SPECIAL REPORT 298:
DRIVING AND THE BUILT ENVIRONMENT:
THE EFFECTS OF COMPACT DEVELOPMENT ON
MOTORIZED TRAVEL, ENERGY USE, AND CO_2 EMISSIONS

GHG Emissions Control Options

Opportunities for Conservation

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This paper summarizes the magnitude of greenhouse gas (GHG) emissions reductions one can expect from a variety of widely discussed (and often debated) policies and design strategies. These include vehicle technologies, transport modes, fuel types, appliances, home and building design, and land use patterns. Through a detailed review of existing literature, the work strives to identify the greatest opportunities for carbon savings, reflecting, to some extent, cost implications and behavioral shifts needed. Greatest near-term gains mostly emerge in relatively conventional vehicle design shifts, dietary changes, and home weathering. In the medium term, significant energy and emissions savings are likely to come from fuel economy regulations approximating those abroad, appliance upgrades, plug-in hybrid purchases, home heating and cooling practices, and power generation processes. In the longer term, building design practices, carbon capture and sequestration, and a shift towards cellulosic and other fuels appear promising. Ultimately, however, to achieve 50- to 80-percent reductions in GHG emissions, relative to current or past levels, major behavioral shifts are probably needed, motivated by significant fuel economy legislation, energy taxes, household-level carbon budgets, and cooperative behavior in the interest of the global community.

Additional Details

Fuel efficiency standards remain a critical part of the energy and climate change equations. Under current targets, the U.S. will only be at 35 mpg by 2020, though China is already there and Europe is already over 40 mpg. Importantly, fuel efficiency standards are not as draconian as the auto industry has made them out to be: the technology to achieve a 35 mpg fleet average (and higher) is already available, and vehicles achieving this fuel economy will pay for themselves within the vehicle's lifetime at gas prices as low as $1.50 per gallon.

In the absence of agricultural land use changes, biofuels (especially advanced biofuels such as cellulosic ethanol) are a good alternative to gasoline and diesel, achieving significant GHG and petroleum savings. However, biofuels are expected to offer such GHG savings only when produced without converting land to agriculture. Planting on abandoned agricultural land or producing biofuels from non-agricultural sources (biomass waste or algae) can avoid land conversion while providing GHG emissions benefits.

GHG savings are expected for mode shifts away from SOV to carpooling and certain transit modes if current occupancy levels are maintained. However, bus occupancies will need to increase in order to achieve such mode-shift benefits. Such occupancy improvements are reasonably likely, if bus supply increases, particularly along lower-occupancy routes and in lower-density neighborhoods, do not match demand increases. While cycling at first appears as a strong contender, increased life expectancies and dietary needs may offset much of the anticipated GHG savings.

Mode shifts from truck to train or water obviously can result in substantial sector-level savings, but mode shifts may be undesirable for certain products, and rail is nearing its capacity. An alternative option lies in improving truck fuel economy. However, even a 9% fuel savings results in rather low emissions savings for the U.S., since trucking represents a relatively small portion of total emissions.

Red meat production is very energy, and carbon, intensive. Eating less red meat or adopting a vegetarian diet can reduce emissions. However, quantifying this savings is difficult, and studies on life cycle energy required for food production differ.

Finally, the fastest way to make buildings more efficient is to find cleaner electricity-generating technologies while insulating attic spaces, particularly in colder climates. In the longer term, reducing space requirements per occupant, promoting shared walls (via multi-occupant buildings), insulated walls (via new construction and renovations), and solar shielding also are important opportunities. Moreover, neighborhood design impacts should prove helpful, as cities grow and densification facilitates reductions in trip lengths along with mode, vehicle ownership, and vehicle-design shifts, while moderating numerous other problems associated with sprawl. Nevertheless, CO2e savings from switching vehicle designs, fuels, meat consumption, building insulation, and a wide variety of other options are estimated to offer far more significant greenhouse gas and energy reductions than neighborhood design appears to, particularly as American household incomes and preferences for rising home sizes, natural light, on-demand travel and many other comforts of modern life continue to climb.

1. INTRODUCTION

Energy and climate change are top planetary issues, and increasingly a part of the U.S.'s political and economic agenda. There is considerable evidence that the earth's climate is indeed changing as a result of excess greenhouse gases (GHG[1]) in the atmosphere. Many nations around the world agree that GHG emissions need to be reduced – and sooner is better (Stern 2006). In order to stabilize the concentration of GHGs in the atmosphere, the United Nations Framework Convention on Climate Change (UNFCCC), many European countries, and the state of California (CA) believe that a reduction of 80%[2] by 2050 is necessary to prevent the most catastrophic consequences of global warming (Stern 2006, Luers 2007). Major changes in

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[1] GHGs include carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6). CO2 makes up the majority of U.S. GHG emissions (84% in 2005, by heat-trapping potential), 80% of which come from fossil fuel combustion (as measured in terms of heat trapping potential). CH4 makes up 7% of all U.S. GHGs, with landfills (1.8% of GHGs), enteric fermentation (1.5%), and natural gas systems (1.5%) serving as the nation's top three methane contributors. N_2O contributes another 7% of all GHGs, with agricultural soil management serving as the top source (5%). HFCs, PFCs, and SF_6 account for only 2% of all GHGs, largely due to the changes in regulations concerning other, ozone-depleting consumer substances. Because CO2 makes up such a large portion of all U.S. GHGs, and an even larger portion of household emissions, and because many reports on GHG emissions provide only CO2 numbers, this paper emphasizes CO2 values and reductions, rather than CO2 equivalents ($CO2_e$) (EPA 2008).

[2] The 80-percent reduction is relative to 1990 levels (the reference point for the Kyoto Protocol), or 82% versus 2005 levels. U.S. 1990 emissions were 6.310 MMTCE, 2006 emissions were 7.202 MMTCE, and the 80% target emissions are 1.262 MMTCE (EPA 2007c).

technology, behavior, and laws are needed to bring about such reductions. This report examines the wide spectrum of opportunities for energy and GHG savings, in order to quantify potential impacts and identify those opportunities with greatest promise. It begins with a look at the potential for changes in motorized vehicle technologies and fuels, along with transportation modes and electricity generation. It then moves into building designs, appliances and land use practices, before offering conclusions and recommendations.

2. THE ROLE OF TRANSPORT

The transportation sector is responsible for 28% of all man-made U.S. GHG emissions[3], which presently tally close to 8 billion tons (over 7,000 million metric tons of carbon-dioxide equivalent [MMTCE]) per year (EPA 2008). Figure 1 provides a breakdown of emissions within the transportation sector. Light-duty vehicles (cars and light trucks) make up 62% of all such emissions (EPA 2006).

In addition to representing a large share of total U.S. emissions, transportation sector emissions are growing at a faster rate than overall GHG emissions. For example, total U.S. GHG emissions rose 13% between 1990 and 2003, while those from the transportation sector rose 24% (EPA 2006). Due to stagnant CAFE standards coupled with suburbanization and income trends, energy use from North American transport is expected to increase by 46% between 2003 and 2025 (CCSP 2006), becoming a larger share the total. Any sizable reductions in transportation sector emissions will translate into meaningful overall reductions in U.S. GHG emissions.

In general, there are three approaches for reducing transportation emissions: improvements in vehicle technology, a switch to lower-carbon fuels, and travel demand management (EPA 2007). Over the 2007-2050 period, EPA (2007) estimates that the transportation sector's CO2e emissions will increase by 2 billion metric tons[4]. Roughly one-half of this growth will come from passenger vehicles, 20 percent from heavy-duty trucks, 10 percent from aviation changes, and nearly 20 percent from other non-road modes (like rail and water). While different approaches to transport efficiency can reduce the rate of emissions increases, no single policy appears able to prevent the transport sector's GHG emissions from rising.

As Kockelman et al. (2008) note, meeting Kyoto Protocol objectives would require a CO_2 emissions reduction of approximately 730 lbs per month per American (to achieve total GHG emissions levels that are 7% below the nation's 1990 emissions). For the average U.S. household, a savings of nearly 2,000 lbs of CO_2 per month can be obtained by switching from a sports utility vehicle (SUV) to a crossover utility vehicle (CUV) hybrid, switching from central AC to a window AC unit during warm months, and turning down the thermostat while away from home during cold months. Additional savings can accrue from other behavioral changes,

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[3] This report refers only to carbon emissions of anthropogenic origin, which includes farming and other agricultural activities (such as animal husbandry). While fossil fuel consumption and tropical deforestation are estimated to release, on average, 7.1 gigatons of carbon per year, natural fluxes from the oceans, soil and plants are on the order of 200 gigatons per year. Fortunately, these non-anthropogenic sources are in relative balance (emissions versus absorption), and the oceans and reforestation of North American forests, among other activities, have been offsetting anthropogenic releases, avoiding far more serious climate change over the past century. (SOCCR 2007) There is, however, concern that anthropogenic emissions have been degrading the Earth's natural absorptive capacity for CO_2 (e.g., Stern 2006).

[4] A metric ton (or "tonne") is 1,000 kilograms, 2205 pounds, or 1.1 English (or "short") tons.

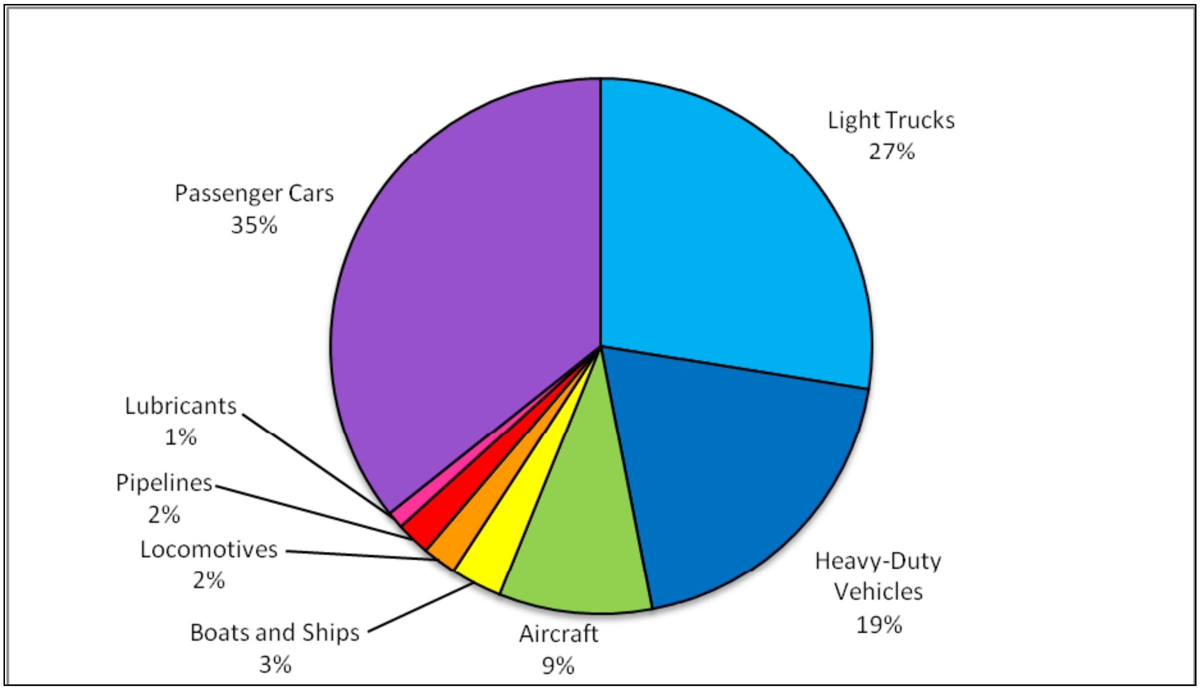

FIGURE 1 Distribution of transportation sector GHG emissions in 2003 (source: EPA 2006).

such as reducing vehicle miles traveled (VMT), reducing home floor area, and replacing old appliances with energy efficient products, among many other possibilities. The following discussion examines these and many other opportunities, in order to appreciate which policies and practices offer the greatest GHG savings, both near and long term.

