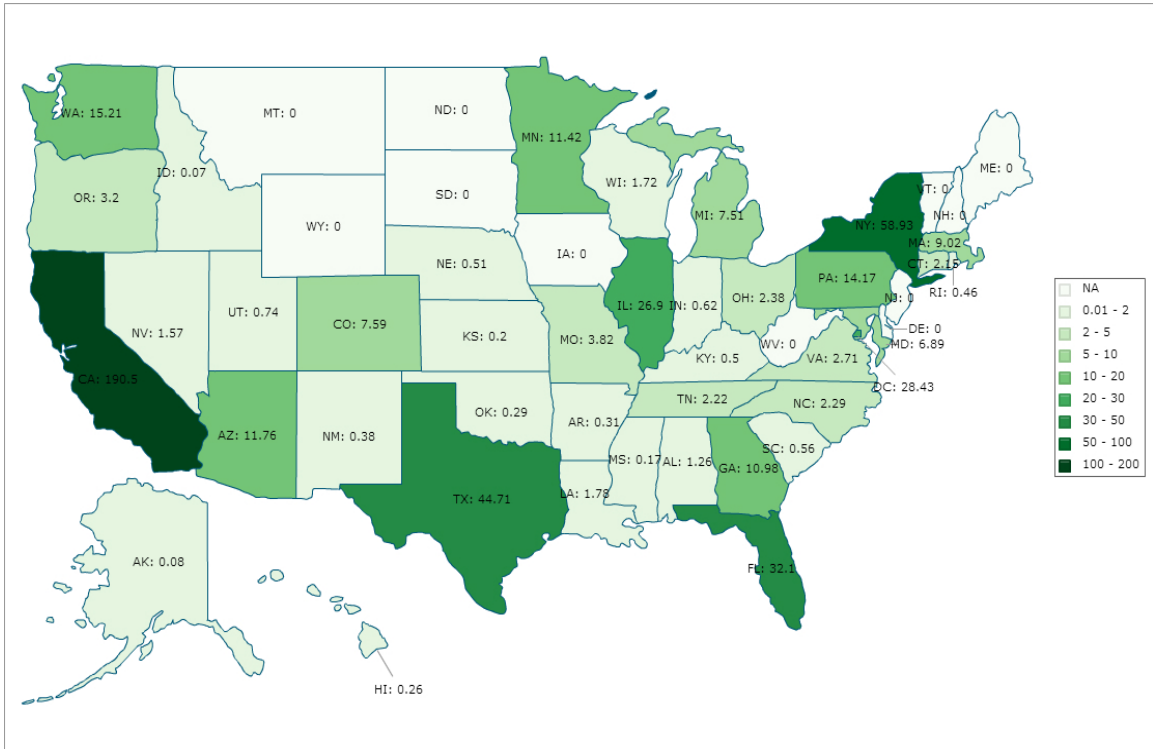
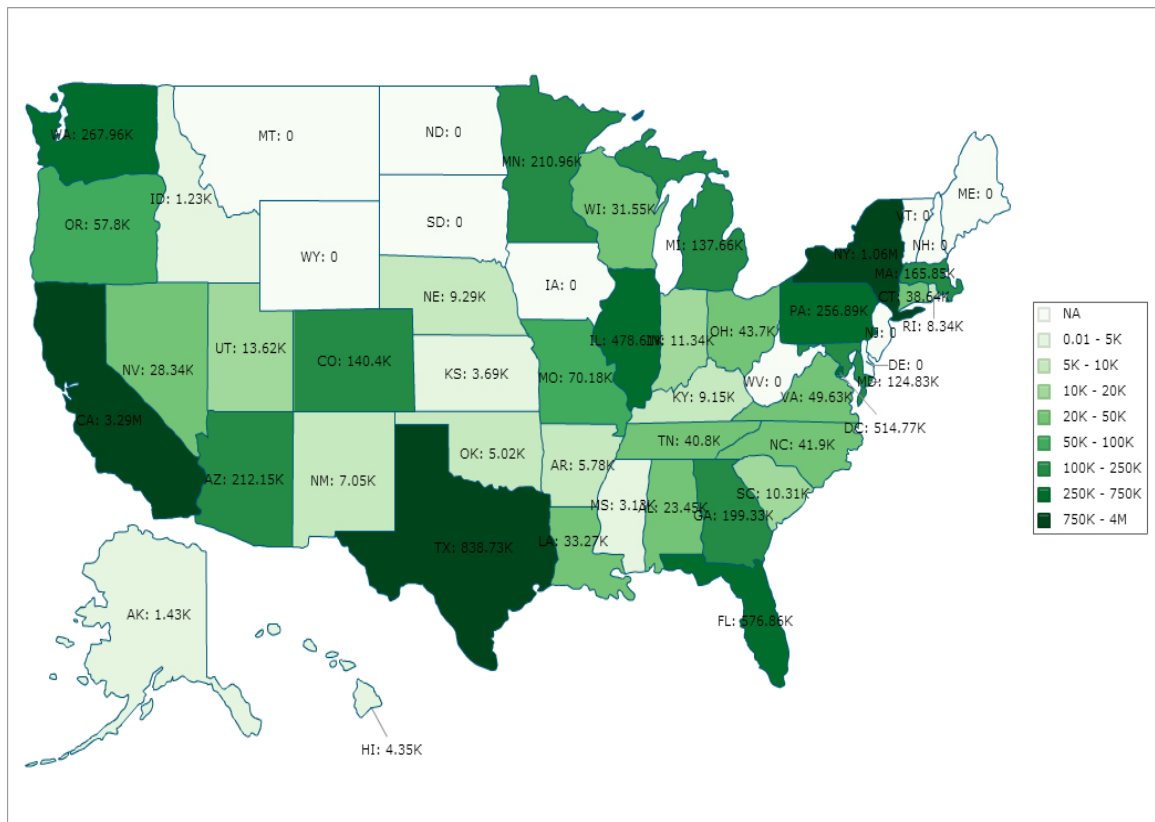


Figure 15: Net Indirect Employment Drop (\$M)

