REDUCING GREENHOUSE EMISSIONS AND FUEL CONSUMPTION

– Sustainable Approaches for Surface Transportation –

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Climate change is rapidly becoming known as a tangible issue that must be addressed to avoid major environmental consequences in the future. Recent change in public opinion has been caused by the physical signs of climate change–melting glaciers, rising sea levels, more severe storm and drought events, and hotter average global temperatures annually. Transportation is a major contributor of carbon dioxide (CO_2) and other greenhouse gas emissions from human activity, accounting for approximately 14 percent of total anthropogenic emissions globally and about 27 percent in the U.S.

Fortunately, transportation technologies and strategies are emerging that can help to meet the climate challenge. These include automotive and fuel technologies, intelligent transportation systems (ITS), and mobility management strategies that can reduce the demand for private vehicles. While the climate change benefits of innovative engine and vehicle technologies are relatively well understood, there are fewer studies available on the energy and emission impacts of ITS and mobility management strategies. In the future, ITS and mobility management will likely play a greater role in reducing fuel consumption. Studies are often based on simulation models, scenario analysis, and limited deployment experience. Thus, more research is needed to quantify potential impacts. Of the nine ITS technologies examined, traffic signal control, electronic toll collection, bus rapid transit, and traveler information have been deployed more widely and demonstrated positive impacts (but often on a limited basis). Mobility management approaches that have established the greatest CO_2 reduction potential, to date, include road pricing policies (congestion and cordon) and carsharing (short-term auto access). Other approaches have also indicated CO_2 reduction potential including: low-speed modes, integrated regional smart cards, park-and-ride facilities, parking cash out, smart growth, telecommuting, and carpooling.

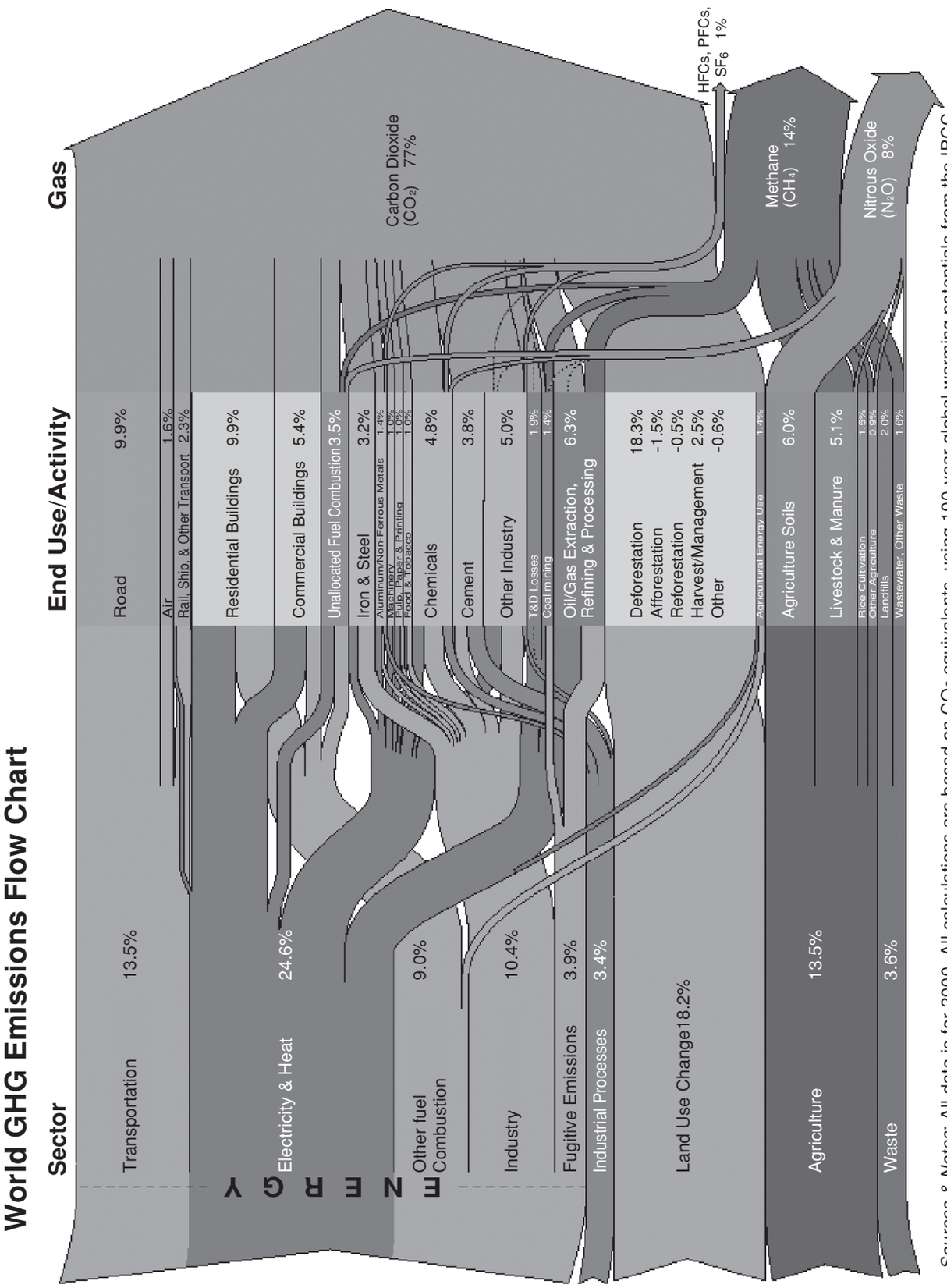
Key Words: Greenhouse gas emissions, Carbon dioxide, Vehicle technology, Alternative fuels, Intelligent transportation systems, Mobility management

1. INTRODUCTION

The use of energy accounts for a major fraction of all anthropogenic emissions of greenhouse gases (GHGs), and in most industrialized countries transportation fuel use produces a major fraction of all energy-related emissions. In the U.S., for example, emissions of GHGs from transportation accounts for over 27 percent of anthropogenic GHG emissions, while globally, transportation contributes approximately 14 percent of GHG emissions[1]. Figure 1 shows the various sources of global GHG emissions from human activity and which specific GHGs are ultimately emitted.

