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ABSTRACT (100 word max.)

Intelligent transportation systems (ITS) represent a group of technologies that can improve transportation system management and public transit, as well as individual decisions surrounding many aspects of travel. ITS technologies include state-of-the art wireless, electronic, and automated technologies with a goal to improve surface transportation safety, efficiency, and convenience. Reducing energy consumption, while not a primary goal for ITS, is a demonstrated ITS benefit in certain circumstances. This paper reviews and summarizes key energy benefits associated with a variety of ITS technologies that have been documented through models, pilot programs/field tests, and full-scale deployment.

- I. Introduction
- II. Definition of Intelligent Transportation Systems (ITS)
- III. ITS and Energy Impact Evaluation Tools
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GLOSSARY

Active Transportation and Demand Management (ATDM): ATDM is a management philosophy and suite of operations tools used to improve transportation reliability, efficiency, and safety. ATDM includes Active Traffic Management, Active Demand Management, and Active Parking Management. ATDM relies on a variety of information sources and dissemination strategies to improve travel experience and reduce delays. Improved throughput and reduced delays is a direct benefit to energy efficiency, as well as information that may reduce single occupancy vehicles and shift travelers to a more efficient mode.

Bus Rapid Transit (BRT): BRT seeks to improve bus service by reducing travel time and providing enhanced rider information. Exclusive rights-of-way, bus lanes, adjusting stop locations, wider doors, pre-boarding payment, and supportive land-use policies contribute to BRT improvements. BRT also relies on Intelligent Transportation Systems (ITS) technologies such as automatic vehicle location (AVL)—computer-based tracking of real-time vehicle positioning via global positioning systems, radio frequency communications, or both; signal control and priority; smart card fare collection; and real-time bus status information. A more flexible bus service results from combining a number of ITS features.

Commercial Vehicle Operations (CVO): Commercial vehicle operations refer to the application of electronic and wireless ITS technologies to address a range of trucking industry concerns. CVO approaches include border crossing clearance and safety via electronic clearance and manifesting; AVL; vehicle-to-fleet management center communications; on-board safety diagnostics to enable more effective roadside safety inspections; and hazardous materials incident response.

Connected Vehicle: Connected vehicles use a number of wireless technologies to communicate with other vehicles, the infrastructure, and the Internet/“cloud” (computing resources provided via the Internet). Connected vehicles include autonomous (driverless) and non-autonomous vehicle technologies that can improve safety, fuel efficiency, and mobility by providing real-time connectivity across the transportation system.

Ecodriving: Ecodriving describes the behavioral modifications that drivers can take to improve their fuel economy. Static ecodriving involves instructions that drivers can follow to reduce their fuel use (e.g., maintaining properly inflated tires, removing heavy items from the trunk, avoiding idling). Dynamic ecodriving encompasses the use of real-time feedback information that informs the driver of vehicle performance.

Eco-routing: Eco-routing is a tool that can aid drivers in reducing their fuel use through more efficient routing and by avoiding traffic congestion. In-vehicle navigation can provide this information to reflect real-time conditions, and if desired, the user’s driving style and road preferences.

Electronic Toll Collection (ETC): ETC technologies enable the instant payment of highway or roadway tolls when a vehicle passes through a toll station via an electronic roadside antenna (or reader) and a pocket-sized tag containing a radio transponder (typically placed inside a vehicle’s windshield). The toll tag transponder transmits radio frequencies to the toll reader, and the appropriate fare is automatically deducted. ETC can also be achieved via license plate recognition technologies linked to vehicle registration.

Incident Management: ITS traffic surveillance technologies—such as radar, lasers, and video image processing used to collect information—can decrease incident detection and clearance time and associated delays for travelers. Incident management consists of three key areas: traffic

surveillance (incident detection and verification), clearance, and traveler information. Also covered by this area are emergency management services, which coordinate local and regional incident response to traffic accidents, security threats, and hazardous material spills. ITS technologies can include traffic surveillance; digital and dispatch communications (including route guidance to the site of an incident); and signal priority (i.e., optimization of traffic signal timings along routes traveled by emergency vehicles).

Intelligent Transportation Systems (ITS): Intelligent Transportation Systems are comprised of a wide-range of technologies—including electronics, information processing, wireless communications, and controls—aimed at improving safety, efficiency, and convenience of the overall surface transportation network.

ITS User Services: User services categorize a wide range ITS technologies from the user's perspective. Thirty-three user service areas currently address high level problems and needs, such as route guidance, electronic payment, and parking services. New or updated user services may be added over time.

Ramp Metering: Ramp meters consist of traffic signals employed at freeway on-ramps to control the rate of vehicles entering the freeway. Metering rates are set to optimize freeway flow and minimize congestion. Rates can be fixed or responsive to local or system-wide conditions.

Shared Mobility: Shared mobility services provide short-term vehicle access to users when needed without the costs and hassles of ownership. These services include carsharing (short-term vehicle access); public bikesharing (access to a shared-vehicle bicycle fleet on a short-term basis); ridesharing (e.g., carpools and vanpools); and for-hire vehicle services (services that provide matches between riders and drivers for short-distance trips typically in urban areas and often by a mobile “app,” such as Lyft, Uber, and taxi e-Hail).

Smart Parking Management: Smart parking management is the use of information technology and wireless communications to monitor and transmit parking availability information to drivers searching for parking at public transit, urban areas, and truck stops. It can also include dynamic pricing to alter the parking price to better manage supply and demand.

Traffic Signal Control: Traffic signal controls can integrate freeway and surface street systems to improve traffic flow, vehicle and non-motorized traveler safety, and provide priority services for public transit or high occupancy vehicles. Traffic control technologies include traffic surveillance, ramp metering, lane control systems, and traffic signals. Centralized control of integrated technologies is accomplished via a transportation management center.

Traffic Management and Surveillance: ITS-based traffic management approaches broadly include incident management, ramp metering, traffic signal control, traveler information, and traffic surveillance. Traffic surveillance tools provide the data needed to manage the roadways. Most metropolitan areas employ loop detectors (sensors imbedded in the road that measure traffic counts and vehicle speeds) for traffic surveillance; others also use closed circuit television, radar, lasers, and video image processing. Vehicles equipped with toll tags or global positioning systems (GPS) as probes can also be used to determine travel times. (In this article, ramp metering and traffic surveillance tools are the focus of this category, as other areas—more broadly included in this grouping, such as traffic signal control and traveler information—are addressed separately here.)

Transportation Management Center (TMC): A Transportation Management Center (TMC) is the hub where transportation, operations, and control data are collected, combined, and distributed to manage the transportation network (including emergencies and incidents) and to

generate traveler information. The TMC relies upon various ITS tools to collect its data, such as electronic toll collection, radar, closed circuit video equipment, and loop detectors.

Transit Management: Transit management consists of four key areas: 1) transit vehicle tracking, 2) fare payment, 3) traveler information, and 4) personalized public transportation alternatives. Transit vehicle tracking includes communication between vehicles and public transit centers. AVL systems—GPS and radio frequency based communications—can be used for scheduling and vehicle tracking. Fare payment is the use of electronic mediums to enable cashless operations, reducing boarding times, money handling, and fare evasion. Transit traveler information is provided via vehicle tracking, the Internet, and changeable message signs at transit stops. Personalized public transportation provides transit services on demand or on an as-needed basis including: dial-a-ride, taxi, shuttle, and carsharing services (short-term vehicle access).

Traveler Information: ITS-based traveler information technologies—such as traffic surveillance and transit management systems—support the collection, processing, and dissemination of real-time information about travel modes and conditions. The objective of traveler information is to provide the traveling public with information regarding available modes, optimal routes, and costs in real time either pre-trip or en-route via in-vehicle information and changeable message signs along roadsides or at public transit stations.