### 5.3.2. Environmental and Ecologic Impacts

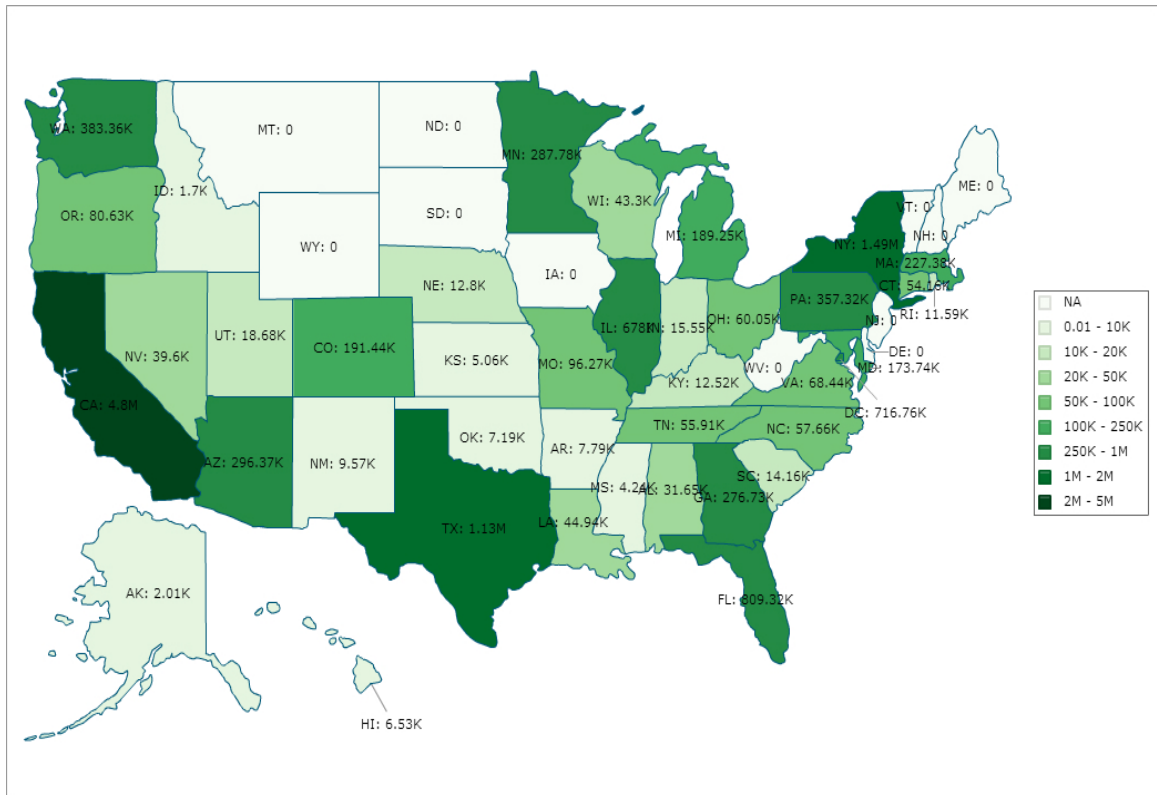
TBL methodology provides the data for the fuel consumption sector related direct and its related sector's indirect savings under the name of indirect savings on figures below. However, only one of the environmental indicators (water consumption) does not include direct savings.

Comparing to socio-economic indicators, in this section the results present only savings. Figure 16 indicates first environmental savings from greenhouse gases (GHG). As it explained in the data collection section, the direct emission savings are calculated by multiplying EPA’s parameters with fuel savings. It also can be named as tailpipe emissions savings. Fuel production and its supply chain generate the indirect emission savings. The tailpipe emission savings (direct) are slightly higher than indirect savings. Similar to the economic results, the major states of the U.S. dominate the figure with their results.



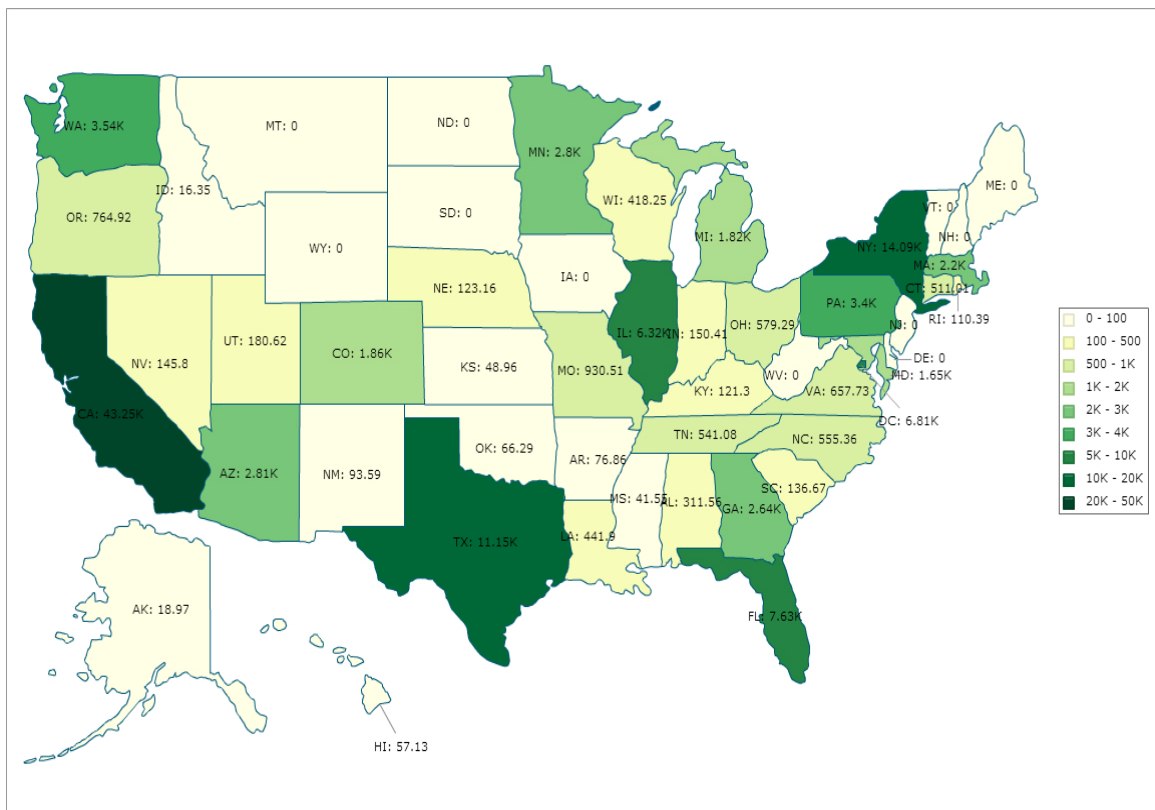
**Figure 16:** Total Direct - Indirect GHG Savings (t CO<sub>2</sub> eq.)

Another environmental concern that is considered in this study is water consumption savings. Figure 17 presents the results for each state in kilo-gallon function unit. Since, direct environmental savings represent tailpipe savings from vehicle operations, there is no direct (tailpipe) savings in water consumption case. Although, there are significant water consumptions during the fuel production and its supply chain sectors. For instance, California (CA) provides the highest saving value all over the U.S. with 4.8M kGal water savings from ITS investments.