Furthermore, transportation sector emissions are expected to increase rapidly over the next few decades. The International Energy Agency (IEA) projects that energy use and CO_2 emissions in developed countries will rise by approximately 50 percent between 2000 and 2030. Emissions in developing countries are expected to rise even faster, in some cases (such as in China and Indonesia) more than doubling between 2000 and 2020[2]. These increases are due to a combination of increases in personal travel and goods movement, coupled with continued heavy reliance on fossil fuels for transportation energy.

Worldwide personal transportation is expected to increase 1.7 percent annually from 2000 to 2050, while worldwide freight transportation is expected to increase by 2.3 percent annually during the same timeframe. Worsening this issue, transit modal share has decreased due to lower density land use and the greater convenience of private vehicles[3]. Given these trends, solutions are needed to reduce emissions and energy consumption from the transportation sector, now widely believed to be



Sources & Notes: All data is for 2000. All calculations are based on CO_2 equivalents, using 100-year global warming potentials from the IPCC (1996), based on a total global estimate of 41,755 MtCO_2 equivalent.

Fig. 1 Flow chart of global GHG emissions by sector and end use activity

contributing to climate change.

The production and use of fuels for transportation also results in emissions of other important GHGs besides CO_2, including methane (CH_4) and nitrous oxide (N_2O). These emissions can be significant, especially for some types of vehicles and fuels. Furthermore, other aspects of transportation, such as the use of refrigerants for automotive air conditioners, also cause significant releases of GHGs. While smaller in quantity, these emissions are important because of the relatively high "global warming potential" values of these gases (i.e., on a 100-year assessment basis a CH_4 molecule has about 23 times the effect of a CO_2 molecule, and an N_2O molecule has about 296 times the effect of a CO_2 molecule[4]). For conventional vehicles, these non-CO_2 GHG emissions can contribute approximately a quarter of the value of overall vehicle emissions, but for alternative fuel vehicles the contribution can be much higher or lower, in the range of 1 to 57 percent[5].

In light of the importance of the transportation sector as an emitter of GHGs, and in the face of growing concern about climate change, analysts have been evaluating long-term transportation and energy policies for their potential impact on global climate change. This paper provides an overview of transportation GHG emissions and a range of emerging technologies that could help to reduce negative transportation sector impacts and ultimately contribute to climate stabilization. These technology approaches include: 1) engine technology and fuels, 2) intelligent transportation systems (ITS), and 3) mobility management. The authors review each of these areas and their GHG reduction potential, as possible. It is important to note that the ITS and mobility management sections are based on limited study, deployment experience, and overall understanding.

There are five main sections to this article. First, the authors provide a background discussion on global climate change and climate change policies since the early 1990s. Next, engine technologies and fuels are described as a key supply-side strategy to reducing GHG emissions and fuel consumption. Third, nine ITS technologies are explored (consisting of a mix of supply and demand management approaches). In the following section, nine mobility management strategies (demand-side approaches aimed at changing behavior) are presented. They range from more traditional approaches, such as carpooling and park-and-ride facilities, to more innovative policy and technology solutions including: road pricing policies, telecommuting, and smart cards. Finally, the authors present conclusions.

2. BACKGROUND

Global emissions of CO_2 and other GHGs have been steadily increasing with population growth and development. The Intergovernmental Panel on Climate Change (IPCC) has examined the potential global temperature impacts of future GHG emissions scenarios, including those with unabated emissions and those where atmospheric concentrations of CO_2 are stabilized at 450 and 550 parts per million (ppm) (compared with an actual level of 383 ppm at the start of 2007). As shown in Figure 2, stabilizing atmospheric concentrations at 450 ppm implies a mean temperature change of 1-2 °C by 2100, while stabilizing CO_2 concentrations at 550 ppm implies a 1.5-3 °C increase. Meanwhile, the unabated "Special Report on Emissions Scenarios (SRES)" high emissions case results in a mean temperature increase of over 5 °C by 2100[4].

Over the past few years, dramatic weather events such as hurricanes and droughts along with the alarming breakup of polar ice sheets have many scientists and members of the general public concerned about the potential impacts of climate change. Potential effects include rising ocean levels, more severe tropical storms and hurricanes, more pronounced heat waves, droughts, and wildfires, and a wide range of other potential impacts on humans and wildlife in environments that are likely to feel the strongest effects (e.g., arctic/polar regions, deserts/drought prone areas, etc.).

Concern about the steady increase in global GHG emissions has been most directly addressed at the international level, through the efforts of the IPCC and the United Nations Framework Convention on Climate Change (UNFCCC). A specific set of GHG emission reduction goals, known now as the "Kyoto Protocol," was

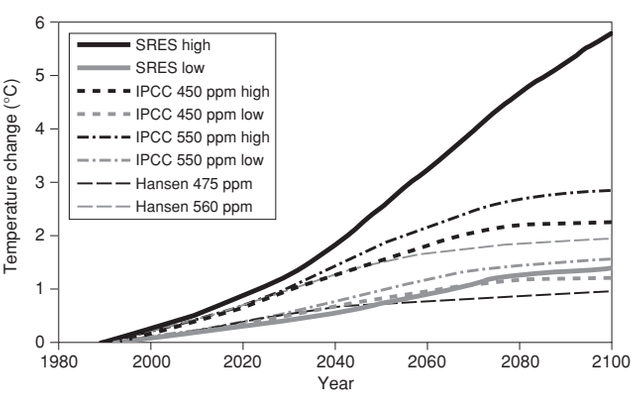


Fig. 2 IPCC mean average global temperature rise predictions by emissions scenario (°C)[4]

established during the UNFCCC 3rd "Council of the Parties" (or "COP-3") meeting of the United Nations on climate change in Kyoto, Japan, in December 1997. The protocol has now been ratified by 168 countries, but notably not by the U.S. or Australia, which together account for over 22 percent of global emissions[1]. If ratified, the agreement would have the U.S. reduce GHG emissions by seven percent, relative to 1990 levels, between 2008 and 2012, compared with an average for all nations of a five percent reduction below 1990 levels. The COP meetings have continued steadily since Kyoto to advance international progress in reducing GHG emissions, with the latest meeting being the COP-12 conference in Nairobi, Kenya in Fall 2006[6].