Vehicle Control Technologies: Advanced sensing, communication, and computing technologies represent the range of ITS technologies that can help to avoid collisions, prevent or lessen injuries when crashes do occur, and ultimately lead to full vehicle automation. Some existing vehicle control technologies include adaptive cruise control, anti-lock brakes, and electronic system malfunction indicators.

I. INTRODUCTION

Energy consumption in the transportation sector increased steadily in past decades, and this trajectory is anticipated to continue. According to the International Energy Agency (2015), between 1973 and 2013, the transport sector's share of world oil consumption increased from 45.4% to 63.8%. World consumption of natural gas in the transportation sector increased from 2.7% to 6.9% during the same period. For electricity, world consumption reduced from 2.4% to 1.5%. Dulac (2012) finds that energy use in transportation could increase by as much as 70% by 2050, if no further policies are adopted to promote energy efficiency, alternative fuels, and modal shift. He further notes that with no dedicated policies, much of this growth will come from passenger light duty vehicles in developing countries. The World Energy Council (2011) scenario projections indicate the number of cars in developing countries could increase as much as 430% between 2010 and 2050. Rising incomes, increasing mobility, and improved quality of life are desirable outcomes. These figures, however, highlight the need for alternative fuels, alternative modes, and increased system efficiency. This paper addresses the potential for increased system efficiency through the use of Intelligent Transportation Systems (ITS). ITS systems include Advanced Transportation and Demand Management (ATDM), Advanced Traffic Management (ATMS), Advanced Traveler Information (ATIS), and Advanced Vehicle Control and Safety (AVCSS).

ITS technologies include state-of-the art wireless, electronic, and automated technologies with a goal to improve surface transportation safety, efficiency, and convenience. Collectively, these technologies have the potential to integrate vehicles (public transit, trucks, and personal

vehicles); system users; and infrastructure (roads and public transit). Automated and in-vehicle technologies include precision docking for buses, automated guideways, collision avoidance systems, and real-time information to drivers that can increase driving efficiency and provide up-to-the minute roadway conditions. Many ITS technologies can help to optimize trips (route guidance) and mode choice per trip, diminish unnecessary miles/kilometers traveled, increase other mode use, reduce time spent in congestion and dependence on foreign oil, and improve air quality. Furthermore, when ITS is applied to system management (public transit and roadways) and vehicle design, it can reduce fuel consumption by:

- Facilitating optimal route planning and timing;
- Adjusting light signalization to smooth accelerations/decelerations and stop-and-go driving (also known as the “green wave”);
- Allowing for automatic toll collection;
- Enabling pricing and demand management strategies;
- Increasing attractiveness of public transportation;
- Increasing opportunities for shared mobility;
- Providing information and payment options for multi-modal travel;
- Adjusting vehicle transmission for varying road conditions and terrain;
- Improving real-time decisionmaking to account for current conditions; and
- Optimizing ramp metering for existing highway conditions.

Many ITS technologies have begun to reduce energy use. During the past ten years, fuel consumption impacts of the following ITS technologies have been studied: 1) traffic signal control; 2) traffic management and surveillance (e.g., ramp metering); 3) incident management; 4) electronic toll collection; 5) driver information and behavior (e.g., ecodriving and eco-routing); 6) traveler information and network behavior; 7) smart parking management; 8) public transit management (e.g. bus rapid transit); 9) commercial vehicle operations; 10) vehicle control

technologies; and 11) shared mobility (i.e., carsharing and public bikesharing). Human factors is also discussed, as it can play a key role in the energy impacts of ITS due to latent demand and pricing response. These topics are the focus of this analysis. Nevertheless, ITS impacts—including unintended consequences and aggregate effects—are still not well understood. The field of intelligent transportation systems, energy impacts, measurement tools, and documented findings are discussed in this article.

II. DEFINITION OF INTELLIGENT TRANSPORTATION SYSTEMS (ITS)

In 1991, the concept of Intelligent Transportation Systems emerged when transportation professionals recognized that electronic technologies could begin to play a significant role in optimizing surface transportation, and the United States (U.S.) Congress legislated the national ITS program. Since then, computer, communication, and sensor technologies have improved dramatically, and ITS technologies have emerged in highway and public transit jurisdictions worldwide.

ITS deployment can be categorized into three stages:

Stage One: Test and Implement Early ITS Technologies (or building blocks)

Stage Two: Link Early ITS Technologies

Stage Three: Develop an Integrated System of ITS Technologies.

The public sector has been the dominant driver of Stage One ITS technology research and development. During this phase, early ITS technologies were applied to improve traditional operations. Key accomplishments include the deployment of:

- Traffic management centers in urban areas to monitor freeway traffic and early incident notification;
- Traffic signal control and ramp metering to improve traffic flow and safety;
- Improved traveler information;
- Commercial vehicle screening and electronic toll collection;
- Satellite-based dispatching systems in public transit operations;
- In-vehicle navigation systems in private vehicles;
- Ecodriving and eco-routing;
- Ridesharing services via the Internet; and
- Carsharing and public bikesharing services.

While Stage One of ITS will continue for years, Stage Two—linking early ITS technologies—continues to progress, as evident by efforts to mainstream ITS with conventional capital improvement projects (e.g., connecting traffic management centers with advanced traffic signal coordination and ramp metering adjusted in real time and traveler information systems coordinated with in-vehicle devices). During this phase, industry has already initiated work to understand the fundamental nature of driving and of driver/operator behavior in transportation models. Furthermore, the process has advanced from a heavy focus on public sector investment towards customer-oriented operations, with numerous businesses offering packages of technologies and services. Examples of next steps—including in Stage Two—are: 1) public transportation system improvements; 2) coordination among various freight modes (e.g., trucks and rail); 3) improved system management through real-time data and performance tools; and 4) in-vehicle crash avoidance systems.

Ultimately, further integration is needed for the longer-term goal—Stage Three—to be realized. An integrated ITS system requires a network of technologies working together along critical corridors and urban centers (e.g., Connected Vehicle). Nevertheless, the challenge remains in deploying a comprehensive network of technologies that manage and disseminate information.

A. ITS Categories and Deployment Planning

To guide the development and deployment of ITS technologies, the U.S. Department of Transportation released its National ITS Architecture (designed in conjunction with its external advisory committee—ITS America—and stakeholder input) in the mid-1990s. The National ITS Architecture reflects an ongoing process to improve and adapt with changing technologies. It provides a common framework and language for planning and implementing ITS so that systems can be integrated functionally and geographically and be interoperable from one location to another. The U.S. DOT maintains the ITS Architecture independent from any specific system design or region with a goal to support ITS implementation in urban, interurban, and rural environments. The National ITS Architecture and Turbo Architecture Version 7.1 was released in April 2015 (US DOT 2016). To date, the National ITS Architecture is comprised of 33 ITS user services bundled into eight categories: 1) travel and traffic management, 2) public transportation management, 3) electronic payment, 4) commercial vehicle operations, 5) emergency management, 6) advanced vehicle safety systems, 7) information management, and 8) maintenance and construction management. See Table 1 below for an overview of the 33 ITS user services. <Table 1 near here>

The National ITS Architecture was initially tied to a 10-Year Plan (released in 2002) that addressed goals, objectives, user service requirements, and expected benefits. The five main goals outlined in the 10-Year Plan, included: 1) safety, 2) security, 3) efficiency/economy, 4) mobility/access, and 5) energy/environment. Furthermore, the 10-Year Plan developed a series of programmatic and enabling themes to describe the opportunities, benefits, and challenges of future transportation systems. The 10-Year Plan included four programmatic themes: 1) an integrated network of transportation information; 2) advanced crash avoidance technologies (including in-vehicle electronics); 3) automatic incident detection, notification, and response; and 4) advanced transportation management (including traffic and public transit).