**Figure 17:** Total Indirect Water Consumption Savings (kGal)

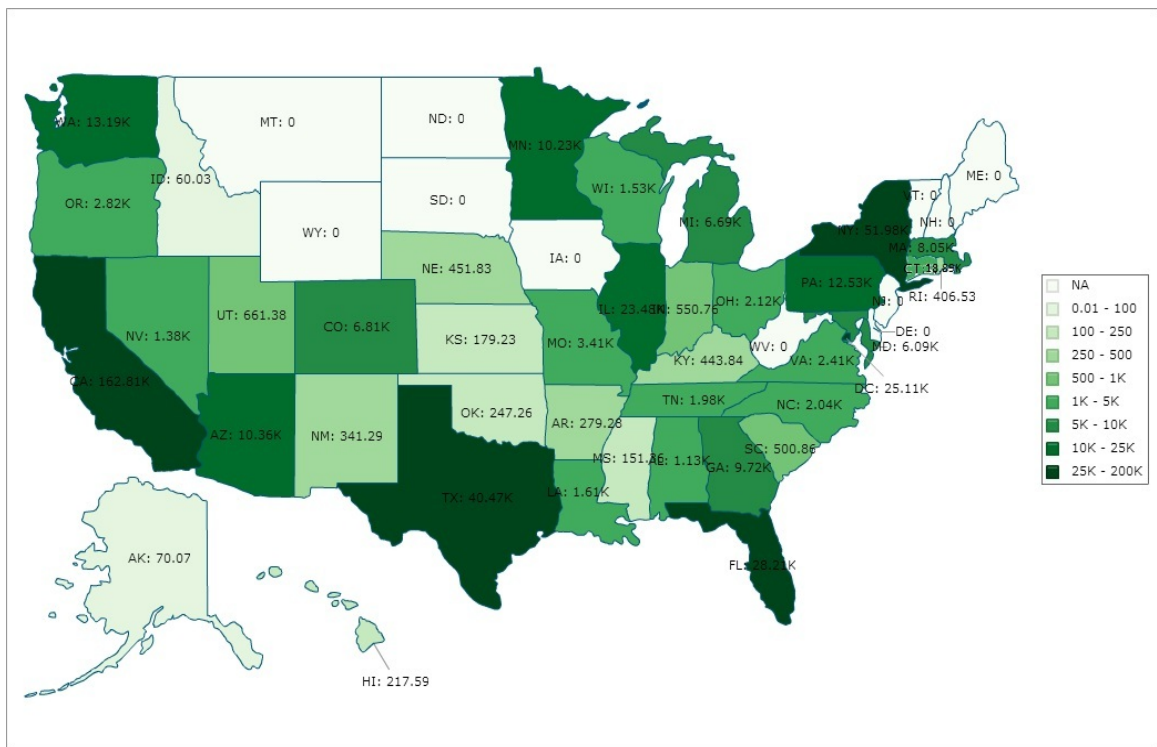
Energy consumption savings are presented in Figure 18. In order to calculate direct energy savings, total fuel savings are converted to its energy equivalence. The indirect energy consumption savings are the complicated part of this calculation. Since, it considers the energy consumption of per million dollar fuel production with its whole supply chain. The direct savings are also slightly higher than indirect savings for this indicator.



**Figure 18:** Total Direct – Indirect Energy Consumption Savings (TJ)

There are three types of different toxic releases that are defined in literature which are; to the air, water and land. This study considers only the toxic releases savings to the air that are made in the U.S. regarding to ITS investments. Figure 19 also consists of direct

and indirect indicators in itself in tone (t) unit. Direct toxic releases savings (tailpipe) includes tailpipe emissions drop from less vehicle operation and less fuel consumption. On the other hand, industries that are producing fuel or supplying them generated less toxic chemicals to the air due to less fuel consumption. The total saving values are dominated by direct savings for each state.

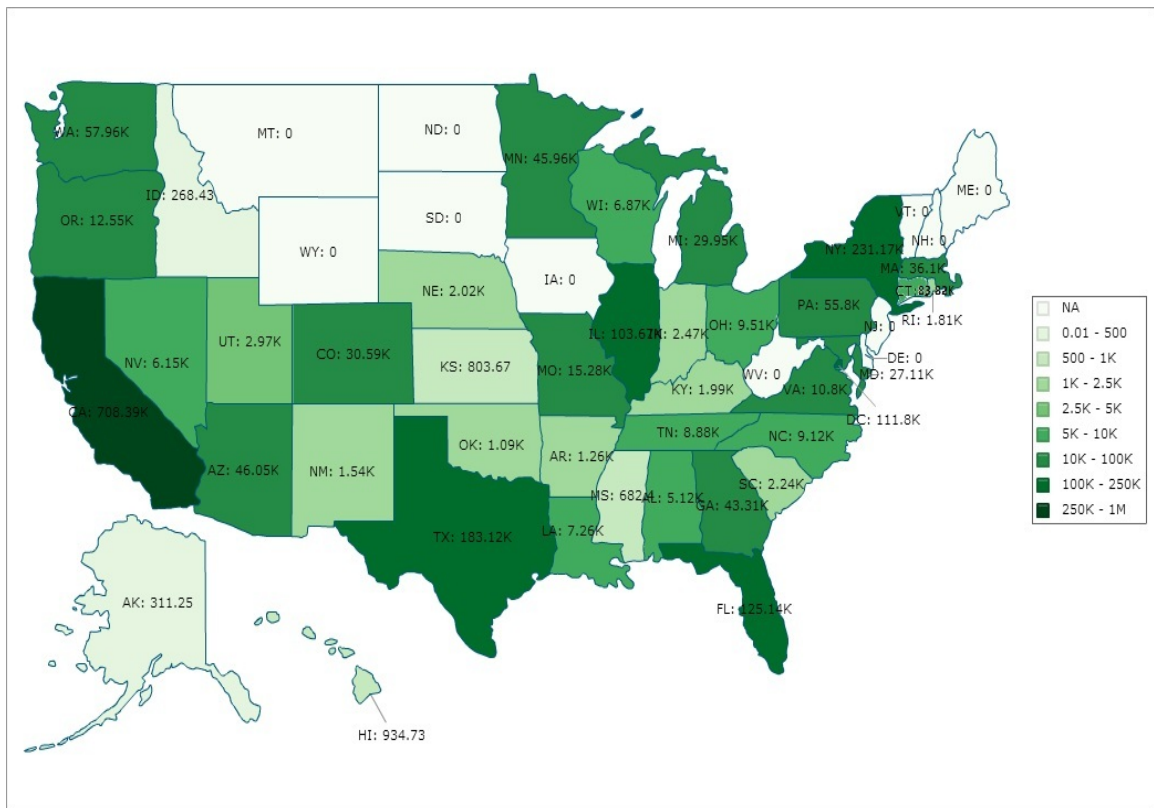


**Figure 19:** Total Direct – Indirect Toxic Releases to the Air Savings (t)

The last indicator of this section indicates the results of ecologic footprint savings (See Figure 20). It also can be named as CO<sub>2</sub> uptake land. The only ecologic indicator of this study provides parallel results to GHG emission savings. The direct and indirect

ecologic footprint savings are calculated with the same methodology of other indicators as explained above. Moreover, direct savings are higher than indirect savings in total.

The same demand can be followed for each indicator due to their same total fuel consumption. In other words, regarding the value of states' fuel consumption, the results show similar trend for all states. For instance, California (CA) has significant values for each figure due to its high VMT and number of vehicles which generates more congestion and savings at the same time.