Personal Transport

Responsible for 12% of the world's anthropogenic CO2 emissions and 19% of U.S. emissions (Wadud et al. 2007, EPA 2006a), personal transportation is a sector that warrants much attention. Recent research shows that trends in technological improvements made to U.S. vehicles over the next 20 years will not meet California's targets (Friedman 2007). If every U.S. household switched to driving only Toyota Priuses (and maintained present driving distances), a 1.1 billion ton savings in CO2 emissions would be expected[5]. Similarly, if every household switched to solar-powered personal vehicles, a near-term savings of 2.0 billion tons could be achieved. However, those sorts of shifts are hardly likely by 2020 (in order to match 1990 levels, which requires a reduction of 2.1 billion tons) (EPA 2007c).

In 2003, light-duty vehicles (LDVs) produced 77% of the nation's on-road transportation CO2e emissions, and 62% of all transportation CO2e emissions (EPA 2006). LDV emissions have increased by 19% between 1990 and 2003, largely due to a 34% LDV VMT increase during that period (EPA 2006). As shown in Figure 2, VMT has been increasing more than twice as fast as the U.S. population.

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[5] This assumes an average LDV fuel economy of 20.2 mi/gal (EPA 2006b), and a Prius fuel economy of 46 mi/gal (taken from 2008 Prius data, posted at fueleconomy.gov).

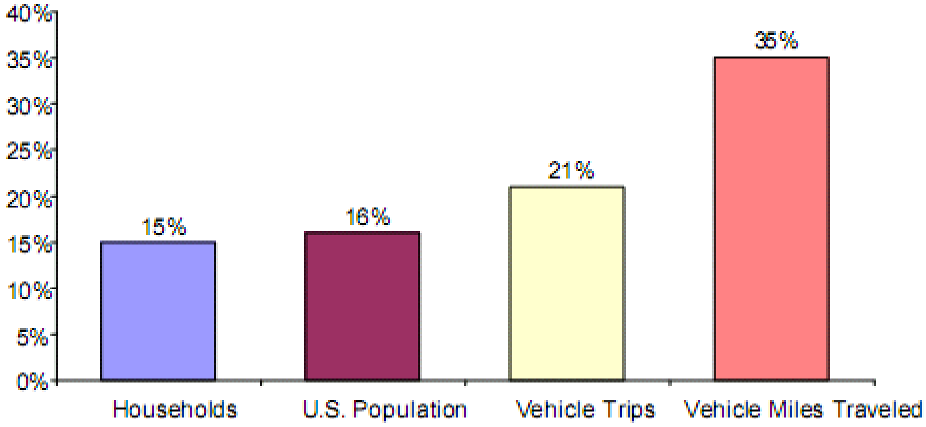

FIGURE 2 Growth rate comparisons, for households, population, vehicle trips by households, and household VMT, 1990-2001 (EPA 2006).

An increasing share of these emissions are being produced by light duty trucks (LDTs – including SUVs, minivans, and pickups), which are held to lower (fleetwide-average) fuel economy standards (20.7 mpg presently[6]) than passenger cars (at 27.5 mpg) (EPA 2006). The LDT share of LDV emissions has risen over time, from 34% in 1990 to 43% in 2003 (EPA 2006).

Light-Duty Vehicle (LDV) Technology

Harnessing vehicle technology to improve fuel economy is a central challenge in reducing GHG emissions from household travel. While reducing and shifting travel from private automobiles to other modes is a viable and important component of a comprehensive GHG reduction strategy, the ubiquity and attractiveness of private automobiles suggests they will remain a popular mode choice in the decades to come. Likewise, while hydrogen fuel cells and a few other technologies may emerge that could eliminate the combustion of fossil fuels, these technologies remain years away and the complete life-cycle implications of fuel preparation are often unclear. In the coming decades, serious energy and climate issues remain.

Vehicle Energy Losses A revealing starting point for discussions of opportunities for energy conservation is a full-system recap of how passenger vehicles powered by internal combustion engines (ICEs) process energy. Figure 3 details the energy flows for a spark-ignited (SI) gasoline mid-sized passenger vehicle under an urban-driving cycle (TRB 2006b). Energy is stored chemically and must be converted from chemical energy to mechanical work. This conversion is performed inside the ICE (at an efficiency which is largely constrained by thermodynamic laws), and the resulting energy then flows to the drivetrain, powers the engine during stand-by and idling, and powers accessories. The drivetrain transfers energy to the

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[6] Recent light-duty truck (LDT) standards were 20.7 mpg, but new targets are in place for 2008 forward, starting at 22.5 mpg and rising over time. Passenger car (PC) standards have remained at 27.5 mpg for some time. Both PC and LDT fuel economy standards will begin a graduated rise to a goal of a fleet-average of 35 mpg by 2020, as discussed in this report's section on Light Duty Fuel Economy Regulation.

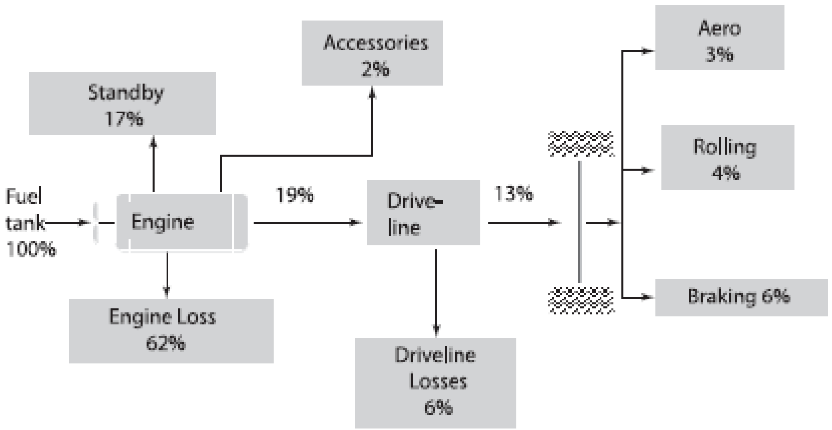

FIGURE 3 Energy losses in the operation of a mid-sized passenger vehicle, using an urban driving cycle (source: TRB 2006b, Figure 3-1).

wheels where energy is exhausted overcoming resistance from various loads including the vehicle's mass (during braking and acceleration), aerodynamic loads, and rolling resistance to the tires as the vehicle is propelled forward. Strikingly about two-thirds of the burned fuel's energy is completely lost as heat and only 10 to 20 percent of the original energy is used to overcome aerodynamic drag, rolling resistance, and braking losses, in order to move the vehicle.[7]

Several opportunities for fuel savings emerge here. Modifying non-engine components including tires and accessories – as well as reducing vehicle mass – can decrease the energy drawn from the engine. Operating the vehicle more efficiently (at optimal speeds and in an optimal driving style) can reduce the aerodynamic drag that must be overcome along with energy lost to braking. While these loads represent small shares of overall fuel consumption, their downstream occurrence translates to more significant reductions in upstream GHG emissions because less fuel must be combusted (with all the attendant losses). Additionally, the engine itself can be modified to more efficient combustive processes (e.g., a shift from SI gasoline to compression-ignited diesel engines) and/or largely eliminated via driveline technologies that optimize use of energy drawn from combustion (e.g., hybridization), yielding longer term, more significant savings.

Non-Engine Components As the points of contact between the vehicle and road, tires constitute an energy sink through rolling resistance. The lost heat comes from tire deformation and recovery under load. This process can be moderated by maintaining *tires at proper pressure*, an aspect of vehicle maintenance that goes overlooked. Tire pressure can drop below optimal pressure for a vehicle, or placard, due to slow leaks that can naturally happen at a rate of 1 psi per month and drops in ambient temperature which can reduce pressure by 1 psi for every 10°F (NHTSA 2004). Maintaining optimum tire pressure thus requires regular checks of tire pressure, yet many drivers check pressure infrequently and are unaware of the correct pressure

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[7] Exact percentages of energy lost from each sink vary across engine designs and driving styles. In general, more energy makes it to the wheels during highway driving than during urban driving, due to lower losses from engine standby (as during idling, coasting, and braking) and because the engine operates more efficiently at higher speeds.

for their tires (e.g., Office of Energy Efficiency 1998). The National Highway Transportation Safety Administration (NHTSA 2004) estimates that 26% of passenger cars and 29% of light trucks have at least one tire 25% or more below placard pressure, and that average under-inflation of all four tires of each of these vehicle types is 6.8 psi (cars) and 8.7 psi (light trucks). Estimates of fuel economy loss due to underinflation vary from 0.2% to 0.4% for every 1 psi below stated optimal tire pressure, per tire (Aerospace Corp. 1978, Goodyear 2004, TRB 2006b, Schuring 1980, Duleep 2005a, DOE 2008c). However, these estimates will be conservative if multiple tires are underinflated.

Table 1 gives estimates of U.S. petroleum consumption and annual GHG savings if one percent of light-duty vehicles with low tire pressure were to be maintained at optimal tire pressures, assuming a fuel economy loss of 2.2% is avoided. Though the total savings are rather minor, in comparison with other forms of fuel savings (and the nation's 8 billion tons of annual CO2e contributions), Congress recently mandated Tire Pressure Monitoring Systems in new vehicles. Public awareness campaigns regarding the efficacy of tire pressure maintenance may be an economical and immediate way to reduce greenhouse gas emissions (Webber 2007).

Low rolling resistance tires offer another near-term opportunity to improve vehicle fuel economy, using existing vehicles. Drivers change their tires every 3 to 5 years, on average (TRB 2006b). While new vehicles typically come equipped with low rolling resistance tires (to help manufacturers meet CAFE requirements), replacement tires generally do not employ such technology. (TRB 2006b) Tread modifications can reduce rolling resistance by 10 percent, which translates to a fuel economy improvement of 1 to 2 percent (TRB 2006b). The range of variability encompasses different driving conditions, ambient temperatures, and vehicle weights/tire loadings (Duleep 2005a). Table 1 provides estimates of the petroleum consumption reduction and annual GHG reductions possible through tire replacement. A 10-percent reduction in tire rolling resistance is technologically and economically feasible (TRB 2006b); however, consumers are not well informed of the benefits. Such tires will more than cover their incremental cost (estimated to be $12 per vehicle per year [Lem 2006]more than a normal tire) thanks to lifetime fuel savings (estimated to be 4% per year [TRB 2006b]). For example, 4-percent fuel savings over 12,000 miles per year at just $2 per gallon is $36, which should more than cover the added cost of the tires, even if such tires need more frequent replacement. (Lem 2006)

Mobile air conditioners (MACs) represent a primary accessory load during vehicle operation in warmer climates, thereby constituting an important source of GHG emissions. The International Energy Agency (IEA 2007a) estimates that cabin cooling represents from 15 to 30 percent of vehicle energy use after combustion (see Figure 3), and EPA (2006a) testing indicates that air conditioner use at 95° F increases fuel consumption by 26 percent in conventional vehicles and 44 percent in hybrid-design vehicles[8]. In addition, MAC refrigerants are powerful greenhouse gases (with global warming potentials [GWPs] 120 to 150 times that of CO_2 [Ayala and Church 2006]), and leakages of these (due to leaks in the A/C system or losses during servicing and end-of-life scrapping) are a direct emission of GHG into the atmosphere. Vincent et al. (2004) estimate that 72 percent of MAC lifetime emissions are due to leakages and that leakages can reach 6 gm of CO_2e per mile (for a vehicle with R-134a, the most common MAC refrigerant).

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[8] The fuel consumption increase for hybrids is higher in percentage terms because hybrid-engine fuel economies are lower to begin with.

The California Air Resources Board (CARB) is encouraging manufacturers to improve MAC efficiency, in order to meet new fuel economy standards. Such improvements – like variable displacement compressors (VDCs) and improved control systems – can reduce CO_2e emissions by 0.016 lb/mile in passenger cars and 0.022 lb/mile in light trucks (Lutsey and Sperling 2007) – or roughly 2 percent. CARB also recommends the use of low-GWP refrigerants. Duleep (2006) estimates that alternative refrigerants, such as R-134a "enhanced" and R-152 versions, could reduce effective CO_2e emissions by 0.0066 lb/mile and 0.0126 lb/mi at incremental costs of $25 and $70 (per vehicle). The deployment of more efficient MACs in conjunction with R-134a enhanced refrigerant could net a 2% reduction in overall GHG emissions.