Two of the four ITS programmatic themes (two and four listed above) could result in significant energy consumption benefits in the future. Advanced crash avoidance technologies—the second programmatic theme—focuses primarily on reducing the number of vehicle crashes. Adaptive in-vehicle electronics, integral to crash avoidance, are anticipated to reduce fuel consumption by: 1) smoothing accelerations and decelerations (particularly for commercial vehicles and public transit vehicles); 2) responding automatically to stop-and-go driving; 3) anticipating and adjusting the throttle and transmission for varying road conditions and terrain; and 4) enabling the safe movement of platoons of tightly spaced trucks, public transit, and other vehicles. In the longer term, such safety devices could also permit the introduction of lighter-weight vehicles for greater fuel economy. In addition, route guidance products that help drivers plan optional routes—in light of an incident—may significantly reduce miles/kilometers driven, saving fuel and helping to mitigate congestion.

The fourth programmatic theme, advanced transportation management, is also predicted to have a considerable effect on energy use in the future. Tools included in this area aim to intelligently and adaptively manage vehicle flows within the physical infrastructure and often across multiple jurisdictions and modes. Advanced transportation management systems rely upon area-wide surveillance and detection, rapid acquisition and evaluation of traffic flow data, and predictive capabilities.

ITS America forecasts that these programmatic areas—transportation management systems and crash avoidance—will be critical to achieving the energy goal of saving a minimum of one billion gallons of gasoline each year. The remainder of this paper focuses on tools (models, field tests/pilot programs, and deployments) used to evaluate ITS impacts on energy consumption.

In January 2012, the U.S. DOT Intelligent Transportation Joint Program office released a five-year ITS Strategic Research Plan that outlines a vision of transforming transportation through a multi-modal initiative to enable all vehicles to communicate wirelessly with each other and the transportation infrastructure (RITA, 2013). This vision includes using ITS connectivity to advise vehicle owners on how to optimize vehicle operations and maintenance for maximum fuel efficiency.

In December 2014, the U.S. Department of Transportation Intelligent Transportation Systems Joint Program Office (JPO) released the ITS 2015-2019 ITS Strategic Plan (2014), which builds on the progress of previous plans. The Strategic Themes for 2015-2019 include: 1) Enable Safer Vehicles and Roadways, 2) Enhance Mobility, 3) Limit Environmental Impacts, 4) Promote

Innovations, and 5) Support Transportation System Information Sharing. The Strategic Goal to Limit Environmental Impacts includes measures that reduce energy consumption, such as managing traffic flow, speeds and congestion, transportation alternatives, avoiding congested routes, taking alternative routes, using public transit, and rescheduling a trip.

The U.S. Department of Transportation Applications for the Environment Real-Time Information Synthesis (AERIS) Program researches interoperable technologies and applications that reduce the negative impacts of transportation on the environment. The AERIS research approach is focused on research questions and projects and has developed five Operational Scenarios: 1) Eco-Signals, 2) Eco-Lanes, 3) Low Emission Zones, 4) Eco-Traveler Information, and 5) Eco-Integrated Corridor Management.

III. ITS AND ENERGY IMPACT EVALUATION TOOLS

In 1998, the U.S. Environmental Protection Agency (U.S. EPA) released a technical report that examined methodologies and research efforts aimed at evaluating the energy and environmental impacts of ITS. Since then other researchers have applied methodologies to evaluate ITS energy/environmental impacts (e.g., Barth and Boriboonsomsin, 2009; Cambridge Systematics, Inc., 2009). The EPA report concluded that developing an ITS fuel consumption and emission impact assessment is an exceptionally challenging exercise due to the complex relationship among ITS, travel behavior, and transportation system management. Traffic simulation and travel demand models can aid in this research, but more work is needed. More recently, the U.S. Department of Transportation AERIS Program has developed modeling capabilities based on scenario analysis that includes energy benefits from Low Emission Zones, Eco-Lanes, Eco-

Traffic Priority, Eco-Traffic Signals, and Eco-Approach and Departure at Signalized Intersections (US DOT AERIS Program).

A key theme of ITS is the integrated deployment of information networks to support travel, increase transportation infrastructure use, and better manage demand. However, this integration requires models that can simulate the effects of information on traffic flow at corridor levels and travel behavior at regional levels. Independently, traditional tools (microsimulation, regional travel demand, and emission and fuel consumption models) cannot adequately capture critical linkages among ITS technologies and various feedback loops.

For example, travel demand models are typically unresponsive to information-related improvements (e.g., road conditions) and intersection and corridor-level changes. Such impacts are usually evaluated using traditional microsimulation tools, which lack the behavioral assumptions of travel behavior models. Thus, new approaches are being developed to capture complex ITS interactions and impacts. These tools must be flexible enough to: 1) reflect different scenarios (e.g., market penetration and behavioral assumptions); 2) capture ITS impacts on dynamic mode, route choice, and induced demand (travel that occurs due to increased supply through mechanisms, such as pricing, which can shift peak demand to other modes or times); and 3) simulate individual vehicle driving patterns.

Another common tool for evaluating ITS technologies is field tests or pilot programs. Researchers and practitioners frequently conduct field tests and pilot projects to demonstrate and evaluate ITS technologies in real-world settings. In some cases, there is an overlap between

microsimulation tools and field tests/pilot projects. Modeling is frequently used to simulate and predict real-world ITS deployment impacts. Furthermore, field test/pilot project data are often employed in modeling studies to simulate ITS impacts at different levels (e.g., corridor and higher market penetration). Results, reported in the following section, reflect modeling, field test/pilot project, and deployment findings.

IV. PREDICTED AND EMPIRICAL FINDINGS

Understanding of ITS fuel consumption impacts has greatly improved over the past decade. A summary of *predicted* impacts for eleven ITS categories—in which fuel consumption has been studied over the last decade (at various levels)—are presented in Table 2 below. <Table 2 near here> The eleven categories include: 1) traffic signal control; 2) traffic management and surveillance (e.g., ramp metering); 3) incident management; 4) electronic toll collection; 5) driver information and behavior (e.g., ecodriving and eco-routing); 6) traveler information and network behavior; 7) smart parking management; 8) public transit management; 9) commercial vehicle operations; 10) vehicle control technologies; and 11) shared-use mobility (i.e., carsharing and public bikesharing). Human factors is also included in this section, as it plays a key role in ITS energy impacts (e.g., latent demand, response to pricing). <Table 2 near here>

Over the past decade, ITS technologies have been modeled; tested in field tests/pilot projects; and evaluated in full-scale deployment (e.g., electronic tolling, ramp metering, bus automatic vehicle location, carsharing). Knowledge about ITS impacts is growing and with it a stronger understanding of how to maximize benefits. Although fuel consumption is not the primary motivator of ITS (congestion relief and traffic/public transit management are the key drivers),

understanding of ITS energy impacts is increasing. By reducing stop-and-go traffic, improving route guidance, and reducing auto use, ITS can have a positive impact on fuel consumption.

In the following sections, energy consumption results from modeling, field tests/pilot projects, and full deployment are quantified (when applicable). While this analysis spans a wide range of ITS technologies, it does not represent an exhaustive review of ITS and fuel consumption impacts. Finally, there is a brief discussion regarding the potential effects and complexities of understanding latent demand, which may result from ITS capacity enhancement strategies.