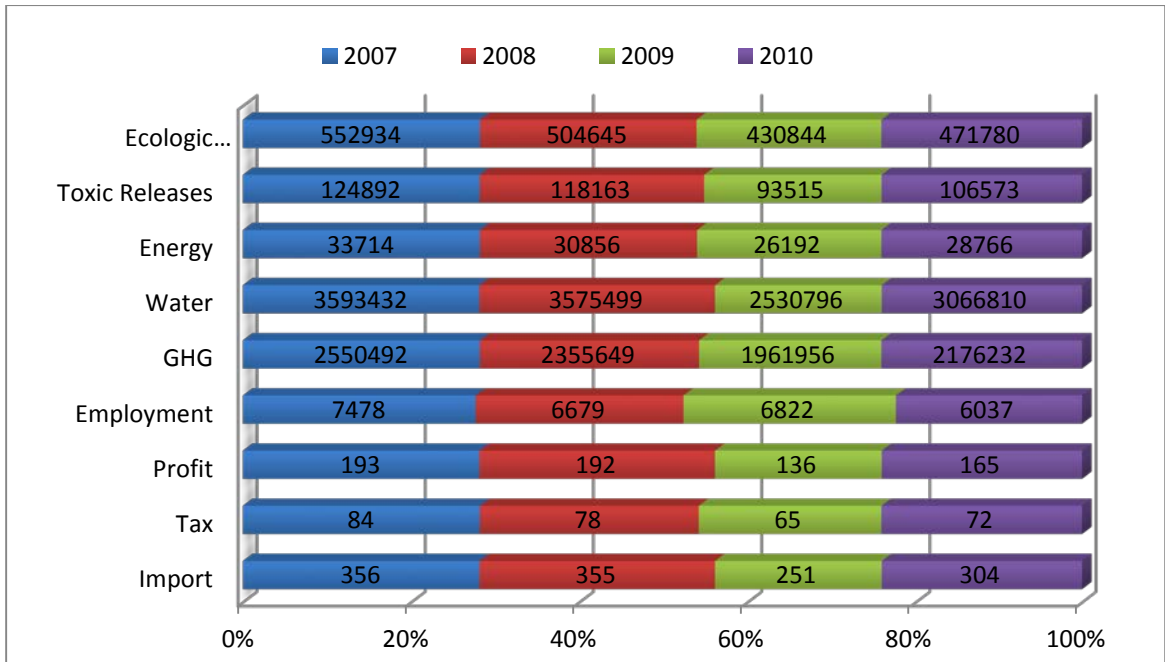


**Figure 20:** Total Direct – Indirect Ecologic Footprint (CO2 Uptake Land) Savings (gha)

### 5.3.3. Summary of Results

In conclusion, the results prove the importance of analyzing supply chain (indirect) impacts on savings. The majority of the direct indicators are slightly higher than indirect impacts. Thus, indirect benefits make significant change on total benefit analysis for 4 years. In 101 cities of the U.S., ITS made significant savings for society. However, it is not enough to reduce traffic congestion to acceptable levels by itself.

The following figure indicates ITS total saving trends yearly (Figure 21). Since the indicators are in different function units, it is shown in cumulative percentage diagram. As it mentioned in Data Collection section, 2007 savings dominates the total savings due to its high traffic volume data.



**Figure 21:** U.S. Annual Total ITS Impacts



## **CHAPTER SIX: SUSTAINABILITY PERFORMANCE ANALYSIS OF INTELLIGENT TRANSPORTATION SYSTEMS**

### **6.1. Background Information**

This chapter outlines how the fuzzy-DEA methodology was used in this study to evaluate the sustainable performance of ITS deployments in the U.S. The study in this chapter is also a working paper in University of Central Florida by Ercan et al. (2013).

A topic of high interests to many researchers is the significant problems associated with unsustainable traffic systems. The efficiency of transportation systems is determined by evaluating different aspects of the system such as fuel efficiency of vehicles, fuel type, and transportation systems (transit, freight etc.) etc. The reason for conducting these studies was to provide clear information about investments that will encourage, or discourage, decision makers to make progressive decisions. These studies are important because transportation systems have a significant impact on society. For instance, travel time affects commuters in terms of wasted time, safety, and environmental impacts (Pagoni, Schafer, & Psaraki, 2012). In order to present these impacts in same fraction unit, cost-benefit studies is still used in literature.

As mentioned above sections, Intelligent Transportation Systems (ITS) are proposed to be a part of the sustainable transportation systems. Moreover, the investments on ITS are increasing every day. Besides, due to ITS' complexity frame compared to the traditional transportation systems, it is unpredictable and difficult to evaluate ITS in terms of economy, environment, and social impacts (He, Zeng, & Li, 2010). Therefore, it is

critical to present expected or gathered impacts of the systems and then compare these impacts to the costs.

The unsustainable impacts of transportation systems lead to environmental, economic, and safety concerns in society. Therefore, it is important to take action by government agencies and to implement treatments such as ITS. Most of the ITS applications are effective investments in terms of their cost-benefit ratios. However, these ratios do not provide adequate information to decision makers for future investments. This study aims to compare different ITS applications' cost-benefit analysis components around the U.S. using DEA methodology in terms of their effectiveness. Due to operation & maintenance cost and benefit analysis' unpredictable and assumption based structure, this study considers uncertainty levels for these components. Hereby, fuzzy DEA methodology is chosen by researchers to provide realistic decision making information for future ITS investments.

## **6.2. Data Description**

This case study consists of 7 different ITS deployments in different states of the U.S. to compare their efficiency scores with the Fuzzy-DEA methodology. These reference ITS studies are, arterial management (adaptive signal control), freeway management (ramp metering), incident management (shoulder usage), Electronic Toll Collection (ETC), Commercial Vehicle Operation (CVO) (electronic credentialing), Advanced Traveler Information Systems (ATIS) (en-route information, dynamic message signs), and

Automated Highway Systems (AHS) (Automated Electronic Highway Systems (AEHS)). This section includes detailed information about these ITS implementations in terms of their cost and savings. The inputs and outputs of fuzzy-DEA methodology consist of costs and savings information. The challenge of the study was finding cases studies which investigated the cost and saving information for same fraction units and methodology for ITS. Since all of the case studies consist of its own unique application, the system (operational) treatment type and development will be explained individually.

The data set that is utilized in fuzzy DEA methodology includes two main components; benefits and cost. In this chapter, benefits comprises of travel time savings, accident prevention savings, and emission reduction where costs contains initial construction cost and 10 years Operating and Maintenance (O&M) cost.

There are many different studies in literature about ITS evaluations. However, in order to provide accurate efficiency scores, the evaluation information should consist of same reference methodology and parameters data set. The baseline factors that are used in this study in benefit calculations are presented in following Table 3a and 3b.

**Table 3: (a) Baseline Table for Value of Time Benefit Calculations (b) Baseline Table for Emission and Safety Benefit Calculations**

	Value of Time (2013 \$) <sup>1</sup>	Vehicle Percentages on the Roads <sup>2</sup>	Vehicle Occupancy <sup>3</sup>
Passenger Vehicle	\$17.46	95%	1.25 person
Commercial Vehicle	\$94.40	5%	1.05 person

[Source 1: (Bureau of Labor Statistics, 2013) adjusted values for 2013 from 2010 data. Source 2:(Department of Transportation Federal Highway Administration; Office of Highway Policy Information (HPPI), 2013) , Source 3: (Lomax et al., 2011)]

(b)

Emission Cost (per kg) <sup>4</sup>	(2013 Adjusted Values)
HC	\$6.19
CO	\$3.85
NOx	\$8.15
Accident Cost (Average) <sup>5</sup>	\$23,736

[Source 4: (Boston Transportation Department / Howard/Stein-Hudson Associates, 2010; Colorado Transportation Management System (CTMS), 2004) , Source 5: (Blincoe et al., 2002)(converting 2000 \$ values to 2013 \$ values with inflation rate of Consumer Price Index and calculate the average of fatality, serious injury, and property damage costs)]

The first case study represents the results for adaptive signal control treatment in Boston in 2007 which is a part of arterial management (Boston Transportation Department / Howard/Stein-Hudson Associates, 2010). The cost and benefit evaluation is prepared by

Boston Transportation Department (BTD) and Howard/Stein-Hudson Associates (HSH). The traffic signal operation improvement includes 8 work orders which focus on 280 signals in over 20 travel corridors. This amount of signal treatment consists of one third of Boston's traffic signal system. The benefits are presented as Phase 1 and Phase 2 which includes signal retiming with current infrastructure and additional retiming physical improvements such as rephrasing, face changing, respectively. This study considers the Phase 2 costs and benefits for the baseline calculations.