Another tactic is reducing the need for MAC use. For example, reducing solar loads via reflective body paint and infrared reflective window glazing can cut cooling demands by 5% and 10%, respectively (IEA 2007a). Of course, benefits from improved MACs and reduced solar loads only accrue on hot days: Meszler Engineering Services (2004) estimates a 34-percent A/C "on time", but this will vary greatly by climate conditions and driver preferences. Finally, Duleep (2006) notes that improving MAC technology could have important trickle-down effects in the rapidly motorizing developing world, which experiences a more tropical climate and tends to have less controlled vehicle scrappage.

Vehicle mass is another aspect of automobile design that influences energy consumption. More massive vehicles mean the engine must overcome more inertia in accelerating the vehicle and then maintaining steady speeds. Environmental and Energy Analysis (EEA 2007) has identified several methods of reducing vehicle mass, including material substitution (replacing traditional, heavier materials like cast iron and steel with new, advanced materials including high strength steels, aluminum and magnesium alloys, or plastics/composites), improved packaging (improving ratio of interior volume to exterior area and thus total weight), downsizing, unit body construction (making the body panels themselves load bearing and thus eliminating the need for a conventional chassis), and parts consolidation (integrating functions and thus eliminating a need for connecting parts). All these methods of reducing vehicle mass are potential options for all vehicles, to some degree. It is difficult to estimate potential fuel savings for improved packaging, unit body construction, and parts consolidation; and downsizing will reduce interior volume, making vehicles somewhat less attractive to consumers. But higher fuel economy is a useful benefit to consumers, and alternative materials are already being used in many vehicle models. EEA estimates that the fuel economy improvements from reducing vehicle mass by 10% range from 4.5% to 10%, depending on the degree to which vehicle drivetrain, engine, and secondary components (like tires and brakes) are optimized to work with the lighter vehicle mass. For example, a 6-percent benefit emerges from a 10-percent mass reduction and drivetrain optimization - without engine downsizing. Tables 2 and 3 provide estimates of petroleum savings and GHG reductions for such a design change.

Of course, reducing vehicle size and mass may compromise occupant *safety*, particularly in collisions involving heavy objects and other vehicles. Wenzel and Ross (2006) contend that vehicle design is more important than mass, arguing that design limitations are most responsible for injurious crash phenomena, including intrusion into the passenger compartment (due to insufficiently stiff materials), rollover (due to higher centers of gravity, typical of SUVs and pickups), and passengers impacting hard interior surfaces (due to inadequate seatbelt restraint and/or absence of airbags). Research results regularly find that light-duty trucks (LDTs) pose added dangers to other road users – and often to their own occupants. (See, e.g., NRC 1992, O'Donnell and Connor 1996, NHTSA 1998, Digges and Malliaris 1999.) Wang and Kockelman's (2005) ordered-logit model results suggest that a shift to the average, heavier LDT, away from lighter passenger cars will result in more deaths. Their results also indicate that a 1,000-lb. (33%) up-weighting of the U.S. LDV fleet would result in a 3-percent lower probability of injury or death, but a 19-percent increase in the (rather remote) possibility of death (due to greater damage sustained by collision partners). A down-weighting would likely show very similar numbers, in reverse. While crash losses are significant in this country, planetary losses due to climate change impacts are likely to take precedence in such cases, particularly when net-safety impacts are on the order of a few percentage points, and design changes can probably overcome down-weighting concerns. More importantly, a shift from heavier LDTs to lighter-weight passenger cars is expected to offer multiple safety, emissions, and other benefits. (See, e.g., Kockelman 2000 and Lemp and Kockelman 2008.)

A key issue in manufacturer adoption of lighter weight vehicles achieved through alternative materials will be the incremental *cost* increase to manufacture these. While alternative materials will eventually achieve lower incremental costs as production volumes increase, in the short run these often only offer comparative advantages in very specific components. EEA (2007) modeled four levels of alternative-materials inclusion on a 3350 lb. conventional vehicle. These materials are advanced steel (which is already being included in many models), plastics/composites, magnesium, aluminum, and magnesium. The results show that weights of 3114 lbs., 3097 lbs., 2763 lbs., and 2637 lbs. are possible at incremental costs of $179, $239, $1388, and $1508, per vehicle. The advanced-steel scenario was found to be the most cost effective, on a dollar-per-pound-reduction basis. Table 4 shows the lifetime cost of employing such advanced materials in a 3,350 lb. conventional vehicle, assuming various gas prices and two different discount rates (4 and 12 percent). Both steel and plastics are cost-effective to a consumer expecting an investment that pays for itself in just 3 to 5 years and a relatively high return[9].

Aside from modifications to vehicle tires, MACs, and mass, a number of conventional fuel-economy-improving technologies already exist in several current models. The NRC (2008) inventoried technologies which have the potential to achieve widespread penetration within the next 15 years and estimated fuel consumption benefits for each of these. Modifications to spark-ignited gasoline engines can improve fuel economy by improving volumetric efficiency, reducing pumping and internal frictional losses, and enabling engine downsizing (for equivalent performance). These modifications include cylinder deactivation, direct-injection, turbocharging (with associated engine downsizing), valve event manipulation, and reduced-viscosity lubricants. Transmission technologies can maximize the fraction of operating time that a vehicle spends in its highest efficiency ranges; these technologies include higher gear (e.g., six-, seven-, and eight-speed) automatic transmissions, automated manual transmissions, continuously variable transmissions and aggressive shift logic. Finally, modifications to vehicle design which have the potential to reduce fuel consumption by diminishing end-uses include improved vehicle aerodynamics and electrification of accessories. Tables 2 and 3 estimate the potential for reduced petroleum consumption and GHG emissions from a fleet of vehicles employing these technologies, as compared to a fleet of average and MY 2007 vehicles, when using NRC's (2008) midpoint values in each fuel economy range. The deployment of a package of conventional improvements currently available or approaching maturity in one percent of

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[9] Consumers exhibit myopic purchase behavior that suggests, on average, they expect fuel savings to cover added costs within a 3- to 5-year payback period (NRC 2002).

passenger vehicles could reduce U.S. petroleum consumption by 0.09% and U.S. GHG emissions by 0.05% (compared to a MY 2007 reference vehicle[10]). While these percentages may seem insignificant, these conventional improvements could be rapidly deployed in *all* vehicles. With the proper policy mechanisms in place and better information provided to consumers (as to the cost-savings benefits of fuel efficiency), 9-percent reductions in petroleum consumption (or 19 percent of petroleum imports) and a 5-percent savings in national GHG emissions could be attained.

The Role of Vehicle Speeds and Driving Style Another mechanism to improve fuel economy using the existing vehicle fleet lies in speed choices. Engines are designed to operate more efficiently at relatively high speeds, resulting in a concave *fuel economy-versus-speed relationship*, as shown in Figure 4. Past government testing indicated that optimal fuel economy for 1997 model year vehicles could be obtained around 55 mph (West et al. 1997), and more recent on-road tests confirm this finding (see, e.g., Rakha and Ding 2003 and El-Shawarby et al. 2005). Gao and Checkel (2007) note that the functional relationship varies little across vehicle classes, and savings are significant. Assuming that West et al.'s 1997-data profile (Figure 4) still holds[11], passenger-car fuel economy declines an average of 9.7% with a 55 to 65 mph cruising-speed increase, 17% with a 55 to 70 mph speed increase, and 21% with a *30* mph to 15 mph speed *reduction*. These added GHG emissions are common on high-speed uncongested facilities as well as heavily congested facilities and lower-speed, urban streets. Presumably, lower speeds on high-speed facilities could be achieved via more stringent enforcement of existing and lowered speed limits, but there are no guarantees, given policing priorities. Table 1 provides estimates of GHG emissions reductions from lowered speed limits (assumed to mimic actual speeds) on urban and rural interstate facilities. For example, reducing limits on 1 percent of 65 and 70 mph interstates (urban and rural) to 55 mph and assuming all drivers follow suit is estimated to save just 0.009% of U.S. GHG emissions and 0.018% of U.S. petroleum consumption; such savings are less than the those estimated to emerge from rather simple vehicle technologies, such as low-rolling-resistance tires.

A TRB (1998) study of speed limit policies concluded that most drivers will obey posted limits only if they perceive a credible threat of detection and punishment for non-compliance, a level of policing that is often difficult to maintain given limited resources. In this regard, planned policing at critical locations for violations, high-profile enforcement campaigns, and automated enforcement techniques can heighten the threat of detection. Of course, automated detection (via video surveillance, for example) often requires overcoming issues of privacy and owner liability (as opposed to driver liability) for infraction (TRB 1998). Most areas of the U.S. require specific enabling legislation to deploy automated enforcement (Turner and Polk 1998). While traffic enforcement cameras are now used in many places across the U.S., many states and cities have passed legislation prohibiting such strategies (including Arkansas, Nebraska, Nevada, New Jersey, Utah, West Virginia and Wisconsin [Wikipedia.org 2008]).

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[10] In fact, the savings are higher if the reference vehicle is an average U.S. vehicle rather than the average *new* vehicle: 0.19% of petroleum consumption and 0.10% of GHG emissions.

[11] West (1997) averaged the gas-consumption results of five passenger cars and three light-duty trucks to produce Figure 4. Rakha and Ding (2003) found fuel economy to be maximized at 56 mpg, using more recent model-year vehicles. So the profile's peak may not have changed much over the past 10 years.

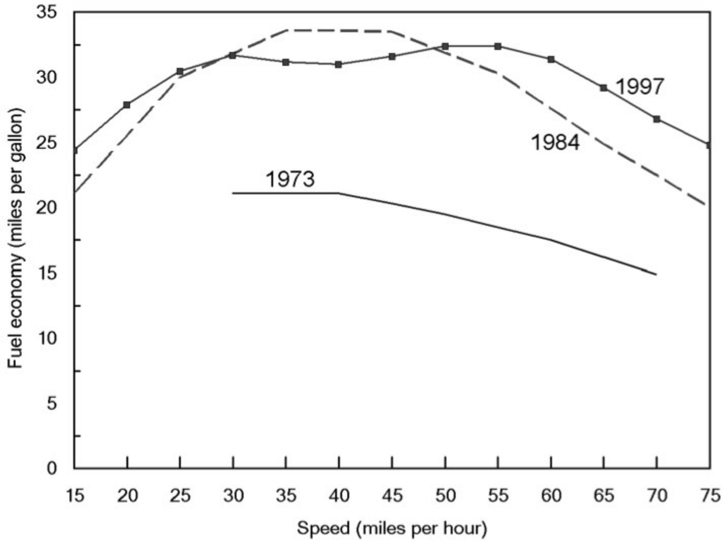

FIGURE 4 Fuel economy-speed relationship (source: West 2007, Figure 4.2).