1. Traffic Signal Control

Traffic signals serve a variety of functions. They can be used to manage traffic speeds, vehicle merging and corridor crossings, as well as interactions among vehicles and low-speed or non-motorized modes—such as bicycles, pedestrians, and wheelchairs—at intersections. ITS microsimulation models enable researchers to assess the impacts of various traffic signal controls on emissions, travel times, and fuel consumption. Traffic signal controls can be set to optimize one or more desired goals (e.g., time savings and energy reduction). To maximize fuel efficiency, traffic signal controls can be fixed to reduce vehicle accelerations, decelerations, and idle times, all of which contribute to increased fuel consumption. Numerous—and sometime conflicting—goals must be balanced in traffic management.

Using traffic signal controls to minimize energy consumption is not new, and studies to quantify energy impacts in this area pre-date ITS. For example, during the two energy crises of the 1970s

(1973-74 and 1979), researchers found energy consumption could be reduced by synchronizing traffic signals to minimize stop-and-go traffic.

More recently, traffic signal control has become a predominant component of ITS, and its impacts have been evaluated in simulation and real-world settings. ITS applications for traffic signals include communication systems, adaptive control systems, real-time data collection and analysis. Recent studies indicate fuel savings of 8 to 9% accompanied by travel time reductions of 8 to 10% (USDOT, 2007b). Another recent study found that infrastructure-to-vehicle (I2V) communication resulted in an overall 22% improvement in fuel economy (Caminiti, Cunningham, and Lovell, 2010). Variability in estimated savings results from the following factors: quality of existing timing plans, network configuration, traffic patterns, and signal equipment.

The U.S. DOT AERIS Program (2014b) has released preliminary results for eco-signal timing scenario/modeling based on varying levels of connected vehicle market penetration. This research finds that under partial connected vehicle market penetration there could be a 2-4% emission and fuel consumption reduction, while under full market penetration the emissions and energy reductions could be 4-6%. Scenario/modeling for public transit and freight (2014b) show that providing transit and freight vehicles with signal priority could result in 1-2% emissions and fuel savings under partial connected vehicle penetration and 2-4% under full connected vehicle penetration. Eco-freight signal priority could result in 1-4% fuel savings for freight trucks, depending on the penetration rate of connected vehicle technology and other factors, such as congestion.

2. Traffic Management and Surveillance

Ramp metering is one of several ITS technologies designed to manage traffic flow. The goal of ramp metering is to safely space vehicles merging onto a highway, while minimizing speed disruptions to existing flows. Considerations include: 1) public misunderstanding and system dislikes, 2) overflow of cars onto surface streets while waiting to enter ramps, and 3) driver use of arterial streets to avoid ramp meters. The most significant benefit of ramp metering is passenger time savings. Emission and fuel consumption impacts are mixed.

Ramp metering causes vehicles on ramps to stop-and-go, and this behavior consumes more fuel than free flow driving. Ramp metering also results in smoother vehicle flow on freeways because vehicles enter in a staggered and controlled manner, reducing bottlenecks that would otherwise impede traffic. This results in reduced fuel consumption. These two factors (increased stop-and-go traffic on on-ramps and decreased traffic flow disruption on highways) appear to negate each other. More detailed studies are needed to understand how ramp metering effects interact and impact fuel consumption.

While the larger category of traffic management and surveillance also includes incident management, traffic signal control, and traveler information, this section focuses on ramp metering primarily, as each of the other categories is examined separately here. Other traffic management tools include improved surveillance using loop detectors, closed circuit television, radar, lasers, video image processing, and vehicles equipped with toll tags or global positioning

systems to determine travel times. Their impacts on fuel consumption directly relate to their use in incident management and traveler information, which are discussed below.

3. Incident Management

ITS contributions to incident management include improved surveillance, verification, and dispatch to manage an incident. The use of changeable message signs and personal communication devices, such as mobile phones, can assist with early notification for upstream drivers resulting in reduced incident-related congestion, as drivers have more time to select an alternative route. Improved incident management can result in decreased fuel consumption of about 1.2% annually by reducing the delay and congestion associated with the blocked traffic (USDOT, 2007a). Tupper, Chowdhury, Klotz, and Fries (2012) found that ITS strategies for incident management are capable of providing sustainability benefits, including carbon dioxide reductions, greater than construction-related strategies designed to reduce energy and environmental impacts.

4. Electronic Toll Collection

Electronic toll collection (ETC) allows for electronic payment of highway and bridge tolls as vehicles pass through a toll station. Vehicle-to-roadside communication technologies include electronic roadside antennas (or readers) and pocket-sized tags containing radio transponders (typically placed inside a vehicle's windshield). Pay-by-plate options, where the license plate of the vehicle is linked to an account or used as the basis for invoicing the registered owner of the vehicle, are now being implemented. Enforcement is accomplished through still and video cameras.

The primary reasons for implementing ETC are to generate revenue and for congestion/demand management. Reductions in fuel consumption due to reduced delays at toll facilities have been reported. A 2000 study of the New Jersey Turnpike found savings of 1.2 million gallons of fuel per year due to ETC (US DOT). Saffarzadeh and Rezaee-Arjroody (2006) calculated fuel savings along two roadways in Iran. They compared ETC to conventional stop and pay methods of toll collection and found fuel savings. Along corridors or bridges, congestion reduction could lead to induced demand (modal shift back to single occupancy vehicles). Cordon pricing (fees for driving in a specific geographic area) appear to result in a shift towards public transit. Six months after London began cordon pricing in London, about 60,000 fewer cars were entering the fee zone daily. Of those, 50% to 60% had shifted to public transit, and 15% to 25% had shifted to carpooling, bicycles, or mopeds. The remaining vehicles diverted around the fee zone (Persad, Walton, and Hussain, 2007).

5. Driver Information and Behavior

ITS is increasingly providing drivers with real-time information to assist with making individual travel decisions, which can reduce fuel consumption. Ecodriving and eco-routing are two forms of driver information that have shown potential to reduce fuel consumption.

Dynamic ecodriving, where drivers are provided with real-time feedback about how their driving affects vehicle fuel efficiency, has shown the potential to reduce reduce fuel consumption. Barth and Boriboonsomsin (2009) ran a simulation model for an ecodriving system that provided dynamic advice to drivers along a highway corridor in Southern California. The results

demonstrated that drivers receiving this information could achieve a reduction of approximately 10% to 20% in fuel consumption and lower carbon dioxide emissions without a notable increase in travel times. Xia, Boriboonsomsin, and Barth (2013) evaluated the effects of ecodriving along signalized corridors where the traffic controller's signal phase and timing communicated directly to the vehicles. This study found a 10% to 15% reduction in fuel consumption is possible, and there is a beneficial network effect because surrounding vehicles that were not receiving signal communication also improved fuel efficiency, even with lower penetration rates of vehicles receiving the signal information. Martin, Boriboonsomsin, Chan, Williams, Shaheen, and Barth (2013) conducted a field test with 18 participants driving with and without the real-time dynamic efficiency feedback. Drivers responded to different aspects of the ecodriving information with some slowing their acceleration or deceleration and more than half reducing their highway speeds. Overall, there was a 1.4% reduction in fuel consumption.

U.S. DOT AERIS (2013) scenario modeling finds a 5-10% fuel savings with the use of eco-approach and departure from intersections when drivers follow speed advice.