The IPCC has made increasingly firmer statements over the past two decades about its certainty with regard to the effects of the large magnitude of GHG emissions that are emitted each year around the globe from human activity.

In 1990, the IPCC said:

"The unequivocal detection of the enhanced greenhouse effect from observations is not likely for a decade or more"[7].

Then, five years later, the IPCC stated that:

"The balance of evidence suggests a discernable human influence on global climate"[8].

Six years later, in 2001, the IPCC took an even stronger stance with its statement that:

"There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities[4].

Most recently, in early 2007, the IPCC made its strongest statement yet on the likelihood of human-induced climate change:

"Most of the observed increases in globally averaged temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations"[9].

Recently, the "Stern Review on the Economics of Climate Change" conducted by the treasury of the U.K. concluded that the likely future economic impacts of climate change are far greater than the cost of stabilizing emissions. The report estimates that the costs of stabilizing atmospheric CO_2 concentrations at around 550 ppm would be about one percent of global gross domestic product by 2050. Meanwhile the report estimates that the economic cost of a "business as usual" scenario of continued increases in emissions could be as high as the value of reducing global consumption by five to 20 percent. The report concludes that the costs of taking action are potentially much lower than those of inaction and that immediate steps are needed to have a chance of restraining CO_2 concentrations to the 550-ppm level[10].

While mandatory actions to reduce GHG emissions in the U.S. have been lacking at the national level, U.S. state-level activities have progressed significantly over the past few years. California has recently taken an aggressive policy stance to limit GHG emissions, and several other states are pursuing similar courses, particularly in the Northeast with the Regional Greenhouse Gas Initiative (RGGI). Currently, Connecticut, Delaware, Maine, New Hampshire, New Jersey, New York, and Vermont are participating in the RGGI effort, which is targeted at developing a cap-and-trade program for CO_2 emissions from the electrical power sector[11].

The most dramatic policy measure at the U.S. state level has been the passage of the California Global Warming Solutions Act (Assembly Bill (AB) 32), which seeks to limit GHG emissions from a wide range of industrial and commercial activities. AB 32 requires that California's GHG emissions be reduced to 1990 levels by 2020 through an enforceable statewide cap and in a manner that is phased in starting in 2012 under rules to be developed by the California Air Resources Board (CARB).

AB 32 requires that CARB use the following principles to implement the California GHG emissions cap:

- Distribute benefits and costs equitably;
- Ensure that there are no direct, indirect, or cumulative increases in air pollution in local communities;
- Protect entities that have reduced their emissions through actions prior to this regulatory mandate; and
- Allow for coordination with other states and countries to reduce emissions.

CARB is required to adopt the formal AB 32 regulations by January 1, 2008, and to produce a plan for achieving the targeted emission reductions, through market mechanisms and other actions, by January 1, 2009[12]. The expectation is generally for a plan that includes a market-based emission credit-trading scheme under the statewide cap, marking the first serious effort to address climate change at a large scale in the U.S.

Finally, a recent international meeting on greenhouse gases from the transportation sector resulted in the "Asilomar Declaration" as a consensus statement among a high level group of scientists, engineers, and policy

analysts in the transportation and environmental fields. While focused on the U.S., rather than globally, this declaration is strongly worded and instructive for other settings as well. The declaration reads:

> **DECLARATION 1:** It is the consensus of the 10th Biennial Conference on Transportation and Energy Policy that climate change is real. Transportation-related GHG emissions are a major part of this global problem, and they must be reduced.
>
> **DECLARATION 2:** U.S. national policy has so far failed to adequately address the role of transportation in climate change. This must be remedied.
>
> **DECLARATION 3:** By judiciously crafting a portfolio of solutions, it is possible to reduce transportation-related GHG emissions while creating an efficient and effective transportation system for current and future generations.

Various papers presented at the 10th Biennial Conference on Transportation and Energy Policy in relation to the Asilomar Declaration examine aspects of the transportation and climate change nexus and were compiled into a book. These include issues such as potential policy measures to restrain emissions (cap-and-trade, feebates, etc.), transportation finance, vehicle technology and consumer response, and "peak oil" and energy considerations[13].

3. ENGINE TECHNOLOGIES & FUELS

Road transportation, as shown in Table 1, accounts for the majority of transportation-sector GHG emissions. As a result, motor vehicles are often among the first targets of efforts to reduce emissions from the transportation sector.

Table 1 Transportation sector contributions to overall GHG emissions[1]

Transportation Sector	Global	U.S.
Road	9.9%	21.6%
Air	1.6%	3.3%
Rail, Ship, and Other Transportation	2.3%	2.3%
Total Contribution	13.8%	27.2%

A wide range of technologies exists to address GHG emissions from vehicles, with some being commercially available and others still under development. Efforts to address GHG emissions through the introduction of new vehicles can be highly effective in the long term, but they are somewhat slow due to the nature of motor vehicle fleet turnover and the penetration of new vehicles into the overall vehicle fleet. Some new vehicle technologies also suffer from limited refueling infrastructure (e.g., biofuels and hydrogen) and others suffer from other important limitations (e.g., short driving range and long refueling time for battery electric vehicles). These intricacies make the introduction of new vehicle and fuel types complex, as this involves a combination of technological, economic, social, and political factors.

The most straightforward way to reduce GHGs from motor vehicles is to simply mandate greater vehicle fuel economy. This translates more or less directly into reduced CO_2 emissions, but may or may not significantly affect emissions of other GHGs such as CH_4, N_2O, and refrigerants. In the U.S., Corporate Average Fuel Economy (CAFE) standards have been constant since the mid-1980s, despite considerable technological progress over the past twenty years. Standards for light trucks have been increased slightly in recent years. Other nations and regions, such as the European Union, Japan, and China, also have vehicle fuel economy standards that are currently somewhat more stringent than those in the U.S. In the U.S., the shift toward purchases of light trucks and sport-utility vehicles has resulted in an actual decrease in on-road vehicle fuel economy, from a peak of 26.2 miles per gallon on average in 1987 to 24.6 miles per gallon in 2004[14].