Aside from policing, speeds in urban settings can be decreased, increased or regulated through a variety of demand management and design strategies, including congestion pricing, parking policies, signal timing and synchronization, design and support for alternative modes, and street geometry (VTPI 2008), several of which are discussed in later sections of this paper. The average emissions reduction per driver, however, ultimately depends on what share of a person's daily driving is done at above and below optimal speeds, and what each vehicle's optimal speed range is. Hybrid-engine vehicles now display information on instantaneous fuel consumption rates, per mile traveled, and that information is of value to drivers. An added consideration is that designs and policies which speed up traffic (e.g., congestion pricing and one-way street designs) can, at some level, compromise the safety of adjacent pedestrians and cyclists, thus deterring alternative-mode users. (See, e.g., DfT 2004.) Moreover, some advanced vehicle types (notably HEVs which perform well in stop-and-go driving) will experience less fuel consumption benefit from speeding up urban traffic. Thus, appropriate speed setting and enforcement remains an important notion. Of course, lower speeds (e.g., via traffic calming measures in residential neighborhoods) also reduce the attractiveness of car travel, thus reducing emissions directly via forgone trips.[12]

In theory, the nature of driving (e.g., stable speeds and smooth speed changes, versus stop-and-go driving and aggressive acceleration and braking) also is a source of fuel savings and GHG emission reductions. Rakha and Ding (2003) examined the role of vehicle stops and acceleration levels on fuel consumption and criteria pollutant emissions (such as oxides of nitrogen and volatile organic compounds [NO_x and VOC]) and found that fuel consumption is

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[12] For example, Goodwin (1996) found an elasticity of travel demand with respect to travel time of -0.27 in the short run and -0.57 in the long run on urban facilities. If one considers slowing traffic from 20 to 10 mph, this will result in a doubling of travel time (adding 3 minutes per mile traveled), and one can expect VMT to fall by 27 to 57% (using Goodwin's [1996] elasticity estimates). If this slowed speed results in 7 fewer miles to the gallon (based on Figure 4 trends), Figure 4 predicts roughly a 33% increase in CO2 emissions, which will be nearly offset by a 27% reduction in VMT (short-run) and fully offset by a 57% VMT reduction (long-run). Thus, slowing low-speed traffic down may actually save on carbon emissions overall and in the longer term.

more sensitive to vehicle cruise speed than vehicle stops (though criteria pollutant emissions appear sensitive to stops). Notably, the controlling factor in the magnitude of effect of a complete vehicle stop is actually cruise speed itself which determines the time and distance over which the vehicle must brake and then accelerate to re-establish cruise speed. The authors conclude that vehicle stops have significant effects on fuel consumption only at high speeds, suggesting that traffic calming measures in urban settings may not greatly increase GHG emissions, even if driving and VMT hold steady. They also find that fuel consumption increases with rate of acceleration, but not dramatically. (Rakha and Ding 2003).

In practice, it is difficult to quantify (and impact) driving styles. A California- and Colorado-sponsored website (ecodrivingusa.com 2008) suggests that the owner of a 27-mpg vehicle driving 11,000 miles per year can save 550 lbs. of CO_2 per year by reducing speeds to safe and legal speed limits and can save 400 lbs. of CO_2 per year by accelerating and decelerating more smoothly. Assuming these levels of savings, the nation could reduce CO2e emissions 0.008% and 0.006% if all U.S. drivers were to obey posted limits and drive more smoothly, respectively.

Advanced Engine and Driveline Technologies So-called “revolutionary technologies” use new engine types and/or fuels to improve upon (and/or eliminate) the process of internal combustion, with its tremendous energy losses (62% in Figure 3). The potential benefits are dramatic, but manufacturers have not yet achieved high enough production volumes to offer such vehicle designs at competitive prices.

Diesel engines deliver higher efficiency via higher temperatures for spontaneous fuel ignition (upon contact with the cylinder air, or compression ignition [CI], as opposed to the use of spark plugs or spark ignition [SI]). Modern CI direct-injection technology enables precise control of air-to-fuel ratios, in order to ensure that fuel is combusted more thoroughly, thus improving power and fuel economy while reducing emissions (compared to past diesel technology). The improved efficiency of combustion from diesel CI engines translates to a 20 to 40 percent improvement in fuel economy over a gasoline SI engine (NRC 2008), and this improvement can be combined with transmission and vehicle design technologies mentioned earlier. For example, a 2008 Mercedes-Benz E320 (midsize car), 2008 Mercedes-Benz ML320 (SUV), 2008 Jeep Grand Cherokee (SUV), and 2006 Volkswagen Jetta (compact car) yield fuel savings of 38%, 23%, 18%, and 32% over their non-diesel counterparts (DOE 2008c). In practice, however, diesel technology is used in many models to increase performance, without compromising fuel economy. Notably, the associated GHG emissions savings from diesel vehicles are less than their fuel economy improvement would suggest, since diesel fuel is more carbon intensive.

Light-duty diesel engine sales are growing in Europe rising to more than half of market share in 2007 (EERE 2007). The growth in diesel in Europe has been driven by manufacturers’ efforts to meet the EU’s voluntary pact on GHG reductions (An and Sauer 2004). The viability of such shifts in the U.S. depends on a vehicle’s ability to meet Tier 2 emission standards for particulate matter; indeed many diesel technologies have been removed from the U.S. market for this reason. Greene et al. (2004) and Duleep (2005b) predict that PM criteria will soon be met by emerging engine designs, perhaps by 2012 (Greene et al. 2004). Other authors (e.g., Kromer and Haywood 2007 and Osborne 2007) question the efficacy of devoting resources to improving diesel technology, and call attention to emerging gasoline engine technologies, such as turbo-charging, which may put these on par with diesel engines.

Tables 2 and 3 show potential petroleum reduction and GHG savings based on a switch to diesel engine technologies and diesel engines packaged with relevant conventional technologies in one percent of light-duty vehicles. Compared to an average fleet of new (model year 2007) vehicles, a fleet of diesel-powered vehicles is estimated to reduce petroleum consumption by about 10 percent and GHG emissions by just 3 percent. A package of conventional technologies (for a gasoline-powered engine) will offer a *greater* GHG reduction (5 percent of U.S. emissions) than a move to diesel engines, due to the greater carbon intensity of diesel fuel. Combining diesel engine technology with various conventional technologies, however, is expected to reduce petroleum needs by 14 percent and GHGs by 5 percent. While gas savings more than covers the cost of such a switch, many Americans still perceive diesels as noisy, smelly, and underpowered, and worry about the availability of fueling and repair locations as well as new-vehicle availability in showrooms (McManus 2003). In reality, diesel owners have far more positive perceptions of their vehicles (McManus 2004). Diesel technology is not noisier or smellier, and often improves acceleration, torque, and vehicle range (Greene et al. 2004), and consumer concerns are likely to disappear as light-duty diesel technology further penetrates the market. Similarly, the availability of refueling and repair locations should increase with additional diesel vehicles on the road. The greatest barrier to diesel technology's success is undoubtedly the incremental cost of a diesel vehicle versus a conventional vehicle. In 2005, such incremental costs were on the order of $1750 to $2500, or $2300 to $3350 in order to cover emission control systems for meeting Tier II standards (Greene et al. 2004). Long term, diesel engines will continue to cost more than non-diesels due to the persistent need for more sophisticated emissions control systems and a greater engine complexity. Kromer and Heywood (2007) estimate an incremental cost of $1200 (as compared to a conventional-engine vehicle) in the year 2030.

Hybrid Electric Vehicles (HEVs) combine ICEs with electric motors powered by a battery pack to reduce vehicle energy use from fossil fuels. Electric motors can achieve conversion efficiencies far greater (on the order of 90%) than those of ICEs meaning that during electric operation the significant engine losses (Figure 3) are reduced. Hybrids also employ numerous engine modifications including idle off, fuel cutoff during deceleration, regenerative braking in which kinetic energy lost during speed reductions is recaptured, and engine downsizing enabled by the supplementing of the ICE with the motor. Hybridization of the drivetrain is often accompanied by conventional innovations (such as lightweighting and advanced transmissions), since such vehicles are typically sold to consumers looking to improve fuel economy; thus, stated fuel economy improvements are not always attributable to hybridization alone. Tables 5 and 6 take a look at current price differences across hybrids and near substitutes, and how these translate to differences in net present valuations, under various gas pricing scenarios, discount rates (of future returns), and duration of discounting.

A variety of hybrid configurations exist, differing in architecture (parallel, series, and split – which prove advantageous under more variable driving conditions) and degree of hybridization (mild versus full, reflecting the fraction of power than can be supplied by the electric motor). Presently, the types of hybrid drivetrains on the market include: Honda's Integrated Motor Assist (IMA), a mild hybrid, GM's Belt Alternator Technology, a mild drivetrain, and Toyota's Toyota Hybrid System.(also used by Ford and Nissan ,a full hybrid based on a "split" parallel and series architecture with two motors. GM, BMW, and Chrysler Daimler are jointly developing the 2Mode drivetrain, which also will use two electric motors. However, Kromer and Heywood (2007) forecast that an area of future innovation will be migrating to single-motor architecture rather than the dual-motor, power-split architecture that is prevalent in the current market. This shift should be driven by innovation in battery technology. Thus far only gasoline-hybrids have been available, though diesel-hybrids may soon be introduced in Europe with a 20% 20%higher fuel economy than a comparable diesel vehicle (Lewin 2007).

As Santini et al. (2007) note, an important feature of hybrids is their ability to enable equivalent performance without sacrificing fuel economy. This is primarily an issue in terms of engine downsizing (fewer cylinders) and front- vs. rear-wheel drive. Absent hybridization, consumers wishing to enjoy the faster acceleration, higher top-speed and greater torque of more powerful engines and RWD vehicles endured less fuel efficient options. The past 15 years of trends in auto-manufacturing support a consumer preference for power and speed (EPA 2006b), and some vehicle owners need engine power for towing. Hybridization offers opportunities for gains in both fuel economy and performance. Of course, hybridization also could be mis-directed towards performance, with little to no improvement in fuel economy (if hybrid engines are simply used with the same number of cylinders). Consumer education will be helpful in ensuring that buyers are aware of hybridization's wide-ranging benefits, in conjunction with engine downsizing.

Numerous estimates of hybrid fuel economies have been published since interest in this technology began. These have relied on various methodologies (e.g., on road vs. simulated driving, and existing technology vs. projected improvements) and as such are not always commensurable. Moreover, earlier estimates are now being revised upwards, as hybrids have penetrated the market faster than expected and more manufacturers have pursued research and development in this area. Burke et al. (2002) estimated that full hybridization (which they define as 50 percent or more of vehicle power coming from electric sources) should improve the fuel economy of small cars, mid-sized cars, and SUVs by 19%, 29%, and 17%, respectively. Using the ADVISOR model, the Electric Power Research Institute (EPRI) has developed hypothetical hybrid vehicles that rival (or better) conventional vehicles in a number of performance targets (like sustained top speed, passing performance and standing acceleration). In two separate studies they estimate that hybridization in a compact car, mid-size car, mid-size SUV, and full-size SUV can improve fuel economy by 24.9%, 33.8%, 41.6%, and 43.6%, respectively (EPRI 2001 and 2002). Duleep (2005b) estimates that full hybridization can improve fuel economy by 20 to 25 percent (or a 50 to 55 percent improvement when combined with conventional improvements). Using a detailed simulation model, Simpson (2006) estimates that HEVs can obtain a fuel economy about 40% higher by 2015. Kromer and Heywood (2007) project that an HEV mid-size sedan could achieve 76 mpg by 2030 (while a 2030 ICE is projected to achieve 43 mpg). More recently, the NRC (2008) cites a fuel economy improvement range (due to hybridization) of 11 to 17 percent in the city driving cycle for Integrated Starter-Generator hybrids (such as those used by Honda) and 17 to 30 percent for parallel hybrids (such as those used by Toyota, Ford, and GM). These hybridization improvements could be further combined with conventional improvements to an SI engine, transmissions, and vehicle design, for added fuel and CO2e savings.

As empirical points of comparison, the U.S. EPA (2008) tested fuel economies of four of the most popular hybrid vehicles: the Toyota Prius (a full hybrid passenger car getting 46 mpg), the Honda Civic (a synergized mild hybrid passenger car getting 42 mpg), the Nissan Altima (a midsize car getting 34 mpg) and the Ford Escape (a full hybrid SUV getting 32 mpg). The EPA found that these enjoy 60%, 45%, 30%, and 34% higher fuel economies, respectively, than their non-hybridized counterparts[13]. Tables 2 and 3 provide petroleum reduction and GHG emissions savings estimates for hybridization, with and without conventional improvements. Compared to a fleet of average of model year-2007 vehicles, a fleet of hybrids could reduce *total* U.S. petroleum consumption by 7 percent and GHG emissions by 3 percent; adding in relevant conventional improvements could increase these reductions to 6 and 13 percent. These are significant savings (though clearly insufficient to achieve 50-percent and higher GHG-reduction targets by year 2050).