Eco-routing shifts the emphasis of route assistance devices from the fastest/shortest route to the route that reduces fuel consumption and/or emissions. A number of studies indicate that eco-routing can reduce fuel consumption and carbon emissions as compared to an individual's choice of route or GPS directions based on the shortest time to destination. Boriboonsomsin, Barth, Zhu, and Vu (2012) developed an eco-routing navigation system to reduce fuel consumption. The system employs a Dynamic Roadway Network (DynaNet) database or a digital map of the road network that is enhanced by historic and real-time traffic information. A study of specific

corridors in Beijing, China found that when the average speed was 48 kilometers/hour the greatest carbon dioxide emission savings of 8% were achieved (Yao and Song, 2013). Another recent study in the Buffalo-Niagara area of New York State used the Multi-Scale Motor Vehicle Emissions Simulator (MOVES) and Transportation Analysis and Simulation System (TRANSIMS) models to evaluate area-wide efficiency benefits of eco-routing. The study found that eco-routing reduced emissions and fuel consumption, but it resulted in longer travel times (Guo, Huang, and Sadek, 2013). Bandeira, Almeida, Khattak, Rouphail, and Coelho (2013) found that there is a trade-off between reducing fuel consumption and carbon dioxide emissions and reducing health-based criteria emissions. While faster intercity routes reduced fuel use and carbon dioxide emissions, these same routes increased carbon monoxide, nitrous oxides, and hydrocarbon emissions.

Eco-Lanes are dedicated freeway lanes, similar to high occupancy vehicle lanes, which allow vehicles with low emissions and/or that are operated in an eco-friendly manner. This could include speed harmonization and eco-cooperative adaptive cruise control. US DOT AERIS (2014c) modeling finds energy savings of 12-50% depending on the technology being used.

Low Emission Zones are geographically defined areas that seek to improve air quality by preventing high emission vehicles from entering the zone, shifting individuals to public transit, and/or encouraging lower emission vehicles. A low emission zone could be dynamic, responding to real-time air quality metrics. US DOT AERIS (2014d) scenario modeling found 3-5% energy and emission savings at modest levels of eco-vehicle penetration and enhanced public transit services.

6. Traveler Information and Network Behavior

Effective traveler information requires the accurate collection and dissemination of real-time travel information to transportation managers and the public to aid them in making informed decisions about travel time, mode, and route. A wide array of ITS technologies assist with traveler information including web sites, mobile phones, and changeable message signs to distribute user information. Fuel consumption benefits resulting from system-wide traveler information might include modal shifts (e.g., from a single occupancy vehicle to public transit or bicycle) and energy savings proportional to travel time reductions achieved by taking alternative modes. Travelers can review current travel conditions including congestion, incidents, and parking availability, as well as bus or rail schedules and routes when planning their trip. Sharma and Mishra (2013) considered ITS for dynamic emissions pricing and showed the potential to reduce network fuel consumption and congestion through modal shifts to public transit.

7. Smart Parking Management

Smart parking refers to a group of technologies that can improve payment methods and enforcement, as well as providing information for finding and reserving a space in advance. Technologies that assist with finding and reserving a parking space can reduce energy consumed while searching for parking and provide an added benefit of reduced congestion for all vehicles in the immediate area. Bayless and Neelakantan (2012) note that 30% of urban congestion is created by drivers cruising for parking. Smart parking technologies for locating parking and

pricing information include sensing systems to detect the presence of a vehicle and communications, such as mobile phone “apps,” to inform and direct drivers to available spaces.

8. Public Transit Management

Public transit managers are already implementing ITS technologies to improve service through: automatic vehicle location, real-time bus arrival signage, traffic signal priority, and automated information announcements. The degree to which ITS technologies improve public transit services and attract new riders determines the range of fuel consumption impacts.

Bus Rapid Transit (BRT) encompasses the use of a series of ITS technologies, route planning, exclusive rights-of-way, and management to improve service—each of which can reduce travel times. BRT and priority bus systems are now operating in 156 cities worldwide (Global BRT Data, 2013). Increases in bus ridership due to BRT implementation vary depending on the local conditions, the sophistication of the BRT system, and the length of time the system has been operating. BRT has been shown to attract new riders and encourage existing riders to use the service more frequently. In North America, ridership growth rates between 27% to 66% have been reported, with new rider growth between 23% and 32% (Victoria Transport Policy Institute, 2012). Generally, if a modal shift occurs from a single occupancy vehicle to BRT, there is an efficiency benefit. If the previous mode was non-motorized, such as walking or cycling, the impact on fuel efficiency is negative. If additional riders are attracted from another bus route, the impact on fuel efficiency is neutral. Furthermore, faster journey times and reduced acceleration, deceleration, and idle times—resulting from fewer stops and signal priority—have been shown to reduce fuel consumption. Hossain and Kennedy (2008) developed a decision support tool

called Sustainable Transport and Energy Planning (STEP) to estimate energy savings from bus transit improvements, ranging from demarcation of exclusive bus lanes to fully segregated high-quality BRT with a large modal shift from private vehicles to BRT. The modal shift with the BRT scenario was assumed to include a variety of policy changes such as financial incentives and enforcement mechanisms. The authors applied this model to a corridor in Kuala Lumpur, Malaysia and found that the fully segregated high-quality BRT scenario reduced gasoline consumption by 33% from the business as usual scenario by 2010 and 49% in 2020 due primarily to modal shifts from the private auto to BRT. The model also predicted an increase in diesel consumption due to the increased number of buses. Nevertheless, the overall energy savings were significant, with a maximum possible savings of 29% in 2010, increasing to 45% in 2020.

9. Commercial Vehicle Operations

Primary ITS applications in commercial vehicle management include automatic vehicle identification and weigh-in-motion. The purpose of automatic identification and weigh-in-motion technologies in commercial vehicle operations (CVO) is to enable the weighing and cataloging of trucks without causing vehicles to stop and queue in line.

Simulation modeling and on-road testing reveal increased fuel efficiency due to weigh-in-motion technologies. Measured against static scales, high-speed weigh-in-motion systems demonstrate the greatest fuel benefits. Weigh-in-motion ramps that require trucks to slow—but not stop—also result in fuel savings, although not as significant as high-speed weigh-in-motion stations. The purpose of automatic vehicle identification is to identify trucks, drivers, and loads as a companion function to weigh-in-motion. An Iowa State University Center for Transportation

Research and Education study showed savings up to 0.4 per gallon of fuel with each successful weigh station bypass (Help Inc., 2013). While commercial ITS applications demonstrate a clear fuel benefit, this value depends on the number and nature of stations passed.

10. Vehicle Control Technologies

ITS technologies that automate vehicle control systems aim to improve vehicle safety, efficiency, and comfort. These technologies include intelligent cruise control, anti-lock brakes, electronic system malfunction indicators, and automated highway systems (e.g., platooned vehicles). Simulation research indicates that some automated vehicle control technologies could have a positive impact on fuel consumption.

Automatic cruise control refers to technologies that can identify the distance in front of a vehicle on a highway and correspondingly modify a automobile's controlled speed to accommodate lane merging and changes in the speed of vehicles ahead. This results in reduced fluctuations in the speed of controlled cars, which has a positive fuel efficiency effect. A recent study for the National Renewable Energy Lab by Gonder, Earleywine, and Sparks (2012) found "ecodriving" through full automation of vehicles and traffic control could result in fuel savings in excess of 30% to 40%.

Another group of vehicle control technologies is being tested for automated highway systems. The concept behind automated highways is to employ technologies that facilitate vehicle-to-vehicle and vehicle-to-roadside communication to improve safety and system efficiency. In this way, vehicles can operate in very close proximity to each other. Simulations indicate a 5% to

15% reduction in fuel consumption due to aerodynamic drafting effects. Tsugawa, Kato, and Aoki (2011) studied energy savings resulting from truck platooning on a test track for an “Energy ITS” project initiated by the Japanese Ministry of Economy. The results showed that three trucks driving at 80 kilometers/hour with a 10 meter gap between trucks, resulted in 14% savings, primarily from reducing the aerodynamic drag.

11. Shared Mobility

Shared mobility (e.g., carsharing, public bikesharing, ridesharing, and for-hire vehicles) entails the use of a shared fleet of vehicles (e.g., bikes and cars) by individuals. In many cases, this can result in reduced mileage, modal shifts, and reduced private vehicle ownership. The impacts of carsharing have been well researched worldwide. A recent North American survey of all major carsharing organizations conducted in November 2008 showed that carsharing resulted in 9 to 13 vehicles being taken off the road (sold or postponed purchases) per carsharing vehicle.