A freeway management example is studied on ramp metering application of ITS in Twin Cities, Minnesota (Cambridge Systematics, 2001). The system evaluation final report is prepared by Cambridge Systematics Inc. for Minnesota Department of Transportation in 2001. The report considered shutting down the entire ramp meter system on freeways. However, the benefits are captured from I-494, I-94, I-35W, and I-35E corridors for five weeks which assumed to represent the whole corridors.

University Transportation Center for Alabama at the University of Alabama prepared a report to quantify the benefit measure of shoulder usage in peak periods and incident conditions in 2009 (Sisiopiku, Sullivan, & Fadel, 2009). The study considers I-65 segment in Birmingham, AL. Since, the report quantifies 7 different scenarios' benefits; this chapter uses only Scenario 7 which used the left shoulder in incident condition for two hours.

As a part of California PATH program, Institute of Transportation Studies in University of California, Berkeley prepared a research report to investigate the costs and

benefits of Electronic Toll Collection (ETC) in 1999 (Gillen, Li, Dahlgren, & Chang, 1999). The existing manual toll collection system was compared to the new ETC system, which was used as the baseline to develop cost benefit framework. Out of total nine bridges of Bay Area, Carquinez Bridge is one of the bridges that is considered in this research report. With the estimation of annual 3% traffic volume growth, the report provides data from 1995/1996 to 2005/2006 fiscal years. In order to present benefit data for efficiency analysis, this chapter uses 2004/2005 fiscal year benefit estimations.

The I-25 truck safety improvement project from Colorado DOT is an application of Commercial Vehicle Operation as a part of ITS (Colorado Transportation Management System (CTMS), 2004). The systems cost and benefit quantification report was prepared by Colorado Transportation Management System (CTMS) in 2004. Since the project consists of 30 different tasks which include variety of ITS applications, the presented benefits is not only limited to commercial vehicle operation but also an entire system. This chapter considers the Port of Entry (POE) activity which includes three task orders and specifies the Electronic Credentialing (EC) part of ITS.

Advanced Traveler Information Systems (ATIS) represented by Dynamic Message Sign (DMS) application which is also named En-Route information. The reference report was prepared by researchers at University of Missouri-Columbia for Missouri DOT in 2011 (Edara, Sun, Keller, & Hou, 2012). I-57 bridge closure information, which was shared with detour travelers earlier, generates the benefit analysis of this report. The scenario includes

one permanent and two portable DMS for 15 days. Since it is a temporary operation, the benefits are not calculated annually.

Last, Lavrenz (2011) investigates the costs and benefits of Automated Electric Highway Systems (AEHS) in his thesis at Iowa State University (Lavrenz, 2011). The evaluation examined on I-70 in Missouri from Kansas City to St. Louis corridor due to its significant role in east-west travelling connection. Similar to the CVO example, this thesis focused on freight movement impacts; however the benefits are not limited to the commercial vehicles operation. Since this study considers ten years cost and benefit results, the thesis' thirty years calculations were converted to the same fraction.

**Table 4:** Summary findings of reference ITS investments

		Delay Hrs Reduction (hrs)	Emission Reductions (kg)			Accident Reduction	Reference Study
			HC	CO	NO <sub>x</sub>		
<b>Arterial Management</b>	Adaptive Signal Control	341	884	3,822	754	6	BTD, HSH. <i>The Benefits of Retiming/Rephrasing Traffic Signals in the Back Bay</i> . (2010). Boston.
<b>Freeway Management</b>	Ramp Metering	101	N/A	1,161,000	N/A	1040	Systematics, C. (2001). <i>final report</i> . Twin Cities, MN
<b>Incident Management</b>	Shoulder Usage (Active Traffic Management)	2,635	3,528	N/A	N/A	528	Sisiopiku, V. P., Sullivan, A., and Fadel, G. (2009). <i>Implementing Active Traffic Management Strategies in the U.S.</i> Birmingham, AL, 1–108..
<b>Electronic Toll Collection (ETC)</b>	Electronic Toll Collection	383	1,122	23,753	2,458	-3	Gillen, D., Li, J., Dahlgren, J., and Chang, E. (1999). <i>Assessing the Benefits and Costs of ITS Projects : Volume 2 An Application to Electronic Toll Collection</i> . SanFrancisco Bay Area, CA, 1–98.
<b>Commercial Vehicle Operations (CVO)</b>	Electronic Credential	370	3,648	38,412	N/A	5	(CTMS), <i>Colorado Transportation Management System</i> (2004). I-25 Truck Safety Improvements Project. 1–37.
<b>Advanced Traveler Information Systems (ATIS)</b>	En-Route Info. – Dynamic Message Signs (DMS)	353	50	1,059	119	-1	Edara, P., Sun, C., Keller, C., and Hou, Y. (2012). <i>Evaluating the Benefits of Dynamic Message Signs on Missouri 's Rural Corridors</i> . Missouri.
<b>Automated Highway Systems (AHS)</b>	Automated Electronic Highway Systems (AEHS)	3,208,000	7,333	100,000	436,667	1070	Lavrenz, Steven Michael, "Economic analysis of automated electric highway systems for commercial freight vehicles" (2011). <i>Graduate Theses and Dissertations</i> . Paper 10392.



## **6.3. Results**

### ***6.3.1. Cost and Benefit Measurement Results of Intelligent Transportation Systems***

The benefits of ITS investments for the U.S. and their initial and O&M costs are calculated as it explained in methodology section. The summary results are presented in Table 3. The table also provides 10 years benefits/costs ratio on the last column. From a benefit/cost ratio point of view, all of the ITS applications are highly efficient investments. However, as an aim of this thesis, comparing these systems in terms of efficiency was found that some investments are not efficient compared to the others.

As a result of case studies' project features the initial cost amount varies from \$16,461 to \$311,240,714. For instance, Automated Highway System requires new technological infrastructures to build and qualified technicians to maintain and operate which costs more than \$300 million. On the other hand, the least expensive example of these case studies (traveler information system) consists of only portable dynamic message signs which are easy and cheap to install and operate. These cost differences do not affect the efficiency score as it does not affect benefit/cost ratio, because this thesis uses the multi criteria decision making tool example (data envelopment analysis).