Hybrids have penetrated the market more quickly than expected in recent years. In 2007, about 3% of new vehicle sales were hybrid models, up from 0.5 % in 2004. Undoubtedly the biggest hurdle for HEVs in terms of mass market potential will be cost. Estimates of incremental costs of full HEVs are on the order of $5600 per vehicle (Duleep 2005b), though these may fall to $3,000 to $4,000 by 2012 (Greene 2004). Some hybrid designs are more affordable while achieving fuel economies near those of fully hybridized models (Duleep 2005b). Moreover, the incremental cost of hybrids costs could fall with increased production volumes and improvement in component parts, particularly their batteries. Simpson (2006) estimates an incremental cost of $3200 in 2015, while Kromer and Heywood (2007) estimate that this cost could fall to $1900 by 2030.

Lipman and Delucchi (2003) find that hybridization is usually cost effective for owners, though they find an advanced package of conventional modifications combined with mild hybridization to be the most effective of the scenarios they analyze (compared to moderate conventional modifications and full hybridization, for instance) and also discount fuel costs over the entire lifecycle of the vehicle (an assumption that manufacturers tend to testify does not hold true). Thus, break-even gas prices to justify a hybrid vehicle purchase (based purely on fuel-cost savings) will likely lie above $3/gallon. Tables 5 and 6 show the lifetime savings (or cost) of purchasing a hybrid – as compared to a comparable, non-hybrid model for consumers expecting moderate and high returns on their investment (in fuel economy). For a consumer expecting a moderate return (i.e., when using a 4-percent discount rate), HEVs appear to be cost-effective only when compared to a more expensive base model or outside of the 3- to 5-year payback period average consumers are assumed to demand. Cost effectiveness is, of course, even more difficult to achieve for a consumer expecting a higher return. Notably, for comparisons that may represent a large set of potential purchasers (e.g., a more affordable base vehicle versus a hybrid vehicle), most higher-gas-price scenarios do not bring cost effectiveness within a realistic payback period. Nevertheless, significant demand already exists for various HEV models, as many consumers anticipate higher gas prices, seek to avoid uncertainty in future fuel costs, wish to reduce their carbon footprint, and/or pursue other objectives via the purchase of an HEV. And, fortunately, battery costs are estimated to have rather minimal impact on returns[14].

From a policy standpoint, McKinsey and Co. (2007) note that the marginal cost of abating carbon from hybridizing LDVs is $100 to $140 per ton, far less cost effective than other

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[13] These are based on Model Year 2008 vehicles. The Toyota Prius comparison is made with a Toyota Corolla, its closest non-hybrid Toyota counterpart (in terms of combined passenger and luggage volumes).

[14] While this analysis does not include potential battery replacement, Lipman and Delucchi's (2003) more detailed lifecycle cost analysis of HEVs assumes battery life to be half the vehicle life, and battery replacement to cost 85% of initial battery cost. They find that batteries (original and replacement) constitute just 3.4% of an HEV's lifetime cost. Battery technology has improved considerably since their analysis, and hybrid-vehicle batteries operate in an optimal state of charge for the vast majority of use, which extends life. Manufacturers like Toyota also offer incentives like an 8 year/100,000 mile warranty on such batteries.

abatement options they consider (for instance, hybridization of medium- and heavy-duty vehicles); this is because the marginal cost diminishes as the reference vehicle (an LDV) becomes more fuel efficient. However, LDV hybridization constitutes a more substantial fraction of total U.S. emissions than various other, lower-cost strategies involving vehicle fleet changes.

Plug-in hybrid electric vehicles (PHEVs) advance hybrid technology by employing more advanced batteries, thus enabling further engine downsizing and direct charging via the electricity grid. PHEVs have been touted for numerous reasons. For example, electrification of a significant share of vehicle miles maximizes the efficiency advantage that electric motors hold over combustion engines. Furthermore, PHEVs directly displace petroleum consumption[15] with electric power, which typically entails use of a less carbon intensive “fuel”. Benefits also can accrue from centralizing combustive processes: from numerous disparate tailpipes to a small number of power plants. This centralization facilitates carbon capture and sequestration (CCS) along with improvements in regional air quality and public health, as emissions shift away from population centers (Pratt et al. 2007). The interaction between PHEVs and the utility industry also could be a favorable one if owners charge their vehicles overnight, as many (e.g., Kromer and Heywood (2007) and Santini (2006)) have speculated is likely. PHEVs also represent a new market for the utility industry by tapping available, overnight electricity generation capacity. In fact, increased demand is expected to drive down electricity prices in some scenarios, while increased revenues could help utility companies make necessary retrofits to dirtier power plants (Pratt et al. 2007). Synergy between wind power and overnight PHEV charging also has been suggested as a possibility (Short and Denholm 2006), since wind power generation usually peaks overnight.

A PHEV works by initially running off of electric charge from the grid in “charge depleting” operation until the allowable lower limit of its charge is reached at which point it switches to “charge sustaining” (essentially normal hybrid operation). A PHEV is designed with a specific range of charge depleting operation (often denoted PHEVx) though the actual range of charge depleting operation achieved will depend on the type of driving the vehicle is used for (Santini et al. 2007). Sizing the battery (for energy and power) is a crucial design decision, involving tradeoffs between cost, range and degree of hybridization (which in turn influence how much of the vehicle’s operation will be powered electrically). Notably, blended mode operation can diminish required battery power, thus reducing cost without greatly reducing a PHEV’s petroleum reduction potential (Vyas et al. 2007).

Battery power influences the degree of hybridization and thus the probability that the ICE will turn on to assist the electric motor. A higher power battery enables all-electric operation which minimizes high-emitting, fuel-consuming cold starts (because the engine does not turn on) and ensures that use of electricity is frontloaded so that electrification of miles is maximized. In contrast, lower-power batteries are used in blended operation, in which the engine may assist. Blended operation is seen as a desirable course for development of PHEV batteries to take because the marginal petroleum reduction from increased hybridization is often negligible and lower power batteries cost significantly less, weight less, and increase usable vehicle volume (Vyas et al. 2007). PHEVs may also vary with respect to battery energy which is closely linked to the electric range of the vehicle. A higher energy battery increases vehicle range, however there are diminishing returns in terms of increasing electrification here because the probability

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[15] Of course, the geopolitical implications of moving transportation away from oil also deserves, and receives, attention. However, it is not addressed by this report.

that a person travels a certain distance between charging decreases with distance (Vyas et al. 2007). Lower energy batteries, however, will age more quickly and require more battery power at greater cost (Kromer and Heywood 2007). In the long-term different models with different ranges are desirable to enable consumers to choose the model that will best suit their daily driving habits though in the short term a mid-range vehicle is likely.

Estimation of potential GHG reductions from PHEVs is a complicated exercise given the lack of real world estimates of PHEV fuel economies and several factors impacting how they will be used. One complicating factor is estimating how much the vehicle will be used in charge depleting (electrified) mode as opposed to charge sustaining (normal hybrid operation) mode (commonly referred to as a utility factor). The range of the vehicle provides a maximum mileage that can be electrified in a given tour, but further doubt remains as to whether or not this range will be exceeded. Several methods (e.g., SAE 1999 and EPRI 2001) exist to estimate the split between these modes; these work by using a probability distribution of daily VMT to predict the fraction of non-electrified miles for a given range as the probability that an individual's daily driving exceeds the range of a vehicle. Markel's (2006) tests have confirmed the range predicted by the SAE and EPRI methods. The charging frequency is another factor in GHG reductions, since infrequent charging will effectively shorten vehicle range on a given day; overnight charging is a common assumption, supported by housing and parking trends. (E.g., more than 60 percent of households have a carport or garage available [AHS 2005].) Finally, the type of electricity generation used to charge the vehicle greatly influences CO2e savings. In the short-term, carbon savings mostly depends the local utility's feedstock, which varies greatly by region. In the longer term, as PHEVs penetrate the market, GHG reductions will tend towards the average grid mix (Kromer and Heywood 2007).

Tables 2 and 3 provide estimates of petroleum consumption reductions and GHG emissions savings for PHEVs with 40 and 60 mile ranges, powered by different types of electricity generation. 40 and 60 mile ranges are expected to translate to 50 and 75 percent electrification.[16] PHEVs are assumed to achieve the same gasoline fuel economy as an HEV with conventional improvements and an electric fuel economy of 3 miles per kWh (Gremban 2006). A fleet of PHEV 40s could reduce petroleum consumption by 23 percent, nearly doubling reductions from diesels and HEVs with all conventional improvements. GHG emission savings vary greatly by electricity feedstock and technology. At grid-average carbon intensity, a fleet of PHEVs offers GHG emission savings only slightly better than HEVs with conventional improvements (8 percent, as compared to 6 percent). PHEVs charged from coal-fired power electricity offer lower savings than an HEV with conventional improvements (5 percent), while PHEVs charged from an advanced grid – including a substantial fraction of renewables and CCS – increases GHG emissions savings estimates to 11 percent of total US emissions.

Several potential barriers exist to successfully deploying PHEV technology. Shifting a significant portion of U.S. VMT to electric power will represent considerable new demand for the utility industry. Management of grid dispatch offers great potential as a solution to this problem. The electric grid tends to consist of base-load sources (such as hydroelectric power, nuclear power, and some coal power) which remain on continuously and variable sources (such as wind power, oil and natural gas, and some coal power) which are turned on to meet demand when it is high. Given the cyclical, peak and valley nature of electricity demand, however, utility companies are often left with excess capacity overnight; PHEVs could be charged without

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[16] 50 and 75 percent are the middle share values for 40- and 60-mile ranges, as plotted by Kromer and Heywood (2007).

requiring new supply investments via valley filling (Kintner-Meyer 2006). Pratt et al. (2007) estimate that up to 43 percent of the LDV fleet could be charged overnight with available generation and 73 percent using available daytime and overnight generation (though the feasibility of daytime charging is a bit unclear as charging will likely require around 4 hours). If PHEVs truly become a market success, however, a daytime charging scenario could significantly tax the electric grid in many regions that have little available generation during daytime peaks. Dynamic electricity pricing has been suggested as a policy mechanism to induce owners to charge their vehicles overnight. Perhaps a more problematic barrier will be the ability of utility companies to continue to meet regulatory standards for criteria air pollutants. Increased electricity demand from PHEVs will require the utility industry to make reinvestments to continue to meet emissions constraints for SO_x and other contaminants (Gaines et al. 2007).

Beyond simply deploying PHEV technology, challenges will exist to fully realizing its benefits. One such challenge is shifting the U.S. electric grid to less CO_2 intensive power plant technologies. Using coal-fired power plants, the most prevalent type in the U.S. today, a PHEV operating in charge depleting mode emits roughly the same GHGs as an ICE – or more, on a per mile basis, according to Gaines et al.'s (2007) near-term (2015) projection, with some variation depending on specific type of power plant and source of petroleum. Other total-energy-cycle pathways involving different power plant technologies offer significant improvements (Gaines et al. 2007). Unfortunately, the outlook for the grid mix in the future does not show dramatic improvement (640 g CO_2e/kWh today to 635 g CO_2e/kWh in 2030) as the grid will face steadily growing demand, an increased fraction of coal generation at the expense of cleaner natural gas and nuclear generation, and little shift in renewable sources which will shift from hydroelectric power to wind power, but little overall change in the shares of the grid powered by each generation type (EIA 2006). The outlook for the grid could, however, look significantly different given factors such as monetization of CO_2 and Renewable Portfolio Studies (RPS), utility restructuring, demand-side reduction, volatile natural gas prices, and difficulties siting new nuclear, coal, and wind plants (Kromer and Heywood 2007). The impact of a truly robust fleet of PHEVs is also itself a possible factor in the future grid mix; in the long-term these could represent an overnight base-load that could increase demand for base-load generators and make investments in cleaner base-load generators more cost-effective. Potential growth in the wind power sector is another hopeful possibility here. Fully realizing PHEV technology potential will necessitate a policy framework that moves the U.S. electric grid in a favorable direction.