Furthermore, this same study documented a reduction in mileage of 27% and 34% decline in greenhouse gas (GHG) emissions per year on average (observed impact, based on vehicles sold) and a reduction of 56% in mileage and a 41% decline in GHG emissions per year on average (full impact, based on vehicles sold and postponed purchases combined) due to carsharing (Martin and Shaheen, 2011). Finally, approximately 25% of respondents sold a vehicle and roughly another 25% of the total sample would have considered obtaining a vehicle, if carsharing disappeared (Shaheen and Cohen, 2013).

Although before-and-after studies documenting public bikesharing benefits are limited, a few North American programs have conducted user surveys to record program impacts. Public

bikesharing operators in Canada (BIXI Toronto and BIXI Montreal) report that 25% to 36% of users drive less, respectively, due to bikesharing. Capital Bikeshare in Washington, D.C. reported that 41% of its users drive less. Approximately 5.5% of public bikesharing users on average in North America (Canada, U.S., and Mexico) have reported selling or postponing an automobile due to bikesharing. Other findings include that 58% of members increase cycling, and 50% of members reduce personal auto use due to bikesharing. Since bikesharing has been operating in North America for a relatively short time, these results reflect early understanding and use dynamics (Shaheen, Martin, Chan, Cohen, and Pogodzinski, 2014; Shaheen, Cohen, and Martin, 2013; Shaheen, Martin, Cohen, and Finson, 2012).

For-hire vehicle services, also known as “ridesourcing” or transportation network companies (TNCs), use smartphone applications (apps) to connect community drivers with passengers. Rayle et al. (2016) of ridesourcing in San Francisco, California (Rayle et al., 2016) found that ridesourcing users were generally younger and more highly educated than the city average (84% had a bachelor’s degree or higher). UberX provided the majority of trips (53%), while other Uber services (black car, SUV) represented another 8%. Lyft provided 30% of trips, Sidecar 7% (ceased operations in December 2015), and the remainder were other services. The survey also asked respondents for key trip data, including trip purpose, origin/destination, and wait times. Of all responses, 67% were social/leisure trips (bar, restaurant, concert, visit friends/family), and only 16% of trips were work related. Forty-seven percent of trips began somewhere other than home or work (e.g., restaurant, bar, gym), while 40% were home based. If ridesourcing were unavailable, 39% would have taken a taxi or 24% a bus. Four percent named a public transit station as their origin or destination, suggesting ridesourcing can serve as a first-/last-mile trip to

and from public transit. Ridesourcing trips within San Francisco averaged 3.1 miles in length compared to taxi trips averaging 3.7 miles. Finally, the study found that ridesourcing wait times tended to be substantially shorter than classic taxi hail and dispatch wait times. This study did not examine e-hail taxi services, as they were not widely deployed at the time of the survey. However, since this survey, there has been a dramatic increase in taxi use of e-hail services. For example, as of October 2014, 80% of San Francisco taxis (1,450 taxis) were reportedly using the e-hail app Flywheel, which have brought taxi wait times closely in line with those of ridesourcing (Sachin Kansal, unpublished data).

Since shared mobility is growing and relies upon ITS technologies, more research is needed into the impacts of such services in taming auto use and its associated impacts on energy use and modal shift.

12. Human Factors

As demonstrated above, many ITS technologies can have a positive impact on fuel consumption. Some of the energy benefits accrue from reduced congestion and stop-and-go driving—resulting in smoother traffic flows. In effect, ITS technologies can increase existing roadway capacity without increasing infrastructure. Latent (or additionally generated) demand is often at the forefront of infrastructure enhancement discussions. In regions with the greatest congestion, travel demand may be suppressed due to travel time costs. Under such conditions, adding or managing infrastructure to ease congestion may result in additional travel demand until delay

costs rise enough to suppress travel again. Studies show that increased roadway infrastructure can also result in modal shifts from public transit ridership to personal vehicles.

If ITS is successful in reducing congestion and travel delay, roadway capacity will be increased without adding new infrastructure. An outstanding question regarding ITS capacity enhancement is whether or not added capacity will result in latent demand for highway use—similar to some infrastructure expansion impacts (e.g., modal shifts from public transit to auto use). If improved traffic throughput due to ITS results in increased highway demand and modal shifts away from public transit, some of the system-wide fuel efficiency benefits may be negated. Since evidence to support latent demand is still not definitive, and final Stage Three ITS implementation has not yet been achieved, no conclusions can be drawn regarding the causal relationship between ITS capacity improvements and latent demand at this time.

Other ITS technologies may be used to offset increased travel demand—such as real-time road pricing—to send signals to the traveling public regarding travel costs. By employing sophisticated surveillance technologies, vehicle identification, and electronic payment systems, ITS can assist in administering value pricing and reducing congestion and energy use.

V. SYSTEM INTEGRATION AND CONCLUSIONS

At the current stage of ITS development and deployment, many fuel efficiency impacts have been realized (e.g., electronic tolling and signal priority for buses). However, modeling and ITS deployments are still largely occurring in discrete applications, rather than across integrated regionwide networks. To understand the full effects of ITS on transportation systems (traffic and

public transit), technologies must be deployed in a comprehensive manner. Similarly, the full energy impacts of ITS cannot be known until technologies are integrated and complex dynamics, including human factors, are modeled and tested. Interrelationships among various ITS elements will determine the ultimate direction and degree of impacts. In addition, impacts will vary among regions with different traffic patterns and system use.

Overall, integration of individual ITS components can be expected to multiply benefits by providing the traveling public with a wider array of choices and real-time information. Key dimensions to a comprehensive ITS include:

- Information across key ITS elements such as public transit management, freeway management, emergency and incident response, and traffic signal control;
- Information across regions, such as coordination among jurisdictions to ensure smoother traffic flow;
- Public transit management systems across regions to assure integrated user services; and
- Incident management information across regions to provide the fastest possible response (US EPA, 1998).

Ultimately, the integrated ITS vision should provide operational efficiencies and inter-jurisdictional coordination benefits that result in comprehensive and improved system management. The magnitude of these benefits will depend on factors, such as market acceptance of available technologies to deliver information, user-perceived accuracy of the information provided, and level of personalized traveler information. Not surprisingly, the greatest travel time and energy benefits will come from traveler information persuading users to take public transportation or postpone their trip until congestion has cleared.

VI. BIBLIOGRAPHY

Bandeira, J., Almeida, T. G., Khattak, A. J., Rouphail, N. M. and Coelho, M. C. (2013).

Generating emissions information for route selection: experimental monitoring and route characterization. *Journal of Intelligent Transportation Systems: Technology, Planning, and Operations* **17**(1), 3-17.

Barth, M. and Boriboonsomsin, K. (2009). Energy and emissions impacts of a freeway-based dynamic eco-driving system. *Transportation Research, Part D* **14**(6), 400-410.

Bayless, S. H. and Neelakantan, R. (2012). Smart parking and the connected consumer: opportunities for facility operators and municipalities. *ITS Research*. Intelligent Transportation Society of America. Washington, D.C., December 2012.

Boriboonsomsin, K., Barth, M., Zhu, W. and Vu, A. (2012). Eco-routing navigation system based on multisource historical and real-time traffic information. *IEEE Transactions on Intelligent Transportation Systems* **13**(4), 1694-1704.

Cambridge Systematics, Inc. (2009). *Moving cooler: an analysis of transportation strategies for reducing greenhouse gas emissions*. Washington, D.C.: Urban Land Institute.