With regard to the introduction of new fuel and vehicle types, GHG emissions can be addressed through the introduction of new fuels (e.g., electricity, biofuels, hydrogen, etc.), different "end-use" technologies (e.g., better or different "prime mover" engines and motors, energy storage systems, etc.), or a combination of both fuel and vehicle changes. For example, more efficient hybrid vehicles can be developed that burn gasoline, but the vehicles could also be designed to burn a fuel mainly composed of ethanol, biodiesel, natural gas, or hydrogen.

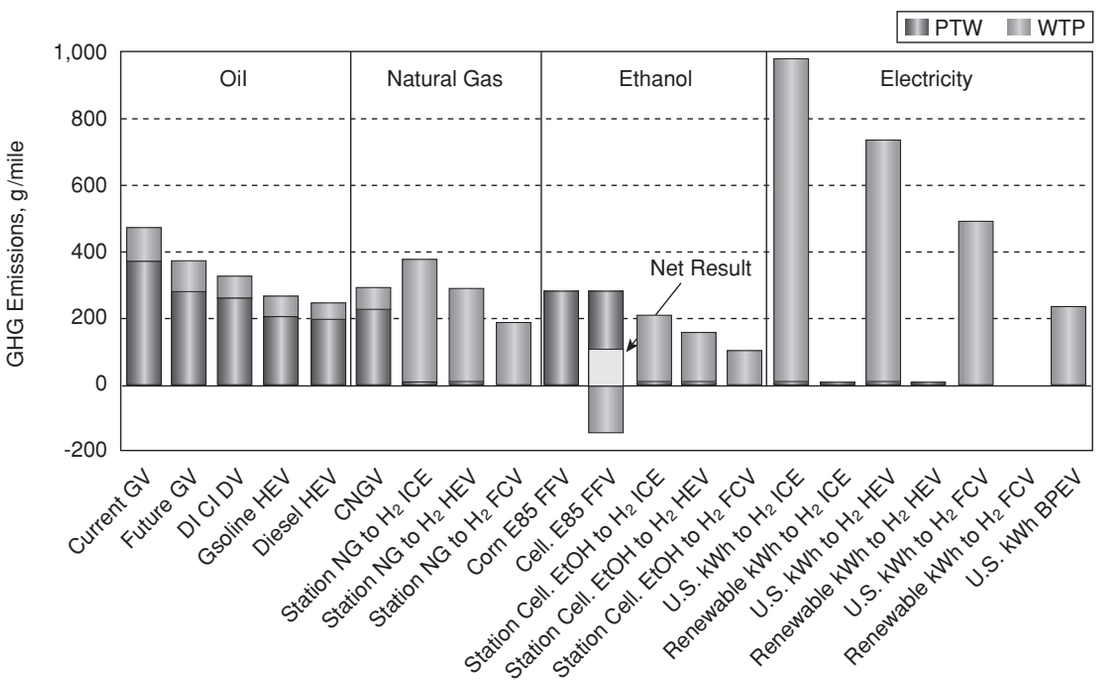
Methods of producing some new types of transportation fuels (especially electricity and hydrogen) at large central plants have the potential of being able in principle to separate out and "sequester" the CO_2 emissions, though the cost and feasibility of this is still being proven. Some fuels can also be produced in a more decentralized fashion, such as small-scale production of hydrogen through steam methane reforming; however, these CO_2 emissions would be harder to capture and remove.

The primary types of vehicle technologies currently being explored include:

- Combustion engine (typically Otto, Diesel, or Atkinson-cycle) vehicles running on gasoline, diesel, bio-diesel, ethanol, methanol, compressed natural gas, liquefied propane gas, or hydrogen (or some blend of these fuels);
- Electric-drive vehicles, powered by batteries, ultracapacitors, fuel cells, or a combination of power sources;
- Hybrid gasoline-electric vehicles that combine both of the above, with a wide range of potential ratios between the combustion engine and electric drive; and
- Other "kinetic" storage/propulsion systems, such as those based on compressed air or mechanical flywheels.

Figure 3 shows the expected GHG emissions from 19 different vehicle type and fuel combinations, compared with current and future gasoline vehicles. These estimates are based on the "Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation" (GREET) model developed at Argonne National Laboratory[15]. Other full fuel cycle GHG emission models, such as the UC Davis "Lifecycle Emissions Model," typically show similar results, but with some differences due to differing input assumptions that can then get magnified as total emissions are calculated through the fuel-chain analysis[16].

As shown in this figure, the GREET model estimates that conventional gasoline vehicles produce about



Notes

BPEV : battery-powered electric vehicle
CNGV : compressed natural gas vehicle
DI CI DV : direct-injection compression-ignition diesel vehicle
E85 : a mixture of 85% ethanol and 15% gasoline (by volume)
FCV : fuel-cell vehicle
FFV : flexible fuel vehicle
GV : gasoline vehicle
HEV : hybrid electric vehicle
ICE : internal combustion engine
NG : natural gas
PTW : pump-to-wheels
WTW : well-to-wheels
WTP : well-to-pump

Fig. 3 GREET model GHG emissions estimates for conventional and alternative fuel light-duty vehicles (grams/mile)[15]

440 grams per mile on a full fuel cycle (or "well-to-wheel") basis. Technological options exist to almost eliminate these emissions, through the use of renewable energy to produce electricity or hydrogen. However, these renewable fuel pathways are at present relatively expensive for both vehicles and fuels (with the exception of wind generated electricity in some areas) and include other barriers, such as limits on vehicle driving range and (for electricity) refueling time.