Perhaps the biggest hurdle for PHEV technology will be cost. As a benchmark, currently, there are several after-market kits that enable conversion of a Toyota Prius into a limited-range PHEV; these retail for \$10,000 to \$12,000 (Shelby 2006). In the mid-term, Simpson (2006) estimates a PHEV with 20 miles of range could come at an incremental cost of \$11,000 by 2010 and \$8000 by 2015. In the longer term, Kromer and Heywood (2007) project incremental costs of \$3000 to \$6000 for vehicles of 10 to 60 miles of range, while McKinsey and Co. project incremental costs of \$4300 to \$5300. The high incremental costs mean that consumers will generally not perceive PHEVs as cost effective; Kromer and Heywood (2007) estimate that a PHEV 30 could save \$645 annually compared to a conventional vehicle (in 2030), however given their estimated incremental cost this represents a payback period of around six years, longer than a typical consumer's expectation. Expanded options in terms of vehicle ranges could increase the market for PHEVs by better matching vehicle range to daily commuting pattern of a consumer, thereby increasing the vehicle's cost effectiveness. Vyas et al. (2007) examine national daily commuting patterns and conclude that if vehicles of 10 mi, 20 mi, 40 mi, and 60 mi ranges were available, 59% of national VMT could be electrified using the assumption that a person will only buy a PHEV if its range exceeds their daily average driving; this is a far greater percentage of national VMT than from a single range alone. Manufacturers will, however, face tradeoffs between concentrating research and development into a single model and bringing its cost down more quickly and developing multiple models to reach a greater potential market. Notably, there has been little discussion of PHEVs in non-passenger cars leaving a large part of the U.S. automobile market uncovered.

In the long term, the technical capabilities and mass-market potential of HEVs and PHEVs depend on breakthroughs in battery technology. Battery power and energy storage must improve. The storage capacity primarily impacts range in PHEVs, while power impacts performance in both HEVs and PHEVs; and both attributes impact fuel consumption. Presently, nickel-metal-hydride (NiMH) batteries dominate because of their favorable durability, safety, and cost. In the future, however, lithium-ion (li-ion) technology are likely to replace NiMH (Kromer and Heywood 2007, and Vyas et al. 2007), due to energy and power advantages (per unit mass), reducing vehicle weight while freeing up cargo space. Whereas NiMH is approaching a maximum specific energy of 75 Wh/kg (which is constrained by its fundamental chemistry) (Anderman 2003), li-ion batteries could reach a specific power of 300 Wh/kg in the coming decades (Chang 2006). Additionally, li-ion batteries will become more cost effective, because they should scale to high production volumes better than NiMH, they rely on cheaper commodity inputs than nickel, and they can offer more power for less metal material (Kromer and Heywood 2007).

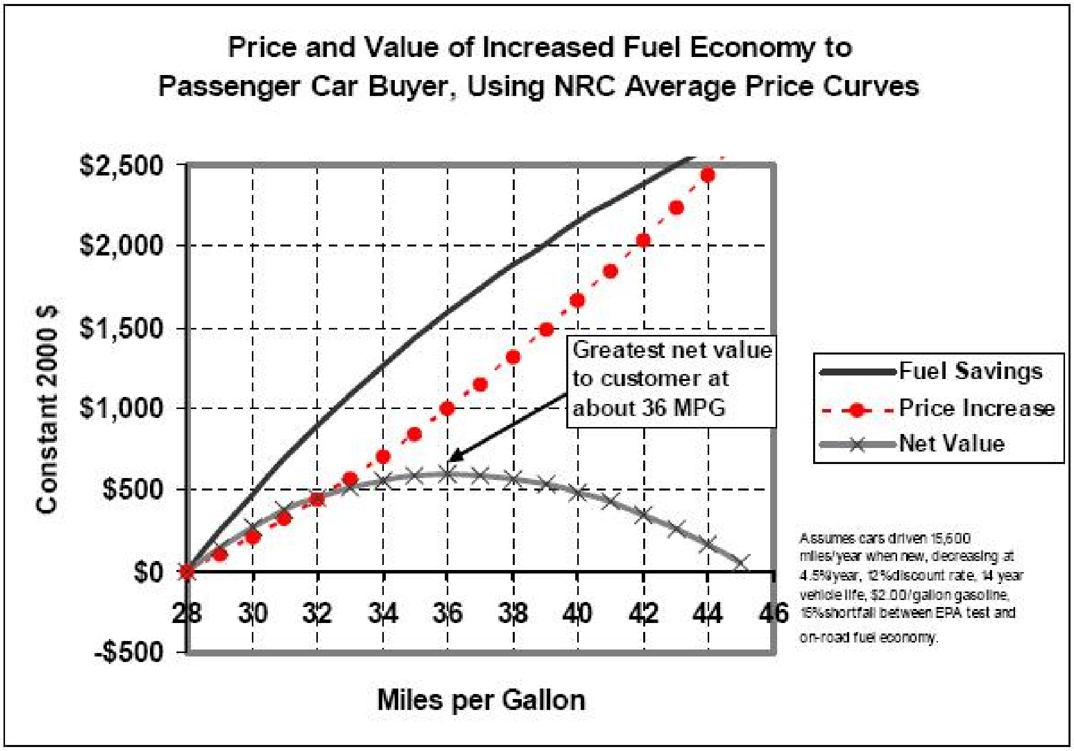
Barriers to immediate market success for li-ion technology exist, however. These include safety, durability, cost, and mutual exclusivity of high specific energy and specific power (due to traditional cell structures in which these factors compete [Srinivasan 2004]). These barriers are expected to dissipate via research and development into new materials and cell structures. In particular, cost should fall as production volumes increase and as specific energy improves. A remaining question, in terms of commercialization, is durability, since it is unclear how li-ion batteries will respond to repeated charge and discharge, extended shelf life, and extreme temperatures (Kromer and Heywood 2007). Currently, potential durability problems are dealt with by oversizing the battery for power and/or energy storage, but this is costly.

There are a wide variety of vehicle manufacturing and fuel use opportunities. Sponsored by the U.S. Department of Energy, Argonne National Laboratory's GREET Model (of Greenhouse gases, Regulated Emissions, and Energy use in Transportation) is an important and now very popular tool for reconciling most of these, by anticipating the life-cycle impacts of evolving vehicle designs and new-fuel mixes. Recognizing over 100 fuel production pathways and 70 vehicle/fuel systems, GREET provides estimates consumption of various fossil and non-fossil fuels, production of several GHGs, along with standard criteria pollutants (such as volatile organic compounds and particulate matter). (Argonne 2008) GREET users can be found around the world. This tool is helpful to analysts and others seeking to improve policymaking, devise new regulations, and target future research and development efforts.

Light-Duty Vehicle (LDV) Fuel Economy Regulation

While many technologically feasible options exist to improve LDV fuel efficiency, an appropriate policy framework is needed to ensure that these catch on. Policy changes for the manufacture and sale of new vehicles are likely to require more enthusiastic legislative support, in order to ensure that consumers recognize the long-term value of fuel savings and the external/social costs of gasoline consumption (including GHG emissions, air pollution, and compromised national energy independence). Manufacturers report that consumers value fuel savings only over the first three to five years they hold a vehicle, meaning that sticker price differences or production costs often exceed perceived fuel savings (Greene 2005). Figure 5 illustrates how the perceived present (discounted) value of increased fuel economy is often small, relative to vehicle price and lifetime fuel expenditure savings and changes little over significant ranges of fuel economy (e.g., 32 to 40 mpg) – when assuming just $2 per gallon gas prices.[17]

Greene's (2006) more recent estimates assume gas prices of $2.50, $3.00, and $3.55 per gallon. Economically rational consumers expecting a moderate return (3 percent discount rates) and valuing (discounted) fuel savings over a vehicle's lifetime would find optimal/cost-effective fuel economy at 38.9, 41.4, and 43.4 mpg (for the three gas prices noted above, respectively). These fuel economies lie well above the nation's current fleet fuel economy, suggesting that consumers are not sufficiently motivated to purchase fuel efficient vehicles.



Price and Value of Increased Fuel Economy to Passenger Car Buyer, Using NRC Average Price Curves

Assumes cars driven 15,600 miles/year when new, decreasing at 4.5%/year, 12%discount rate, 14 year vehicle life, $2.00/gallon gasoline, 15%shortfall between EPA test and on-road fuel economy.

FIGURE 5 Cost effective fuel economy improvement for consumer after discounting lifetime fuel savings (source: Greene 2007, Figure 2).

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[17] Greene's assumption of a 12-percent discount rate is designed to capture a consumer expecting a near-term or higher rate of return on fuel economy (thanks to asset depreciation). Price increase is plotted based on NRC's (2002) supply curves, and fuel savings are computed using gas prices of $2.00 per gallon with discounting over vehicle lifetime.

From the manufacturer's perspective, it is quite costly to shift product lines – and unreasonable when consumers are indifferent to fuel savings. Consumers may improperly value fuel economy because of limited or poor information about their own fuel consumption or how long they will hold the vehicle, because they do not have the foresight to consider fuel consumption far into the future or discount the future value at a high rate, because they foresee an inability to recapture the costs in a future resale, or because they value other attributes more (Fischer 2007). Nevertheless, there is debate on this question of whether consumers fully value fuel economy, and Espey and Nair's (2005) hedonic analyses suggest that vehicle prices reflect fuel savings benefits, at gas prices of $1.50 to $2.00 per gallon. However, they assume that a vehicle's market price reflects its true value to consumers (when in fact it may cost more or less to manufacture than apparently comparable vehicles, or appeal to very different market segments). Regardless, even if consumers were to properly value the private benefits of fuel economy, fuel consumption levels remain inefficient due to the externalities of fossil fuel use.

Policies intended to improve vehicle fuel economy may target vehicle purchases by influencing manufacturers to offer more fuel efficient product mixes and prompting consumers to more properly assess the cost of fuel consumption and fuel savings. After significant fuel economy improvements between 1975 and 1987, U.S. fuel economies have leveled off and even declined over the past 20 years. Manufacturers have shifted the emphasis of their research and development groups from improving fuel economy to increasing vehicle size and power, consistent with many consumers' aspirations (EPA 2006b). These supply- and demand-side trends are mutually reinforcing, and may have emerged from a couple decades of relatively low gas prices and rising incomes. Policy changes probably should focus on improving fuel economy of the nation's fleet, thereby addressing both supply and demand.

CAFE Standards and Related Options The Corporate Average Fleet Economy (CAFE) standards are a sales-weighted standard that must be achieved for a particular model year, by nearly every manufacturer of new vehicles. Manufacturers pay penalties for failing to meet CAFE standards and earn credits which may be passed forward or backwards three years when standards are exceeded. CAFE is specified separately for passenger cars and light trucks, a distinction originally intended to allow truck manufacturers to continue producing powerful work vehicles. According to the Energy Policy Conservation Act of 1975 which established CAFE standards, Congress and the President are charged with setting standards for passenger cars while the NHTSA is responsible for establishing standards for light-duty trucks for each vehicle model year that are the "maximum feasible standard" given consideration of technological feasibility, economic practicability, effect of other standards on fuel economy, and the need of the nation to conserve energy. In spite of this charge, after increasing steadily during the late 1970s and much of the 1980s, CAFE standards remained generally stagnant through the 1990s and early 2000s. The standard for passenger cars has been at 27.5 mpg since 1985, while the standard for light-duty trucks was 20.7 mpg for most of the 1990s reaching 22.5 mpg in 2008.

Recently, the Energy Independence and Security Act (EISA) of 2007 provided the first major reform to CAFE law since its inception. The act covers fuel efficiency standards beginning in 2011 and established a single CAFE standard of 35 mpg to be reached by 2020. It maintained the distinction between passenger cars and light-duty trucks, however the final 35 mpg standard will be applied to an average of these fleets. Moreover, it shifted the basis for standards to a mathematical function that is to be based on vehicle attributes; this will likely primarily reflect vehicle footprint, with smaller vehicles being held to more stringent fuel economy standards than larger vehicles. The attribute-based standards should help to enable improved fuel economy via "lightweighting" without compromising safety.

The passage of the 2007 EISA happened amid two legal disputes relating to CAFE standards. In the Commonwealth of Massachusetts vs. EPA, the Supreme Court ruled on behalf of 12 states and the District of Colombia that the EPA is required to establish GHG standards for automobiles or explicitly justify the infeasibility of doing so. Then, in November 2007, the U.S. Court of Appeals overturned the NHTSA's proposed light-duty truck fuel economy standards for model years 2008 through 2011. A central reason for the Court's decision was NHTSA's failure to meet the "maximum feasible standard" due to their decision not to monetize CO_2 emissions costs. These court decisions raised the issue of whether states have the right to regulate CO_2 emissions (as part of air quality), and this issue was clarified somewhat, as the EISA established that states have the right to regulate CO_2 emissions. This power seems to have been undercut by the December 2007 decision to deny California and other states the ability to set more stringent standards than the EPA. Several other issues involved in the Appeals Court's overturn went unaddressed by the EISA. These include the failure to provide a "backstop" prohibiting the manufacture of very low fuel economy vehicles and the failure to regulate SUVs as PCs, though many of these are built on PC platforms and not used for work purposes.