Caminiti, L., Cunningham, D. and Lovell, J. (2010). Fuel economy benefit of traffic signal to vehicle communication system. In: ITS America (eds.) *17th ITS World Congress, Busan, 2010: Proceedings*. Busan, South Korea: Intelligent Transportation Society of America.

Dulac, John (2012). Global Energy Outlook to 2050: Targets and scenarios for a low-carbon transport sector. International Energy Agency.

Global BRT Data (2013). <http://www.brtdata.org/>. Change Log Version 1.20, April 25, 2013. Accessed on May 5, 2013.

Gonder, J., Earleywine, M. and Sparks, W. (2012). Analyzing vehicle fuel saving opportunities through intelligent driver feedback. In: SAE International (eds.) *2012 SAE World Congress*. Detroit, Michigan: SAE International.

Guo, L., Huang, S. and Sadek, A. W. (2013). An evaluation of environmental benefits of time-dependent green routing in the Greater Buffalo-Niagara Region. *Journal of Intelligent Transportation Systems: Technology, Planning, and Operations* **17**(1), 18-30.

Help Inc. (2013). *Calculate your savings*. Prepass.
<http://www.prepass.com/services/prepass/Pages/CalculateYourSavings.aspx>. Accessed May 6, 2013.

Hossain, M. and Kennedy, S. (2008). Estimating energy savings from bus improvement options in urban corridors. *Journal of Public Transportation* **11**(3), 19-40.

ITS America (2002). *Delivering the future of transportation. The national intelligent transportation systems program plan: a ten-year vision*. Intelligent Transportation Society of America. <http://www.itsa.org>. Accessed February 18, 2003.

International Energy Agency (2015). *2015 Key world energy statistics*. International Energy Agency. www.iea.org

Martin, E. and Shaheen, S. (2011). Greenhouse gas emission impacts of carsharing in North America. *IEEE Transactions on Intelligent Transportation Systems* **12**(4), 1074-1086.

Martin, E. W., Boriboonsomsin, K., Chan, N. D., Williams, N., Shaheen, S. A. and Barth, M. (2013). Dynamic ecodriving in Northern California: a study of survey and vehicle operations data from an ecodriving feedback device. In: Transportation Research Board (eds.) *Transportation Research Board 92nd Annual Meeting*. Washington, D.C.: Transportation Research Board.

Rayle, L., Dai, D., N. Chan, R. Cervero, and S. Shaheen (2016). “Just A Better Taxi? A Survey-Based Comparison of Taxis, Transit, and Ridesourcing Services in San Francisco,” *Transport Policy*, Volume 45, pp. 168-178.

RITA (2013). *The National ITS Architecture 7.0*. Research and Innovative Technology Administration, U.S. Department of Transportation. <http://itsarch.iteris.com/itsarch/index.htm>.

Persad, K., Walton, C. M. and Hussain, S. (2007). *Toll collection technology and best practices*. Center for Transportation Research, The University of Texas, Austin.

Saffarzadeh, M. and Rezaee-Arjroody, A. (2006). Cost-benefit analysis of electronic toll collection (ETC) system in Iranian freeways (case study: Tehran-QOM freeway). In: *PIARC International Seminar on Intelligent Transport Systems (ITS) In Road Network Operations*. Kuala Lumpur, Malaysia: PIARC.

Shaheen, S., E. Martin, N. Chan, A. Cohen, and M. Pogodzinski (2014). *Public Bikesharing in North America During A Period of Rapid Expansion: Understanding Business Models, Industry Rends and User Impacts.*” MTI 12-29. San Jose, CA, Mineta Transportation Institute.

Shaheen, S., Martin, E., Cohen, A. and Finson, R. (2012). *Public bikesharing in North America: early operator and user understanding*. MTI-11-26. San Jose, CA: Mineta Transportation Institute.

Shaheen, S. and Cohen, A. (2013). Carsharing and personal vehicle services: worldwide market developments and emerging trends. *International Journal of Sustainable Transportation* 7(1), 5-34.

Shaheen, S., Cohen, A. and Martin, E. (2013). Public bikesharing in North America: early operator understanding and emerging trends. *Transportation Research Record: Journal of the Transportation Research Board*. Forthcoming.

Sharma, S. and Mishra, S. (2013). Intelligent transportation systems-enabled optimal emission pricing models for reducing carbon footprints in a bimodal network. *Journal of Intelligent Transportation Systems: Technology, Planning, and Operations* **17**(1), 54-64.

Tsugawa, S., Kato, S. and Aoki, K. (2011). An automated truck platoon for energy saving. In: Institute of Electrical and Electronic Engineers (eds.) *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems*. San Francisco, CA: Institute of Electrical and Electronic Engineers.

Tupper, L. L., Chowdhury, M. A., Klotz, L. and Fries, R. N. (2012). Measuring sustainability: how traffic incident management through intelligent transportation systems has greater energy and environmental benefits than common construction-phase strategies for “green” roadways. *International Journal of Sustainable Transportation* **6**(5), 282-297.

USDOT (2013) Applications for the Environment: Real-Time Information Synthesis (AERIS). *Eco-Approach and Departure at Signalized Intersections: Preliminary Modeling Results*. Fall/Winter Webinar Series. November 20, 2013.

USDOT (2014a) Applications for the Environment: Real-Time Information Synthesis (AERIS). *Eco-Traffic Signal Timing Application: Preliminary Modeling Results*. Fall/Winter Webinar Series. January 29, 2014.

USDOT (2014b) Applications for the Environment: Real-Time Information Synthesis (AERIS).

Eco-Lanes: Preliminary Modeling Results. Summer Webinar Series. July 23, 2014.

USDOT (2014c) Applications for the Environment: Real-Time Information Synthesis (AERIS).

Low Emission Zones: Simulation of Behavioral Impacts. September 24, 2014.

USDOT (2016) Applications for the Environment: Real-Time Information Synthesis (AERIS).

http://www.its.dot.gov/aeris/aeris_progress.htm. Accessed January 13, 2016.

USDOT (2001). Benefit: The E-ZPass electronic toll collection system on the New Jersey

Turnpike reduced delay for all vehicles by 85 percent saving an estimated 1.2 million gallons of fuel each year and eliminating approximately 0.35 tons of VOC and 0.056 tons NO_x per weekday. Intelligent Transportation Systems Joint Program Office, U.S. Department of Transportation.

<http://www.itscosts.its.dot.gov/ITS/benecost.nsf/0/78B2ACEBB79ED67785256AC0006E29ED?OpenDocument&Query=Home>. Accessed April 15, 2013.

USDOT (2014). *ITS 2015-2019 Strategic Plan*. FHWA-JPO-14-145. Intelligent Transportation systems (ITS) Joint Program Office (JPO).

USDOT (2013). *Intelligent transportation systems (ITS) program overview*. FHWA-JPO-11-036, Intelligent Transportation Systems Joint Program Office, Research and Innovative Technology

Administration, U.S. Department of Transportation.

http://www.its.dot.gov/its_program/its_factsheets.htm. Accessed May 7, 2013.

USDOT (2007a). *Intelligent transportation systems for traffic incident management*. U.S.

Department of Transportation. <http://ntl.bts.gov/lib/jpodocs/brochure/14288.htm>. Accessed May 7, 2013.

USDOT (2007b). *Intelligent transportation systems for traffic signal control*. U.S. Department of

Transportation. http://ntl.bts.gov/lib/jpodocs/brochure/14321_files/a1019-tsc_digital_n3.pdf.

Accessed May 7, 2013.

USDOT (2016). *National ITS Architecture News*.

<http://www.iteris.com/itsarch/html/news/news.htm#04-2015>. Accessed January 13, 2016.

U.S. EPA (1998). *Assessing the emissions and fuel consumption impacts of intelligent transportation systems (ITS)*. EPA 231-R-98-007. Washington, D.C.: U.S. Environmental Protection Agency.