Incremental vehicle technology options, such as operating on diesel fuel or "hybridizing" the combustion engine with an electric motor and battery system, can reduce GHG emissions to 220 to 300 grams per mile or to about 57 to 65 percent of the emission levels expected from future gasoline vehicles. Compressed natural gas (CNG) vehicles offer similar emission reductions to about 300 grams per mile.

Vehicles operating on ethanol (with 85 percent ethanol mixed with 15 percent gasoline) produce similar GHG emission levels as CNG vehicles and diesel vehicles or about 300 grams per mile. However, if the ethanol can be made from "cellulosic" rather than corn-based sources, emissions can be dramatically reduced to about 100 grams per mile.

Hydrogen-powered vehicles can either burn the hydrogen directly in a combustion engine or convert it to electricity using a fuel cell system to drive an electric motor. Emissions from these vehicles can vary dramatically depending on how the hydrogen is produced. On one hand, as noted above, emissions can be nearly eliminated if the hydrogen is produced from renewable sources of electricity and the electrolysis process of splitting water molecules. Using cellulosic ethanol to produce hydrogen reduces emissions to 100 to 150 grams per mile or similar levels as burning ethanol. However, if instead of renewable electricity, hydrogen is made through electrolysis using the current mix of generating sources for the U.S. power grid, GHGs are significantly increased to about 500 grams per mile (fuel cell vehicle), 750 grams per mile (hydrogen combustion hybrid), or even 980 grams per mile (hydrogen combustion without hybrid).

Finally, vehicles running directly on electricity with batteries also have emissions that vary greatly with how the electricity is produced. Emissions can range from near zero, again with renewable electricity, to about 240 grams per mile with a typical U.S. power grid fuel mix.

3.1 Summary

In summary, both incremental and revolutionary options are possible for reducing the GHG emissions impacts from motor vehicles. Incremental approaches are estimated to be capable of reducing emissions by up to about 25 percent over a several year period[2]. More dramatic and revolutionary options, such as powering electric vehicles from solar or wind power or converting that electricity to hydrogen to power fuel cell vehicles, could essentially eliminate GHG emissions from the full vehicle fuel cycle. However, there are major barriers to such a dramatic transition, including economic, technical, and consumer acceptance obstacles. To address the transportation energy and climate change challenge, both near-term options–with more modest impacts but with a high chance of success–and longer-term but more dramatic options should be considered. Based on the resource base, land form, and demographic and socioeconomic conditions in a given setting, options for introducing new fuels and vehicle technologies can be selected that are the most effective and likely to be adopted.

4. INTELLIGENT TRANSPORTATION SYSTEMS

Intelligent transportation system (ITS) technologies include state-of-the art wireless, electronic, and automated technologies. Collectively, these systems have the potential to integrate vehicles (transit, trucks, and personal vehicles); system users; and infrastructure (roads and transit). Automated and in-vehicle technologies include precision docking for buses, automated guideways, and collision avoidance systems. When ITS is applied to highway and transit system management and vehicle design, it can reduce fuel consumption and emissions by:

- Facilitating optimal route planning and timing;
- Smoothing accelerations/decelerations and stop-and-go driving;
- Reducing congestion;
- Enabling pricing and demand management strategies;
- Increasing attractiveness of public transportation mode use;
- Adjusting vehicle transmission for varying road conditions and terrain; and
- Facilitating small platoons of closely spaced vehicles (i.e., safer vehicles could enable weight reduction without compromising occupant safety).

While ITS technologies are still in the early phases of deployment, many have the potential to reduce energy use and CO_2 emissions. During the last decade, fuel consumption (and to a lesser extent CO_2) impacts of a wide range ITS technologies have been considered including: 1) traffic signal control, 2) ramp metering, 3) automated

Table 2 ITS strategies associated with reduced fuel use and CO_2 emissions

ITS Area	Definition
Traffic signal control	Traffic signal controls can integrate freeway and surface street systems to improve traffic flow and vehicular and non-motorized traveler safety and provide priority services for transit or high occupancy vehicles. They can 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.
Ramp metering	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.
Automated speed enforcement	Automated speed enforcement (ASE), also known as photo-radar or speed camera enforcement, combines speed-detecting radar and light detection and ranging (LIDAR) units with image capturing technologies, such as film and digital cameras[17]. Photographs of vehicles and/or drivers taken at the time of the violation, along with data from the radar device, are used as evidence in the issuance of citations[18]. ASE programs have been widely applied in Australia, France, Germany, and the U.K. to address speeding-related safety problems[19]. In the U.S., ASE programs are currently operating in only six states and in Washington, D.C., and most of these are located on residential streets and not highways[20].
Incident management	ITS traffic surveillance technologies—such as radar, lasers, and video image processing used to collect information—can help to reduce detection and incident clearance costs. 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 employed can include traffic surveillance, digital and dispatch communications (including route guidance to the site of an incident), and signal priority (optimization of traffic signal timings along routes traveled by emergency vehicles). ITS contributions to incident management include improved surveillance, verification, and dispatch to manage an incident. The use of changeable message signs (CMSs) and personal communication devices, such as mobile phones and personal digital assistants (PDAs), can assist with early notification for upstream drivers resulting in reduced incident-related congestion, as drivers have more time to select an alternate route.
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).
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 CMSs along roadsides or at transit stations. 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 in-vehicle guidance, web sites, mobile phones, PDAs, and CMSs to distribute user information.
Bus rapid transit	Bus rapid transit (BRT) encompasses the use of a series of ITS technologies, route planning, exclusive rights-of-ways, and management to improve service—each of which can reduce travel times. Increases in bus ridership due to BRT implementation have been reported in the U.S., Australia, and Europe. If a mode 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/CO_2 emissions is negative. If additional riders are attracted from another bus route, the impact is neutral.
Weigh-in-motion technologies	The purpose of automatic identification and weigh-in-motion (WIM) technologies is to enable the weighing and cataloging of trucks without causing vehicles to stop and queue in line. A WIM scale imbedded in the pavement triggers a camera when an overweight truck passes over (so that a citation may be issued later). In addition, this can result in fewer trucks being forced to bypass weigh stations due to full queues at static scales.
Vehicle control technologies	ITS technologies that automate vehicle control systems aim to improve vehicle safety, efficiency, and comfort. These technologies include intelligent cruise control, speed alert, collision avoidance, anti-lock brakes, electronic system malfunction indicators, and automated highway systems (e.g., platooned vehicles). 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, called Vehicle Infrastructure Integration (VII). "VII offers the opportunity to know much more about traffic and roadway conditions than ever before. Vehicles equipped with VII technology will be able to anonymously send information that includes travel time and environmental conditions"[21]. In this way, vehicles can operate in very close proximity to each other.