While the new CAFE standards are a welcome improvement over previously stagnant standards, they lie well below average fuel economies enjoyed in much of the developed world and are less aggressive than targets sought by several U.S. states. For example, under its Clean Cars program, California pursued policies to improve light-duty fleet fuel economy to 31.8 mpg by 2012 and 35.6 mpg by 2016 (using weighted averages of PC and LDT standards) (An and Sauer 2004). Many states[18] planned to follow these standards, until California was denied a waiver to establish fuel economy standards different from EPA standards, in December 2007.

Standards are far more aggressive abroad, as well. China is currently at a 35 mpg standard while the European Union has reached a voluntary agreement with manufacturers to achieve an EPA-test-equivalent fuel economy rating of 44.2 mpg by 2008 (An and Sauer 2004). Of course, the U.S. and international situations are not necessarily commensurable since the fraction of LDTs in the U.S. fleet (nearly 50%) far exceeds that of Europe and China. Nevertheless, the NRC (2002) concluded that a fleetwide fuel economy of 37.1 mpg is technically feasible within a 10- to 15-year horizon (i.e., by 2012 or 2017), based on existing or presently under-developed technologies and not considering the additional potential of mass reductions (which could increase the nation's fleetwide fuel economy to 42 mpg [Friedman 2006]). New CAFE standards thus hold manufacturers to a less stringent standard in a longer time frame than the NRC study suggests. Furthermore, trends in vehicle sales since 2002 – including increased sales of hybrid vehicles and diminished sales of SUVs and other low-fuel economy vehicles – should enable manufacturers to achieve an even higher level of fuel economy (by pulling up their sales-weighted averages). The NRC (2002) report concludes that a 37.1 mpg fleet is cost-effective, assuming a 12-percent discount rate and 14-year vehicle payback period, average annual VMT levels, and gas prices of just $1.50 per gallon. With present gas prices more than double the NRC's assumption, improving fuel economy now offers further consumer savings. While consideration of manufacturers' economic interests will

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[18] 15 states and five environmental groups filed petitions asking federal courts to overturn the EPA's waiver denial.

undoubtedly require the incremental introduction of higher standards, many of the technologies needed to meet these already exist, as discussed earlier.

Table 7 shows the petroleum and GHG savings from adopting more stringent fuel economy standards for all U.S. light-duty vehicles. A fleet of such vehicles at 2020 CAFE levels would reduce the nation's current petroleum consumption by 19 percent, while 2016 California standards would bring a 20 percent reduction and 2008 EU standards would bring a 25 percent reduction.

A powerful criticism of CAFE is that it does not provide adequate incentives to improve fuel economy *above and beyond* the standards. As suggested in many studies (e.g., Fischer 2007 and Kromer and Heywood 2007), consumer choices suggest a required fuel-savings payback period that is much shorter than the average life of a vehicle, so manufacturers have little incentive to improve fuel economy on their own, relative to other vehicle attributes. To some degree, a new incentive may now exist, thanks to allowances for CAFE-credit trading, as enabled by the 2007 EISA. However, a concern in the 9th Circuit Court of Appeal's recent overturn of NHTSA's 2007 proposed LDT fuel economy standards was the lack of a backstop, to prevent stagnation in free-floating fuel economy standards (Yacobucci and Bamberger 2007).

An alternative strategy for increasing passenger vehicle fuel economy is the use of *feebates*, a semi-market-based policy wherein vehicles are assessed a fee or awarded a rebate (to be reflected in the vehicle's sale price) based on falling short of or exceeding a designated "pivot" fuel consumption rate. Feebates are intended to provide a continuing incentive to manufacturers (to improve fuel economy) while ensuring that the price differentials are strong enough to lure many consumers who do not value the full benefits of fuel savings (Greene et al. 2005). Model results suggest that manufacturers respond to feebates by incorporating fuel-saving technology in order to maintain the retail price of their vehicles while nearly meeting pivot targets. (Davis et al. 1995, DRI/McGraw-Hill 1991), Greene et al.'s (2005) modeling results for vehicle choice (in a future year in which manufacturers have adapted to a variety of feebate schemes) suggests that under an average-technology price curve with feebates assessed independently for cars and light trucks, and assuming consumers discount only the first three years of fuel savings at a 6 percent rate, fleet fuel economy will rise 16% with a $500 per gallon per mile (GPM) feebate and , 29% with a $1000 per 0.01 GPM feebate. [19] Table 7 shows the predicted GHG emissions under these two feebate scenarios. However, Greene's (2005) study sets no clear timeframe (for market equilibrium) and assumes incremental technological improvements in vehicle design for fuel economy (rather than revolutionary new technologies, that may not mesh with the technology cost-vehicle price curves he used).

One concern with policies that promote higher fuel economy in vehicle design is the "*rebound effect*" in which consumers use their savings on fuel purchases to drive additional miles. However, Small and Dender (2007) estimate that the rebound effect is on the order of just 2 to 3 percent of direct fuel savings in the short term and 10 to 15 percent in the longer term. The effect was on the order of 20 to 25 percent in prior decades, but the demand for gasoline has become less price elastic over time.

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[19] Given a 3-year discounting window, these feebate rates essentially translate into average taxes of $1.13 and $2.26 per gallon.

Managing the Demand for Fuel Rather than mandating that manufacturers offer a more fuel-efficient product mix, there are measures that incentivize less driving and greater fuel efficiency, in driving patterns and vehicle purchases. Such measures include increasing the cost of fuel consumption (e.g., gas taxes), the cost of less efficient vehicles (e.g., the U.S. gas guzzler tax), and/or driving itself (via tolls, congestion pricing, and registration and licensing fees). Such measures also can include incentives for the retirement of less efficient vehicles.

Gas taxes are both a way to raise revenues (for road maintenance or vehicle technology research, for example) while helping drivers appreciate the external costs of their energy consumption. In theory a higher gas tax will diminish demand for driving. However, recent experience suggests that the price elasticity of demand for gasoline is relatively low now, after declining over time (Hughes et al. 2008). Numerous reasons have been suggested for diminishing elasticity of gasoline including more suburban land-use creating more rigid auto commuting patterns, declining urban mass transit undermining substitute modes, improved fleetwide fuel economy (relative to the 1970s) and higher household incomes in which transportation represents a smaller share (also relative to the 1970s) (Hughes et al. 2008). These factors mean that, more than in the past, market prices for gasoline may need to be augmented to communicate the true cost of driving.

Looking abroad, in the first quarter of 2007, gas prices in France, Germany, Japan, and the U.K. were 2.5, 2.6, 1.8, and 2.7 times higher than in the U.S., largely due to higher motor fuel taxes (IEA 2007b). While gas taxes are more economically efficient than vehicle sticker price changes (because they apply per gallon of gasoline or BTU of energy consumed), they are less obvious to consumers. As a result, many experts (e.g., Duleep 2005b and Greene 2007) argue that gas taxes alone are insufficient for enticing consumers to purchase fuel efficient vehicles. Gas taxes high enough to produce such desired changes are expected to be on the order of several dollars per gallon (far more than the current 18.4 cent/gallon federal excise tax and current average 26.8 cent/gallon state excise tax) and thus probably are political infeasible (especially considering the reluctance of Congress to even adjust it for inflation, a measure which has not been enacted since 1994). However, gas taxes are a valuable complimentary measure as they can help send initial market signals to consumers of the value of fuel economy (Duleep 2005b) and also offset increases in VMT that come from a “rebound effect” when consumers purchase more fuel efficient vehicles (Greene 2007).

A long run concern with the gas tax is that improving fuel efficiency will make consumers feel the gas tax less and thus diminish its potency as a deterrent to driving. This is a concern from the standpoint of energy consumption because even with a fuel efficient vehicle fleet congestion and long driving distances will continue to increase GHG emissions. The power of the gas tax as a revenue raising tool would likewise be eroded in such a scenario. A recent estimate in decline in the gas tax base concluded that by 2025 fuel consumption per mile could be 20 percent less because of fuel economy regulation or sustained fuel price increases (TRB 2006) which would likely mean problems of fiscal solvency for states and agencies depending on funding from gas tax receipts. In the long run, user-fees may need to be reformed to be aligned with use in terms of mileage, road design, vehicle characteristics, and traffic conditions, thereby better reflecting the true cost of each (TRB 2006). The state of Oregon recently conducted a pilot experiment into per-mile and rush hour based road pricing compared to the gas tax finding VMT reductions from both of the alternative pricing schemes and favorable feedback from participants though there were some problems with execution of the experiment and questions as to how the experiment might translate to a permanent replacement of the gas tax (Rufolo and Kimpel 2007).

Another important aspect of vehicle policy related to adoption of new technologies is how long vehicles are held before they are replaced with newer, hopefully more energy efficient models. *Vehicle lifetime optimization* requires recognition of vehicle contributions to global warming beyond just the use phase to encompass materials production, manufacturing, maintenance and vehicle scrappage. The Institute for Life Cycle Analysis (1998) estimates that the production and combustion of fuel account for 105,000 MJ and 878,000 MJ of a vehicles' 1.2 million MJ lifecycle burden, based on a study of a 1990 Ford Taurus. While the fuel economy of passenger vehicles has not increased and driving distances have not fallen during the past 15 years, energy intensity of manufacturing and materials production may have fallen so these phases may represent smaller shares of lifecycle energy burden. Kim et al. (2003) employ a Life Cycle Optimization (LCO) model to find the optimal lifetime for a 1995 mid-sized passenger vehicle over a 36-year horizon (representing model years 1985-2020) using five environmental burdens (energy use, CO_2, CO, NO_x, and NMHC) as criteria. In the model, environmental burdens change with vehicle age and model year and use patterns are held constant over the modeled years. The use phase dominates for all environmental burdens. Both energy use and CO_2 burdens fall with longer lifetimes (because these result from internal combustion, which happens rather uniformly over a vehicle's lifetime and does not improve drastically from one model year to the next). Thus, vehicle lifetime does not represent a tremendous opportunity for GHG reductions under scenarios of incrementally improving vehicle technology.

In scenarios of a switch to a substantially more fuel efficient vehicle, the lifecycle GHG emissions implications can be quite different. Moon et al. (2006) study the vehicle-cycle and total energy-cycle of special, low-weight ("lightweighted") vehicles and HEVs compared to conventional vehicles. The advanced vehicles have more CO_2 intensive materials manufacture phase because of the increased use of aluminum (to reduce weights) and more advanced batteries (HEVs). However, over the total vehicle lifecycle the reductions in GHG emissions from more fuel efficient use phases far outweigh the more energy intensive materials production meaning that the lifecycle GHG reductions from lightweighting and HEVs can be substantial.

Notably, there may be tradeoffs between minimizing GHG emissions, other criteria pollutant emissions and solid waste. In the conventional vehicles, CO, NO_X, and NMHC emissions are minimized by lifetimes in a 4 to 6 year rangel, because vehicle emission control systems tend to deteriorate with age and rising regulatory standards mean older models pollute more (Kim et al. 2003). The benefits of short lifetimes with respect to criteria air pollutants are, however, decreasing as air quality legislation has affected increasing shares of the vehicle fleet. Moon et al. (2006) find that lightweight vehicles actually decrease lifecycle PM_{10} emissions because less steel is used in materials manufacturing, but HEVs increase lifecycle SO_x emissions due to the manufacture of more advanced batteries. Accelerating vehicle retirement will, of course, also increase solid waste.[20] One area of the total vehicle lifecycle requiring further study is the scrappage phase. Vehicles that achieve greater fuel efficiency due to advanced materials and drivetrain technologies may have higher energy burdens from scrappage than conventional vehicles (see, e.g., Moon et al. [2006]). More advanced vehicles may require more administratively burdensome policies to ensure scrappage of advanced components, though many manufacturers may be willing to accept the responsibility. With respect to hybrid

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[20] Another possible fate for retired vehicles is re-sale in other countries, which diminishes concerns about solid waste from scrappage but provides limited to no reduction in GHG emissions.

batteries, for instance, Honda and Toyota, offer recycling at no extra cost and Toyota charges owners a $200 “bounty” on the battery to ensure its return for recycling.