Compared to the input data of ITS investments, the value of benefits are presented as output of the investments. Except the freeway management example, the value of time results dominates the benefits for output section. ITS deployment on freeway management contributed a significantly less number of stop-and-go for vehicles according to the simulation results. Moreover, these less number of stop-and-go provide more emission and

safety benefits than value of time benefits. Two of the safety results are presented as zero, because these are the systems that caused 1-3 more accidents in that corridor instead of benefits. These negative values of safety results are close enough to neglect in this analysis.

In addition to the input and output data of efficiency analysis, the total value of 10 years benefits and benefit/cost ratio columns are presented to provide better understanding for the ITS investments' significant benefits compare to inputs values (costs). The benefit/cost ratio varies in a wide range, such as from 3.01 to 112.89. Furthermore, it is clear that all of these ITS applications are beneficial to the society. However, the benefit/cost ratio does not mean system is efficient in comparison to others which are stated in following efficiency score section.

**Table 5:** Summary Results of Inputs & Outputs and B/C Ratio of ITS investments

DMU No	DMU	Inputs		Outputs			Total Benefits (10 years)	B/C Ratio
		Cost of Project (2013\$)	Life Cycle Cost (10 years)	Value of Time (2013\$)	Safety	Emissions		
1	<b>Arterial Management</b>	279,289	230,202	2,270,527	142,416	26,309	24,392,523	47.88
2	<b>Freeway Management</b>	2,001,813	15,540,000	672,502	24,685,440	4,464,045	298,219,872	17.00
3	<b>Incident Management</b>	1,202,140	1,247,709	17,544,983	12,538,928	21,824	301,057,350	122.89
4	<b>Electronic Toll Collection</b>	4,612,664	3,775,513	2,550,182	-71,208	118,304	25,972,772	3.10
5	<b>Commercial Vehicle Operation</b>	1,669,734	4,206,410	8,732,000	118,680	170,261	90,209,407	15.35
6	<b>Traveler Information/ ATIS</b>	16,461	3,524	30,848	-23,736	5,351	124,626	6.24
7	<b>Automated Highway System</b>	311,240,714	21,437,672	68,350,000	27,780,000	3,988,698	1,001,186,980	3.01
	<b>Uncertainty Level</b>	Static	3%, 5%, 10%	10%, 15%, 20%				

### 6.3.2. Efficiency Scores and Rankings

Fuzzy-DEA methodology’s rapid development of uncertainty level results for efficiency score enable researchers to provide performance metrics which are also named SPI. As was proposed in previous sections, total initial and O&M costs generate the input values where value of time, emissions, and safety generate the outputs. In other words, it can be stated that more benefits with less cost investments makes the ITS application more efficient compare to others.

This study consists of inputs and output data that contain different uncertainty levels according to their determination methods. Besides, the reference studies do not

contain uncertainty levels for initial cost of project. The operation & maintenance cost has 3%, 5%, and 10% uncertainties due to the inflation rate that is used in the 10 year calculations. The output data consist of more uncertainty level, because they are mostly based on simulation studies. For instance, Edara et al.'s (2012) study states the uncertainty level for the benefit calculations. As a result, the uncertainty levels are assumed as 10%, 15%, and 20% for output data.

Based on the uncertainties of inputs and outputs, efficiency rankings, overall efficiency score, and lower & upper bound SPI sets are resulted as shown on Table 6. Each SPI number represents the different uncertainty levels of inputs and outputs. SPI-1 stands for static initial cost, 3% uncertainty for O&M costs where it includes 10% uncertainty for outputs. Without making any changes to the initial cost, SPI-2 includes 5% uncertainty for O&M costs and 15% uncertainty for outputs. Finally, SPI-3 increases the uncertainties to 10% for O&M costs and 20% for outputs. These different uncertainty levels provide us efficiency ranges instead of gathering one efficiency score from a traditional DEA model. It can be assumed that with a traditional DEA model all of the ITS applications will be efficient with their high benefit/cost ratios.

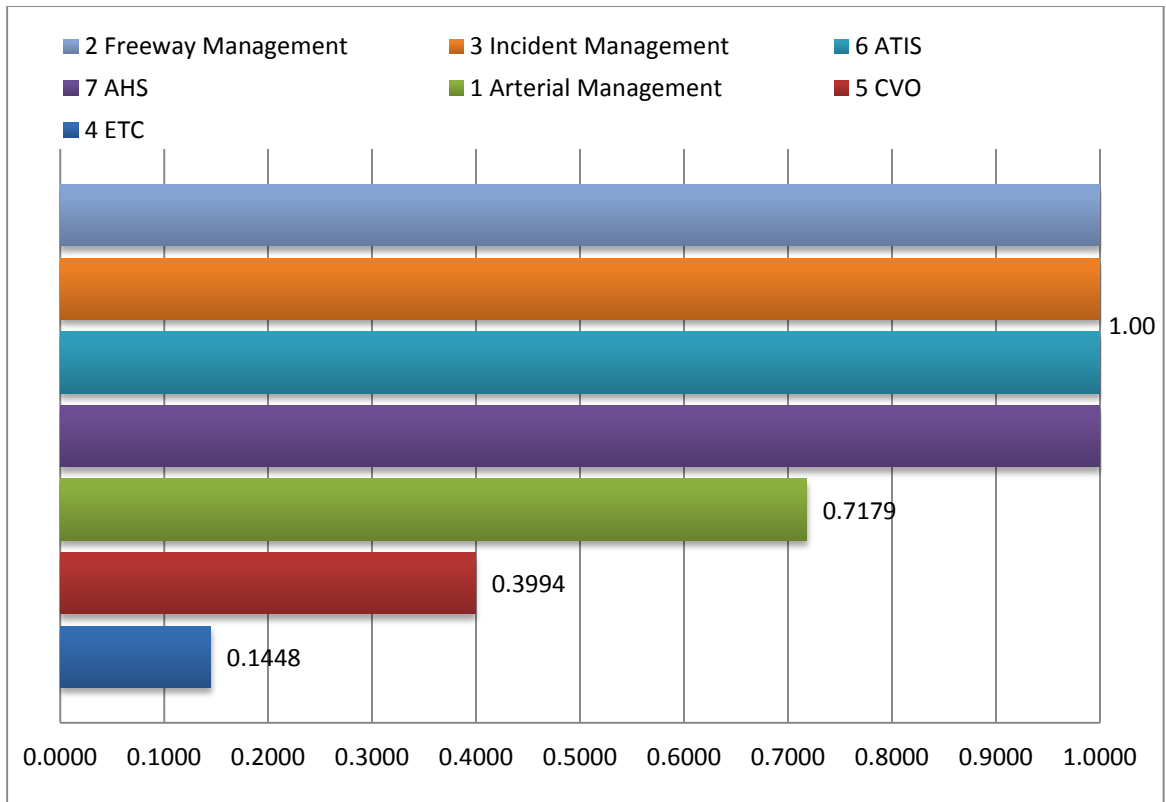
Since the fuzzy – DEA methodology provides efficiency range for systems, the overall efficiency scores for each system can be used to list ranks. In DEA methodology, 1.00 efficiency score presents the efficient results for any output cases. Out of 7 systems 4 ITS applications resulted efficient in this study which can be seen on Table 6. They all ranked as number 1 because these systems are resulted 1.00 efficiency score in any of the

uncertainty level scenarios. On the other hand, arterial management provides the closest score to the efficient ranking with 0.72 ranking score. Commercial vehicle operation and electronic toll collection applications result in the least efficiency scores with their 0.40 and 0.14 ranking scores, respectively. In addition, the overall efficiency scores are presented on the Figure 22 to provide more visual understanding.