Table 3 ITS energy and CO_2 impacts: a summary of early findings

ITS Strategy	Energy/CO_2 Emission Impacts
Traffic signal control	Overall, traffic signal control studies reveal fuel savings ranging between 1.6 to 50 percent, with most results at less than 20 percent[23-27]. In addition, results from a signalized intersection, using a real-time control strategy, resulted in a "four percent reduction for CO_2 emissions in peak traffic, corresponding to a 14 percent reduction in the part of costs due to stops and delays." These effects are reduced by approximately one half when traffic is fluid[24] (p. 4).
Ramp metering	Emission and fuel consumption impacts of ramp meters 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[28].
Automated speed enforcement	The authors identified only a few estimates of CO_2 reduction due to automated speed enforcement (ASE). Meers and Roth (2001) found that speed cameras saved 400 kilotonnes of CO_2 per year between 1998 and 2000 in Queensland, Australia[29] (as cited in Haworth and Symmons[30]). In addition, an ASE application employed to reduce vehicle accidents and improve traffic flow, particularly stop-and-go traffic, in the Kaisermühlen Tunnel in Austria has been projected to reduce more than 12,000 tons of CO_2 emissions between 2003 and 2013[31].
Incident management	Improved incident management has the potential to decrease fuel consumption by reducing the delay and congestion associated with blocked traffic. While incident delay reductions are limited, model calculations for a Maryland initiative (called CHART) have shown fuel savings of 5.06 million gallons per year[32].
Electronic toll collection	Studies show that electronic toll collection (ETC) saves time and reduces energy consumption and emissions by reducing the stop-and-go traffic associated with vehicle queues approaching toll plazas, stopping to pay a toll, and accelerating to rejoin regular traffic flow[3]. One recent study along the New Jersey Turnpike found savings of 1.2 million gallons of fuel per year due to reduced delays at toll plazas employing ETC. Approximately three-fourths of the reported savings accrued to passenger cars and one-fourth to commercial vehicles[33].
Traveler information	The actual impact of traveler information on fuel consumption and CO_2 emissions depends on a number of factors. For example, if ITS technologies assist drivers with route selection and guidance, benefits will likely be greater the less familiar a driver is with an area. Fuel economy benefits of route guidance systems could reduce non-optimal route driving and save up to 10 percent of miles driven and proportional fuel consumption[34]. The timeliness and delivery of information will also influence the degree to which travelers use it and subsequent energy/CO_2 emission impacts. Benefits might result from mode shifts (e.g., from a single occupancy vehicle to transit or bicycle) and savings proportional to travel time reductions achieved by taking alternate routes.
Bus rapid transit	Bus ridership increases due to bus rapid transit (BRT) implementation in five cities ranged from 18 to 76 percent (Houston, Los Angeles, Adelaide, Brisbane, and Leeds)[35]. 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. Signal priority modeling results indicate a five percent reduction in fuel consumption[36]. Using data from the 2001 National Household Survey and emissions data from the Department of Environmental Protection and the Energy Information Administration, Vincent and Jerram[37] concluded a BRT system, employing 40-foot compressed natural gas buses, provides the greatest decrease in CO_2 emissions when compared to light rail and 40- and 60-foot hybrid diesel BRT buses[37]. The 40-foot CNG buses used in a BRT system exceed light rail CO_2 reductions by approximately 300 percent.
Weigh-in-motion technologies	Simulation modeling and on-road testing reveal increased fuel efficiency due to weigh-in-motion (WIM) technologies[38]. It is important to note, however, that an expert interview with California Air Resources Board (CARB) mobile sources enforcement personnel revealed that WIM technologies that identify gross polluters still require more research and are not very reliable at present. For instance, remote sensing technology used to detect CO_2 emissions is not effective on multi-lane roads or freeways (Denise Allen, unpublished data, August 2006).
Vehicle control technologies	One recent simulation study showed fuel savings ranging from 8.5 to 28.5 percent when 10 percent of vehicles in a lane are equipped with intelligent cruise control[39]. In-vehicle electronics that smooth acceleration/deceleration and anticipate changes in terrain could also reduce fuel consumption[34,40]. Furthermore, simulations of automated highways indicate a five to 15 percent reduction in fuel consumption due to aerodynamic drafting effects[41].

speed enforcement (ASE), 4) incident management, 5) electronic toll collection (ETC), 6) traveler information, 7) bus rapid transit (BRT), 8) commercial vehicle weigh-in-motion (WIM), and 9) vehicle control technologies. Definitions of each of these areas appear in Table 2 (on page 13). This array of ITS technologies is the focus of this section. At present, ITS impacts—including benefits, unintended consequences, and aggregate effects—are still not well understood.

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. The report concluded that it was exceptionally challenging to assess ITS fuel consumption and emission impacts due to the complex relationship among ITS, travel behavior, and transportation system management[22]. In addition, impacts vary among regions that reflect different traffic patterns and system use. While traffic simulation and travel demand models can aid in this understanding, more research is needed[23].

In Table 3 (on page 14), the potential energy and CO_2 impacts of nine ITS strategies are examined. Data presented typically reflect early modeling, field test, and deployment findings. While this analysis spans a wide range of ITS approaches, the literature on the energy and CO_2 impacts of ITS is rather limited. Overall, fuel consumption impacts are more commonly found (and can serve as a proxy for CO_2 emissions). In fact, CO_2 reduction estimates were obtained for just three of the nine ITS approaches examined.