Victoria Transport Policy Institute (2012). *Bus rapid transit*. TDM Encyclopedia, Victoria

Transport Policy Institute. <http://www.vtpi.org/tdm/tdm120.htm>. Accessed May 7, 2013.

World Energy Council (2011). *Global transport scenarios 2050*. London: World Energy Council.

Xia, H., Boriboonsomsin, K. and Barth, M. (2013). Dynamic eco-driving for signalized arterial corridors and its indirect network-wide energy/emissions benefits. *Journal of Intelligent Transportation Systems: Technology, Planning, and Operations* **17**(1), 31-41.

Yao, E. and Song, Y. (2013). Study on eco-routing planning algorithm and environmental impact assessment. *Journal of Intelligent Transportation Systems: Technology, Planning, and Operations* **17**(1), 42-53.

Table 1: ITS User Services

User Services Bundle	User Services
Travel and Traffic Management	<ul style="list-style-type: none"> • Pre-tip Travel Information • En-route Driver Information • Route Guidance • Ride Matching and Reservation • Traveler Services Information • Traffic Control • Incident Management • Travel Demand Management • Emissions Testing and Mitigation • Highway Rail Intersections
Public Transportation Management	<ul style="list-style-type: none"> • Public Transportation Management • En-route Transit Information • Personalized Public Transit • Public Travel Security
Electronic Payment	<ul style="list-style-type: none"> • Electronic Payment Services
Commercial Vehicle Operations	<ul style="list-style-type: none"> • Commercial Vehicle Electronic Clearance • Automated Roadside Safety Inspection • On-board Safety and Security Monitoring • Commercial Vehicle Administration Processes • Hazardous Material Security and Incident Response • Freight Mobility
Emergency Management	<ul style="list-style-type: none"> • Emergency Notification and Personal Security • Emergency Vehicle Management • Disaster Response and Evacuation
Advanced Vehicle Safety Systems	<ul style="list-style-type: none"> • Longitudinal Collision Avoidance • Lateral Collision Avoidance • Intersection Collision Avoidance • Vision Enhancement for Crash Avoidance • Safety Readiness • Pre-crash Restraint Deployment • Automated Vehicle Operation
Information Management	<ul style="list-style-type: none"> • Archived Data Function
Maintenance and Construction Management	<ul style="list-style-type: none"> • Maintenance and Construction Operations

From Iteris, Inc. and U.S. DOT, *Key Concepts of the National ITS Architecture*. The National ITS Architecture Version 7.0. <http://itsarch.iteris.com/itsarch/index.htm>

Table 2: Predicted ITS Technology Impacts

ITS Technology	Predicted Impacts
Traffic Signal Control Traffic control technologies include traffic surveillance, ramp metering, lane control systems, and traffic signals.	<ul style="list-style-type: none"> • Reduced stop/idle delay times for vehicles traveling on main lanes and at intersections; • Better response to incidents and special events; • Some mode shifts to/from transit; and • Reduced bus roundtrip travel time, implying increased speed.
Traffic Management and Surveillance ITS-based traffic management approaches include incident management, ramp metering, traffic signal control, traveler information, and traffic surveillance.	<ul style="list-style-type: none"> • Improved freeway travel flow due to ramp metering; • Increased ramp travel times; • Changes in acceleration (increased emissions); • Dynamic changes in freeway exit-points due to changeable message signs, thus increasing freeway speeds; • Increases in high occupancy vehicle (HOV) travel resulting from HOV bypass to ramp metering; • Increased travel times on arterials due to spillage of vehicles waiting to get on freeways; and • Better use of existing freeway capacity as a result of lane control improvements.
Incident Management Incident management consist of three key areas: traffic surveillance (incident detection and verification), clearance, and traveler information. In addition, this area includes emergency management services.	<ul style="list-style-type: none"> • Reduced incident response times; • Increased travel reliability; • Reduced delays, especially those due to incidents on highways and freeways (e.g., lane closures); • Fewer secondary incidents caused by initial incidents; and • Dynamic changes in destination, mode, and/or route choice.
Electronic Toll Collection (ETC) ETC technologies enable the instant payment of highway tolls when a vehicle passes through a toll station via an electronic roadside antenna (or reader) and a pocket-sized tag containing a radio transponder.	<ul style="list-style-type: none"> • Increase in toll lane capacity; and • Fuel savings and a decrease in mobile emissions by reducing or eliminating waiting times.
Driver Information and Behavior (e.g., Ecodriving and Eco-routing)	<ul style="list-style-type: none"> • Improved vehicle efficiency due to feedback to the driver • Gentler acceleration and braking • Reduced energy consumption • Potential for longer travel times
Traveler Information and Network Behavior Traveler information systems serve two primary functions, providing 1) information about transportation services and performance of the system to users, and 2) an information linkage among various ITS components.	<ul style="list-style-type: none"> • Increased shifts in mode, destination, time of trip, and route choice over time.

Smart Parking Management	<ul style="list-style-type: none"> • Reduced time to find parking • Reduced congestion • Electronic payment methods
Public Transit Management Transit management consists of four key areas: 1) transit vehicle tracking, 2) fare payment, 3) traveler information, and 4) personalized public transportation alternatives.	<ul style="list-style-type: none"> • Decreased boarding and alighting times; • Increased transit system reliability; • Improved transit fleet utilization; • Improved coordination between transit services, such as bus and rail transfers, promoting overall transit usage; and • Increased opportunity to provide more demand-responsive transit services (e.g., modal shifts).
Commercial Vehicle Operations CVO approaches include border crossing clearance and safety via electronic clearance and manifesting; automatic vehicle location; vehicle-to-fleet management center communications; on-board safety diagnostics to enable more effective roadside safety inspections; and hazardous materials incident response.	<ul style="list-style-type: none"> • Electronic clearance, safety, credentialing, and administrative processing save time by automating traditionally manual screening and inspection procedures; • Due to vehicle location technologies, emergency response teams can more easily locate and respond to HazMat accidents; • Reduced waiting times at international borders due to electronic clearance (inspectors can focus on non-compliant vehicles); and • Onboard safety monitoring automatically alerts drivers of deficiencies in their vehicle's performance, thus ensuring greater roadway maintenance and safety.
Vehicle Control Technologies Advanced sensing, communication, and computing technologies represent the range of ITS technologies that can help to avoid collisions, prevent or lessen injuries when crashes do occur, and ultimately lead to full vehicle automation. Some existing vehicle control technologies include adaptive cruise control, anti-lock brakes, and electronic system malfunction indicators.	<ul style="list-style-type: none"> • Reduce accidents resulting from unsafe headway, driver inattention, and errors in recognition and judgment; • Reduce antisocial driving behavior, such as road rage; • Increased freeway capacity due to more closely spaced vehicle platoons; and • Reduced fuel consumption and emissions due to traffic flow smoothing and vehicle platooning.
Shared Mobility (Carsharing, Bikesharing, Ridesharing, and For-Hire Vehicle Services)	<ul style="list-style-type: none"> • Removes 9 to 13 vehicles per carsharing vehicle • Reduces mileage per year on average of 27% (observed impact, based on vehicles sold) and 56% (full impact, based on vehicles sold and postponed purchases combined) due to carsharing • 34% to 41% reduce GHG emissions on average per household due to carsharing • Approximately 25% of respondents sold a vehicle and roughly another 25% of the total sample would have considered obtaining a vehicle, if carsharing disappeared • 5.5% of members sold or postponed a vehicle purchase due to public bikesharing • 58% of members increased their cycling due to bikesharing

	<ul style="list-style-type: none">• 50% of members reduced their personal auto use due to bikesharing
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