**Table 6:** ITS Efficiency Rankings, Overall Efficiency Ranking Scores, and Lower & Upper Bounds of SPI sets

Ranking	ITS Applications	SPI-1 (LB)	SPI-1 (UB)	SPI-2 (LB)	SPI-2 (UB)	SPI-3 (LB)	SPI-3 (UB)	Overall SPI
1	Freeway Management	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1	Incident Management	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1	Traveler Information/ATIS	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1	Automated Highway System	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2	Arterial Management	0.75	1.00	0.65	1.00	0.52	1.00	0.72
3	Commercial Vehicle Operation	0.33	0.49	0.30	0.54	0.27	0.60	0.40
4	Electronic Toll Collection	0.11	0.20	0.10	0.23	0.08	0.28	0.14

These results indicate that the benefit/cost ratio is not related with the efficiency scores. The least efficient examples (Commercial vehicle operation & Electronic toll collection) of this study result 15.35 and 3.18 benefit/cost ratios however the automated highway system provides 3.01 benefit/cost ratio which is one of the most efficient systems. Indeed, it can clearly be stated that there is no relation between the benefit/cost ratios with efficiency scores.

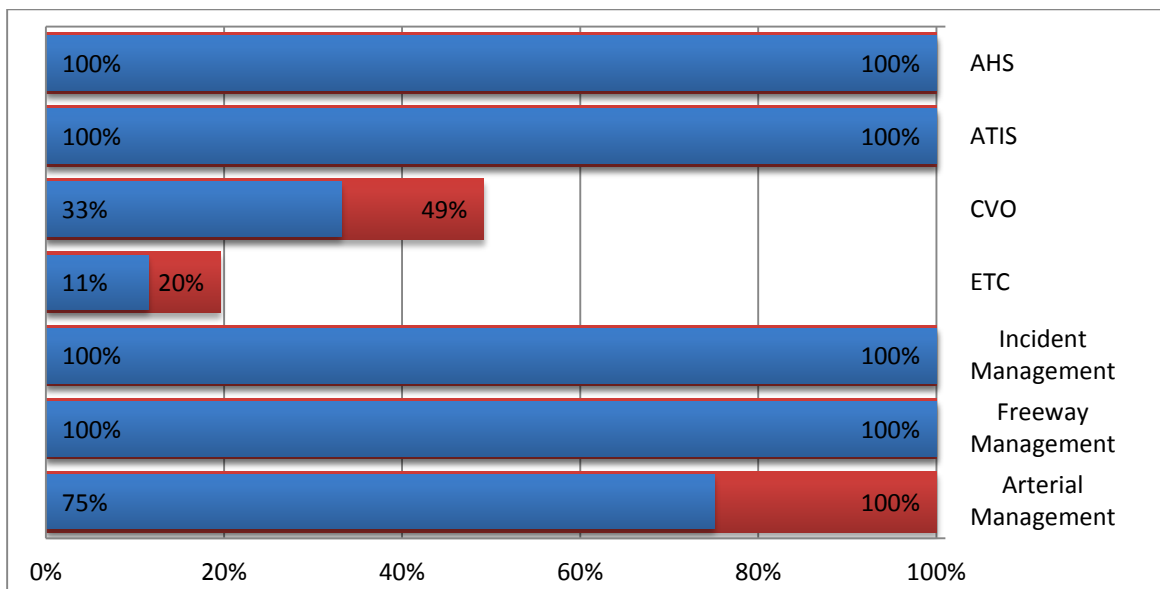


**Figure 22:** Overall (Difuzzified) Efficiency Scores

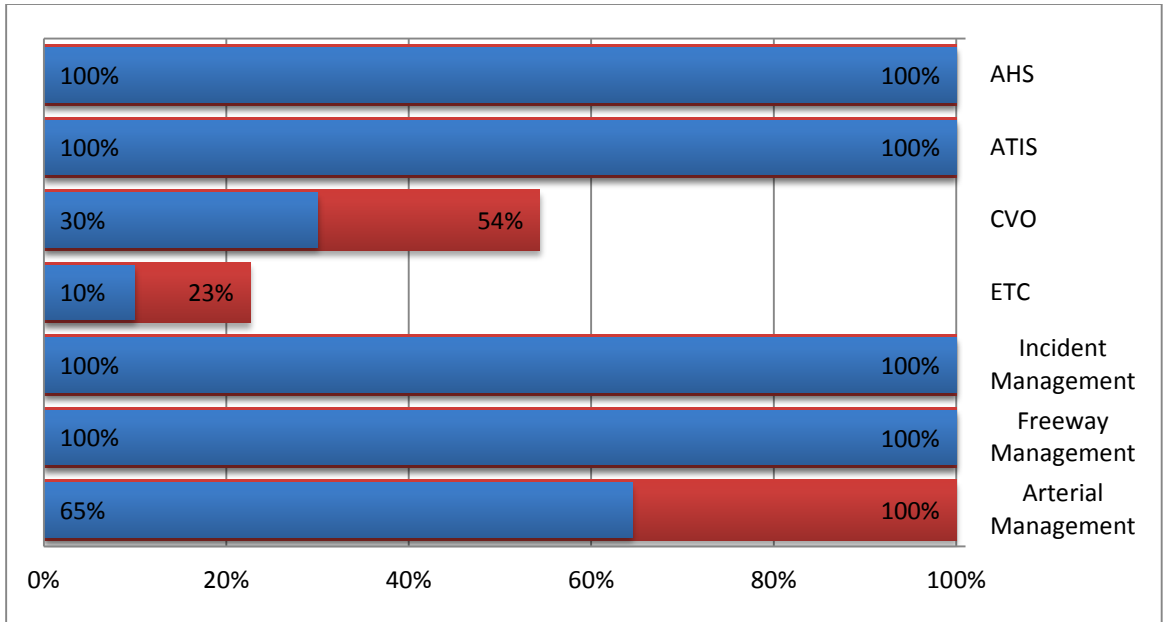
Parallel to the findings of Table-6, following figures (Figure-23,24, and 25) presents the efficiency range for ITS applications. The DMUs that ranked as first place in terms of efficiency provide total efficient results in any uncertainty scenarios. On the other hand, the other 3 ITS application which resulted less efficient results in comparison, indicate the efficiency range on graph clearly. In Figure-23 the upper bound of Commercial Vehicle Operation (CVO) efficiency is 49% where the lower bound is 23%. In other words, the efficiency range of CVO in SPI-1 is in between 23% and 49%. Electronic Toll

Collection (ETC) and Arterial Management’s efficiency scores can be seen in figures with same visual expression.