4.1 Summary

Across the nine strategies presented, more studies were found on traffic signal control, BRT, and vehicle control technologies. A large range in fuel saving estimates was reported for traffic signal control, BRT, and intelligent cruise control, reflecting modeled scenarios or the specific deployments evaluated. While ramp metering is widely deployed today, energy and emission impacts are mixed. Several technical and institutional issues must be addressed prior to widespread deployment of ASE, WIM, and vehicle control technologies, such as improving remote sensing technologies for WIM and garnering political support for ASE. Traffic signal control, ramp metering, BRT, and traveler information are more widespread and have demonstrated positive deployment results.

While several of the ITS approaches presented have reduced fuel consumption and CO_2 emissions (electronic tolling, traffic signal control, and signal priority for buses), modeling studies and early deployments are still largely focused on discrete applications rather than on integrated regionwide networks. The full energy and CO_2 effects of ITS cannot be known until multiple strategies are deployed on a large scale and complex interactions, including human factors, can be modeled and tested.

5. MOBILITY MANAGEMENT

This section is focused on mobility management, which encompasses a range of strategies for helping to change driving consciousness and behavior. The total energy and emission reduction potential of this area has typically been more limited due to less availability and demand for such alternatives. It has been suggested that a national GHG reduction strategy should consider investment in a range of innovative mobility approaches, such as transit, ridesharing, park-and-ride facilities, bicycling, etc.[42]. Nevertheless, it is important to note that some mobility management strategies, if more widely adopted, such as telecommuting, could potentially encourage more tripmaking due to latent demand effects (less cars on the road during peak travel times).

The authors present nine mobility management strategies, providing fuel and CO_2 emission estimates when available. Similar to the ITS section, the literature on the energy and emission impacts of mobility management approaches is more limited at present. Even so, these strategies have the potential to impact fuel consumption and CO_2 emissions, particularly if their use becomes more widespread. Options include: 1) carsharing, 2) ridesharing (or carpooling), 3) park-and-ride facilities, 4) parking cash out, 5) smart cards, 7) telecommuting, 8) smart growth and transit villages, and 9) road pricing policies.

5.1 Carsharing

Through carsharing (or short-term vehicle access) individuals gain the benefits of private vehicle use without the costs and responsibilities of ownership. Carsharing is most commonly deployed in locations where transportation alternatives are easily accessible and is complementary to transit[43, 44]. Carsharing has been documented to reduce vehicle ownership and vehicle miles/kilometers traveled as trips are shifted to transit, biking, and walking. This results in lower greenhouse gas emissions.

In Europe, carsharing is estimated to reduce the average user's CO_2 emissions by 40 to 50 percent[45]. In addition, many carsharing organizations include low-

emission vehicles, such as gasoline-electric hybrid cars, in their fleets. More recently, Communauto announced a 13,000-ton reduction in CO_2 emissions as a result of their 11,000 carsharing users in the province of Quebec, Canada. Communauto calculates that each carsharing user reduces his or her distance traveled by car by 2,900 kilometers per year on average. Furthermore, they anticipate with a potential market of 139,000 households in Quebec that annual CO_2 emission reductions could be as high as 168,000 tons per year[46].

5.2 Ridesharing (or carpooling)

Ridesharing (or carpooling) is an arrangement where two or more individuals agree to share a vehicle for tripmaking (typically commute trips). Frequently, the motivation for this is to save money, spend less time in traffic by traveling on a high occupancy vehicle lane, or reduce hassle (e.g., searching for a parking space at the office).

A carpooling project in Stockholm, Sweden allows carpools, carrying three or more people, to travel in bus lanes into the city. It is estimated that this effort will reduce CO_2 emissions by 15 tons per year by 2050[47].

5.3 Park-and-ride facilities

Park-and-ride lots are public parking facilities that enable commuters to leave their personal vehicles in such lots and transfer to transit or a carpool for the rest of their travel. Private vehicles are parked in the facility throughout the day; they are picked up when travelers return at the end of the day. Typically, such facilities are found in the suburbs of large metropolitan areas. Development and management of park-and-ride lots is important to promoting sustainable transportation[48]. Increasing park-and-ride facility capacity in Stockholm is estimated to reduce CO_2 emissions by 600 tons per year by the 2030 to 2050 timeframe[47].

5.4 Parking cash out

Parking cash out offers "commuters the option to 'cash out' their employer-paid parking subsidies. [It gives] commuters the choice between free parking or its equivalent cash value….The cash option also rewards those who carpool, ride public transit, walk, or bike to work"[49] (p. 262).

Estimates of CO_2 reduction from parking cash out programs range from 123 tons annually in Pleasanton, California (offered to city employees) to 200 tons in Santa Monica, California[50,51]. Furthermore, Donald Shoup has estimated that offering all employees in the U.S. the option to cash out their parking subsidies could lead to a reduction in 40 million tonnes of CO_2 emissions per year[52].

5.5 Smart cards

Another strategy to reduce CO_2 emissions is smart cards. Smart cards contain electronic chips. They are used for a variety of applications, such as transit, tolling, and parking payments. Stockholm is interested in integrating smart cards for use on transit, taxis, and carpools throughout the city. This approach is estimated to reduce CO_2 emissions by 1,500 tons per year by the 2030 to 2050 timeframe[47].

5.6 Telecommuting

Telecommuting is "generally defined as work at a remote location or home office rather than working at a fixed employer-provided site or office"[53]. Estimated fuel savings per telecommuter range from 49 to 177 gallons per year across three studies[54-56] (as cited in Shafizadeh, et al.[57]). This range converts to approximately a 0.5 to 1.7 ton CO_2 reduction using a standard assumption of 19.4 pounds of CO_2 emitted for every gallon of gasoline combusted[58].

Kitou and Horvath[59] used a systems model to evaluate the greenhouse gas emissions from business-sector energy (e.g., commuting, office temperature control, lighting, and electric office equipment) in telecommuting and non-telecommuting scenarios. Both deterministic and probabilistic analyses were conducted and evaluated. The "probabilistic analysis [Monte Carlo simulation] over a set of likely parameters" demonstrated that telework may reduce CO_2 emissions[59] (p. 3467). While telecommuting could potentially reduce CO_2 emissions related to commuting, reductions may be offset by increased home office energy use and/or commercial electricity use at the business office.

5.7 Low-speed modes

Low-speed modes are motorized and non-motorized devices that travel at lower speeds, such as bicycles, electric bicycles, Segway Human Transporters, and neighborhood electric vehicles. Many involve active movement by users and do not produce CO_2 emissions. By enhancing the bicycle and pedestrian environment, it is possible to encourage travelers "to take entire trips or partial trips with non-motorized modes that link with mass transit"[40] (p. 120). One way to encourage bicycling as an alternative mode is through a better low-speed mode infrastructure, particularly on-street bike lanes[60, 61].

The city of Stockholm's long-term plan to reduce CO_2 emissions includes replacing 30 million short car trips with bicycling annually. For longer trips, the City's goal is to encourage an additional 2,000 cyclists to give up car travel or public transit use every day during the summer months. Not surprisingly, this will require improving the low-speed mode infrastructure. It is estimated that such improvements will reduce CO_2 emissions by 2,900 tons per year by 2050[47].

5.8 Smart growth & transit villages

Smart growth is an urban planning and transportation strategy that emphasizes growth near city centers to prevent urban sprawl. This approach includes promoting mixed-use development, transit and bicycle-friendly infrastructure, and other land-use strategies, such as reduced non-residential speed limits, roundabouts, "parking maximums, shared parking, flexible zoning for increased densities and mixed uses, innovative strategies for land acquisition and development, and design emphasis on sense of place"[62, 63] (p. 61).

Transit villages are generally mixed-use (residential and commercial) areas that are designed to maximize transit access and encourage ridership. They are typically located within one-quarter to one-half mile (0.4 to 0.8 kilometer) of a transit station. Such strategies can reduce CO_2 emissions and vehicle miles traveled. Not surprisingly, "there is a direct correlation between low CO_2 emissions and the reductions in the auto use that accompany transit friendly neighborhoods with high residential densities"[63] (p. 41). More specifically, the California Department of Transportation estimates that the average household living in a transit village "could emit 2.5 to 3.7 tons less CO_2 yearly" than a traditional household[64] (p. 43). This estimate is based on a California Air Resources Board (CARB) study estimating transit village household private vehicle mileage reductions of approximately 20 to 30 percent annually[65].

5.9 Road pricing policies

Road pricing policies induce shifts from autos to public transportation, including cordon pricing (toll rings in high-activity centers like central business districts that charge drivers for entry into a specific area), FAIR lanes (fast and intertwined regular lanes that charge drivers to use express lanes and transfer a portion of the collected money to drivers using the non-express or regular lanes), and HOT lanes (or high occupancy toll lanes that enable drivers without the minimum number of passengers access to high occupancy vehicle lanes)[66]. Roadway pricing makes drivers more aware of the true cost of driving and may ease congestion as they switch modes[40] (p. 100).

Transport for London reports that the central London congestion charging program was responsible for a 16 percent reduction in CO_2 traffic emissions within the charging zone during 2002 and 2003 (annual averages)[67]. In addition, the city of Stockholm implemented a six-month trial of cordon pricing in January 2006, including provisions for expanded transit services and park-and-ride facilities. Using emission models, the Stockholm trial is estimated to have reduced CO_2 and particle emissions by "approximately 100 tons per weekday 24-hour period or by 14 percent"[68] (p. 89).

5.10 Summary

Based on limited study and real-world experience, mobility management strategies appear to have the potential to reduce energy and CO_2 emissions in the future. Of the nine approaches reviewed, road pricing policies (congestion and cordon) and carsharing already have demonstrated notable CO_2 reduction potential in both Europe and North America. Low-speed modes, integrated regional smart cards, and park-and-ride facilities are estimated to produce CO_2 emission reductions ranging from 600 to 2,900 tons per year in Stockholm, Sweden in the 2030 to 2050 timeframe. Other strategies that could result in noteworthy CO_2 reductions, including parking cash out (123 to 200 tons per two California cities), smart growth (2.5 to 3.7 tons per transit village households in California), and carpooling (15 tons in Stockholm in 2050, reflecting a limited project), are expected to impact CO_2 emissions. Finally, telecommuting impacts could range from a 0.5 to 1.7 CO_2 ton reduction by household per year, based on three U.S. studies conducted in the early 1990s. While these options show potential, their impact is dependent upon demand for such options throughout regions. Further study is needed to better understand the fuel consumption and CO_2 reduction potential of these options.

6. CONCLUSION

Carbon dioxide emissions from the transportation sector are projected to rise due to ongoing reliance on fossil fuels and increases in vehicle miles traveled. Projections are also expected due to growth in the developing world. A range of strategies is needed to address fuel consumption and emissions in the future. In this paper, the authors examined three strategies to addressing GHG emissions including: 1) engine technology and fuels, 2)

ITS, and 3) mobility management. In the future, the ultimate mix of emission reduction measures will depend upon a number of factors including: technology development costs; comparative costs among modes/solutions; interaction effects, such as latent demand; and support for governmental policies. These policies might include broad approaches, such as sector or inter-sector cap-and-trade programs and carbon taxation schemes, and/or more specific policies for road pricing and ASE, for instance.

Given the complex interaction of ITS technologies, mobility management, and human factors, development and use of suitable tools to measure environmental consequences will remain important. This makes analyzing and measuring the environmental consequences of transportation systems a challenging endeavor. Interrelationships among various vehicle, ITS technology, and mobility management strategies will determine the ultimate direction and degree of impacts. Overall, wider deployment of individual strategies can be expected to multiply benefits by providing the traveling public with a wider array of choices and real-time information. Near term, the greatest travel time and energy benefits are likely to come from traveler information persuading travelers to use public transportation or other available mobility alternatives or to postpone their trip until congestion has cleared. In the longer term, major switches to low carbon vehicles and fuels could have a major impact. These could be enhanced through artful integration of the vehicle and fuel systems with ITS to lower adoption barriers and enhance their prospects for major market penetration.

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