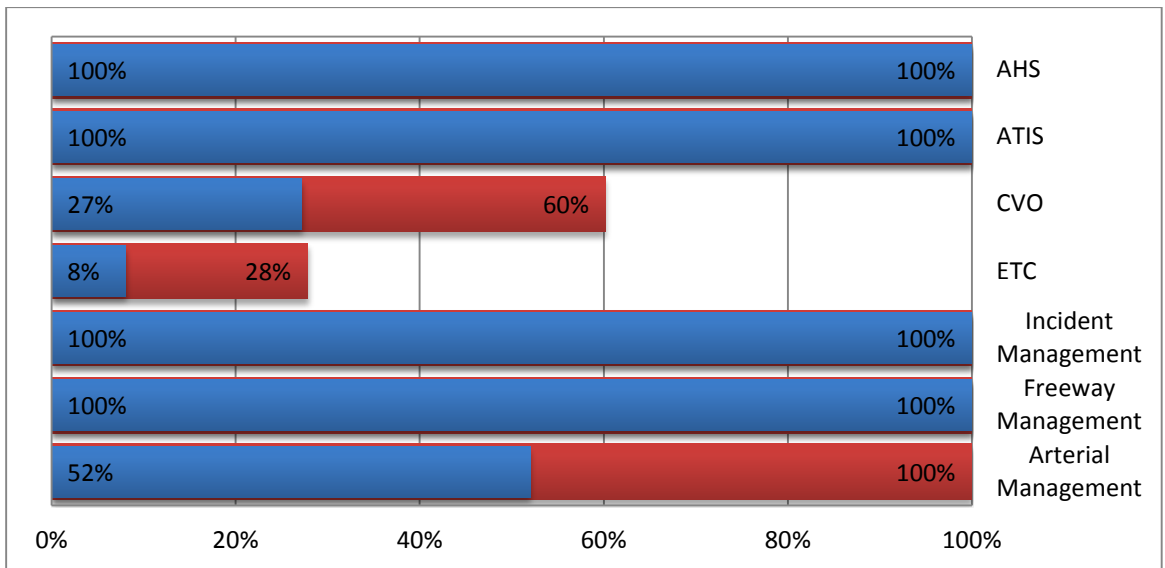
Figures-23, 24, and 25 compare the power of fuzzy-DEA methodology and provide interesting results that the efficiency score range becomes wider with higher uncertainty levels. For instance, Arterial Management resulted efficiency score range of 75% to 100% in first uncertainty scenario (SPI-1) which can be seen on Figure-23. Moreover, it followed by 65% to 100% efficiency score range and finally concluded with 52% to 100% range. Therefore, it can be stated that in the worst case scenario of inputs and outputs of Arterial Management the system can score up to 52% in terms of efficiency. The inputs and outputs of Freeway Management, Incident Management, Traveler Information, and Automated Highway Systems provide very efficient values that fuzzy-DEA methodology does not result in any range even in high uncertainty levels.



**Figure 23:** Performance labels of ITS on 3% input and 10% output uncertainty levels



**Figure 24:** Performance labels of ITS on 5% input and 15% output uncertainty levels



**Figure 25:** Performance labels of ITS on 10% input and 20% output uncertainty levels



### ***6.3.3. Summary of Results***

The costs and benefits of seven different ITS investments in the U.S. were examined in order to evaluate their sustainability performance. All of the ITS investments provided significant benefit/cost ratios with their value of time, emission and safety savings. However, as an aim of this study, the sustainability performance does not provide the same conclusion. With the consideration of uncertainty levels on O&M costs and benefits, a fuzzy-DEA approach ranked the ITS implementation in terms of efficiency.

## CHAPTER SEVEN: CONCLUSION

### **7.1. Summary of Findings**

Congested roadways are negatively affecting the quality of life for society on a daily basis. Intelligent Transportation Systems (ITS) are one of the approaches that aim to reduce traffic congestion and provide socio-economic, environmental, and safety benefits. In order to encourage decision makers to proceed with new ITS investments on transportation infrastructures, it is crucial to present their impacts in a holistic point of view.

This thesis summarized detailed sustainability impacts and performance of ITS investments with TBL-LCA and fuzzy-DEA methodologies in the United States. First, the results of the impacts of ITS on seven metropolitans in Florida were analyzed; this was performed by using TTI's UMR (2011) congestion relief results for those metropolitans. The thesis then expanded to an U.S. level study which summarized sustainability impacts of the U.S. on a state level. Finally, the reference ITS investments were compared in terms of their sustainability performance. Therefore, this thesis fills a gap by presenting nine sustainability indicators results of ITS implementations from city to state level, or sustainability performances of these implementations.

An input-output based TBL approach was implemented for seven urbanized areas in Florida. As a result, additionally to the cost savings related to delay reduction and fuel savings, their nationwide economic (profit, employment, tax revenue, import), and environmental (GHG emissions, energy and water consumption, toxic releases to air,

ecologic footprint) impacts were quantified. This analysis expanded by considering 101 metropolitans of the U.S. for 4 years. The studies' results prove the importance of analyzing supply chain (indirect) impacts on savings. The majority of the indirect indicator results are slightly close to the value of direct indicators.

The key finding of this TBL approach analysis is that it presents widespread “net” socio-economic, environmental and ecologic saving results, since some of the socio-economic indicators are not positive impacts. Although there are negative impacts associated with ITS, the net impacts are highly positive. Even though the total sustainability benefits of ITS in 4 years benefits are significant, it is not enough to reduce traffic congestion to acceptable levels by itself. In order to reduce congestion, ITS only can be a part of “sustainable transportation” approach.

In addition to a detailed sustainability impacts analysis, this thesis included the ITS investments in terms of their sustainability performances. In order to provide accurate efficiency analysis the cost and benefit components are converted to same fraction units while using same coefficient units. Value of time, emission and safety benefits provide significant savings on economy. Benefit / cost ratio of ITS investments are presented to compare with efficiency results which is the aim of this study. With the consideration of uncertainty scenarios for O&M costs and benefits resulted 3 of the ITS applications are not efficient compare to others.

## **7.2. Thesis Limitations**

Free-flow travel time and travel time index values are the main indicators of TTI Urban Mobility Report which were used to generate this study's results (Lomax et al., 2011). The TTI's research only investigates freeway ramp metering, incident management, traffic signal coordination programs, arterial street access management program and High Occupancy Vehicle (HOV) lane applications of ITS's congestion relief impacts in certain detector available areas. In addition, the data only covers the ITS implementations in urban areas. The complete picture of U.S. ITS benefit analysis could be extended to cover rural areas. Therefore, the net impacts of whole ITS applications in urban areas could be more than what is summarized in this study.

Sustainability performance analysis of ITS investments is based on seven different applications in the U.S. It was difficult to find additional reference studies which use same methodology for benefit calculations. Moreover, the lack of information about ITS investments' detail cost and benefit analysis was the limitation of sustainability performance analysis.

## **7.3. Future Study Recommendations of the Thesis**

Consequently, utilizing our methodology, direct and indirect sustainability impacts of ITS systems were quantified. This study could be extended by including more sustainability indicators. Comparisons for the impacts regarding ITS vs. new road construction with respect to congestion can be investigated using this new in-depth and

holistic approach. Thus, the efficiency of different implementations to reduce congestion could assist decision makers. In addition, including more DMUs in the sustainability performance analysis could extend the study with more comprehensive results about ITS investments.

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