Vehicle lifetimes must be considered in the context of how long consumers typically hold their vehicles. A commonly assumed vehicle lifetime (see, e.g., NRC 2002) is 14 years; however, vehicle ownership durations are increasing as vehicle designs improve, and larger, rear-drive, and higher-end foreign vehicles all tend to be held much longer than lower cost, smaller, domestically manufactured vehicles (DesRosiers 2008). Median vehicle age has increased to 9.0 years for passenger cars and 9.6 years for light trucks (from 7.9 years and 7.7 years in 1996), while scrappage rates have fallen to 4.5% and 4.1% annually for passenger cars and light trucks (from 6.4% and 7.4% in 2000) (Polk and Co. 2006). In comparison to 1995 numbers, vehicles currently on the road are being driven 26,000 miles more over their lifetimes, in each vehicle class (Lu 2006). While the average LDT may be driven 180,000 miles over its lifetime, versus 152,000 for the average passenger car, cars are catching up. Lu’s (2006) analyses suggest that median ages of these two vehicle types are presently 14 and 13.2 years, respectively. From a policy standpoint, accelerated vehicle replacement could be encouraged through measures that make consumers value fuel economy more (e.g., higher gas taxes), along with subsidies and/or tax credits for purchasing more fuel-efficient vehicles. Concerns about solid waste and contaminants from scrappage could be decreased by legislating specific recycling procedures designating responsibility to some party (manufacturer or consumer) similar to laptop disposal laws in Europe or even aluminum can recycling in many U.S. states.

Alternative Fuels for Light-Duty Vehicles

The Department of Energy (DOE) currently recognizes the following as alternative fuels: methanol, ethanol, and other alcohols, blends of gasoline containing at least 85% alcohol with gasoline, natural gas (and their liquid fuel derivatives), liquefied petroleum gas (propane), coal-derived liquid fuels, hydrogen, electricity, biodiesel, and the P-series[21] (Davis & Diegel 2007). Figure 6 (EPA 2007a) compares the lifecycle GHG emissions of these alternative fuels, using conventional gasoline as a base (0% change).

The fuels with a positive percentage will emit more GHG per BTU provided, while fuels with a negative percentage will emit less (per BTU). For example, if a BTU of gasoline is replaced by a BTU of cellulosic ethanol, the lifecycle GHG emissions for that BTU will be reduced by 90.9%.

According to CCSP (2006), biofuels are the best near-term alternative, and hydrogen will be important in the long term, but probably not before 2025. There are still several problems with storage, transportation, and production that require resolution before hydrogen will be ready for widespread public use. Depending on how it is made, hydrogen’s lifecycle emissions can be worse than those of gasoline produced via coal gasification or may be virtually zero (CCSP 2006).

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[21] “P-Series fuel is a blend of natural gas liquids (pentanes plus), ethanol, and the biomass-derived co-solvent methyltetrahydrofuran (MeTHF). P-Series fuels are clear, colorless, 89-93 octane, liquid blends that are formulated to be used in flexible fuel vehicles (FFVs). P-Series fuel can be used alone or freely mixed with gasoline in any proportion inside an FFV fuel tank.” (DoE website, 2007b)

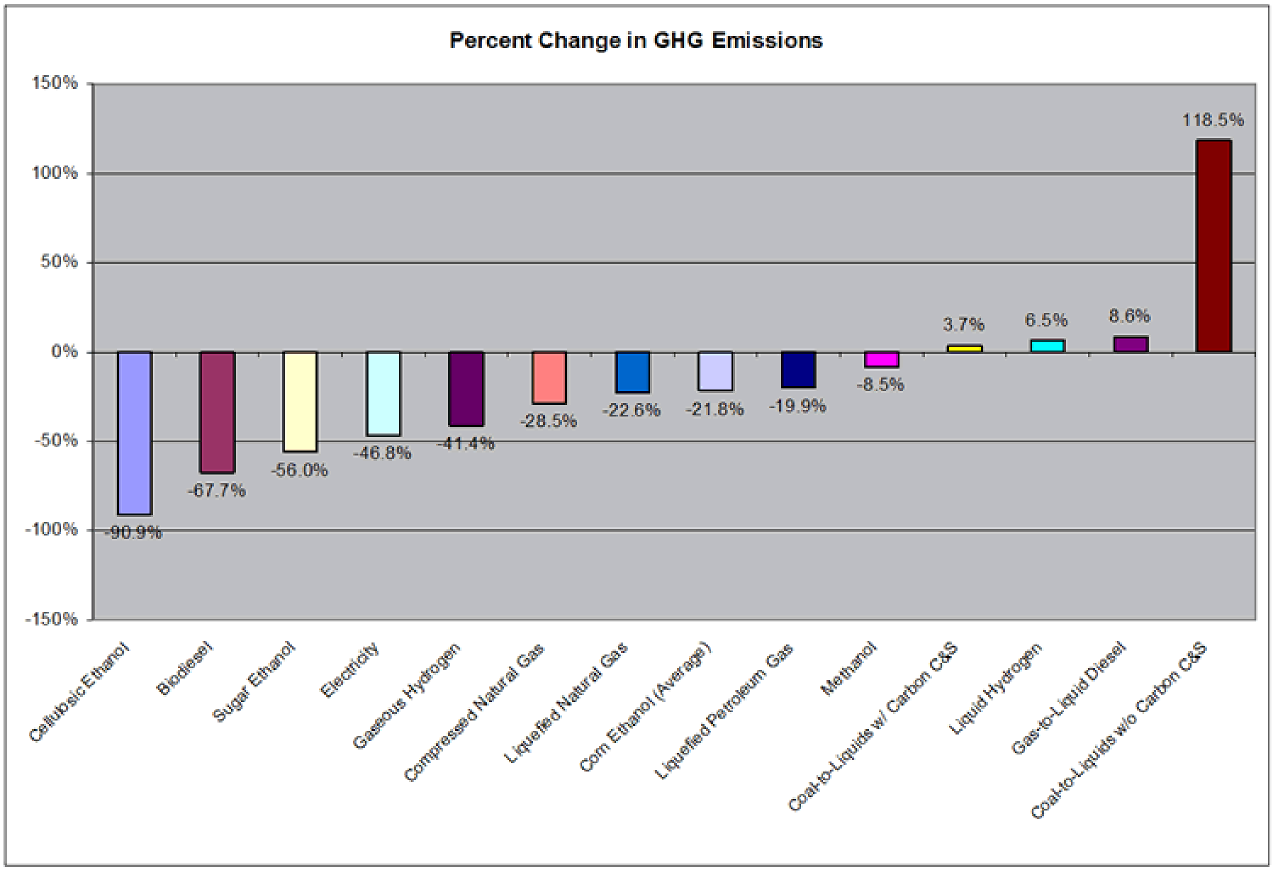

FIGURE 6 Percentage changes in lifecycle GHG emissions for a variety of fuels, relative to gasoline (EPA 2007a).

There is also variance in estimates of ethanol's carbon intensity. Corn ethanol can be produced in a wet mill or dry mill, but dry mill methods are more efficient (EPA 2007b, Wang et al. 1999). Fortunately, 99% of new plants are dry mill (EPA 2007b). In addition to this milling distinction, life cycle emissions vary by how the fuel production process is powered (coal versus natural gas). Of course, cellulosic ethanol is becoming much less emitting than the most efficiently produced corn ethanol (Farrell et al. 2006, EPA 2007a, Wang et al. 1999).

Several studies have sought to estimate the potential of ethanol fuel to reduce carbon emissions with dramatically different results. Some even suggest that using ethanol will increase emissions (Farrell et al. 2006, Wang et al. 1999). Key factors at play are the assumptions regarding co-products of ethanol production. In producing ethanol, corn syrup, corn oil, and dry feed are made, which will reduce the production of these items as well as the emissions associated with their production. Net energy estimates are most sensitive to the assumptions about co-products, and Farrell et al. (2006) note that studies claiming ethanol will increase emissions have not considered the effect of such co-products (Farrell et al. 2006).

Of course, biodiesel can be made from multiple sources, including soybeans and yellow grease. In general, producing biodiesel from yellow grease requires 1.7 times the energy needed to produce this fuel from soybeans (EPA 2007b). Soybean biodiesel is estimated to reduce CO2 emissions by 41% (Hill et al. 2006) – not accounting for land conversion effects, as discussed below.

Another factor to consider is the ability of these alternative fuels to meet the nation's demand for fuel. For example, if all U.S. corn and soybean production were used for biofuels, this would meet only 12% of the nation's gasoline needs and 6% of its diesel needs (Hill et al. 2006). Moreover, farming biofuels would require extensive changes in rural land use. Very recent studies (Searchinger et al. 2008 and Fargione et al. 2008) have estimated that the increased production and use of biofuels can be expected to *increase* CO2e emissions climate change. As shown previously, in Figure 6, increased ethanol use is estimated to save 20 and 90% of emissions (from corn and cellulosic, respectively) when replacing gasoline. However, such estimates do not consider emissions effects arising from necessary land conversions (both direct and indirect). According to Searchinger et al. (2008), it would take 167 years for corn ethanol's emissions savings to counteract the increased emissions due to land conversion. In order for biofuels to be effective in reducing emissions, they must be produced with little or no land use "carbon debt" (e.g., fuels should be produced from biomass waste, algae, or from feedstocks planted on abandoned agricultural land).

After having dramatically peaked in 2003, domestic production of natural gas has grown recently, leading to much discussion of gas's potential to displace petroleum consumption. However, this resurgence has been led by industry exploitation of shale natural gas, which is not as clean as conventional natural gas, in terms of GHG emissions per BTU (Webber 2008). Natural gas is technically workable: the distribution network is largely already available (in the form of natural gas pipes that connect to many households, for in-garage re-fueling) and other nations have successfully deployed tanks that accommodate either gasoline or natural gas rather seamlessly. While a vehicle's range can be compromised on a single tank of natural gas, the more challenging issue likely is the availability of natural gas for the transportation sector. In the short term, increasing natural gas use in the transportation sector would likely require freeing up fuel from the electricity generation sector. It is not clear if domestic natural gas reserves are sufficient for natural gas to be a substantial option for passenger transport in the long term. (Webber 2008) Use of natural gas in other fleets (for instance, buses and government vehicles) is also an option and many metropolitan areas around the world already have buses running on natural gas.

Table 8 summarizes potential savings from switching the U.S. light-duty vehicle fleet to a variety of alternative fuels, and Table 9 shows the carbon intensity of these fuels. The issues of hydrogen energy production, distribution and use prevent it from being a realistic option in the near term. While first-generation biofuels (e.g., corn ethanol) are widely available, they are not guaranteed to offer emissions savings due to the array of production methods and the possibility of causing direct and indirect land conversions. Second-generation biofuels (e.g. cellulosic ethanol) could address these problems and offer substantial reductions, but are not yet being commercially produced.

Mode Alternatives for Passenger Travel

According to the EPA (2006), U.S. GHG emissions from *bus use* increased by 15% between 1990 and 2003. About 46% of bus emissions come from intra-city transit, 38% come from school buses, and 16% come from intercity transit (EPA 2006). Apparently, transit bus VMT increased 45% between 1990 and 2002, while school bus VMT increased only 21% (EPA 2006).

Rail produces just 2% of all U.S. transportation GHG emissions, with 89% of this coming from freight rail transport (EPA 2006). U.S. passenger rail emissions (light rail, heavy rail, commuter rail, and intercity rail [Amtrak]) are relatively insignificant when compared to LDV emissions: 5 million tons of CO2 per year versus 1.4 billion tons per year. (EPA 2006)

Table 10 shows the potential emissions savings for a 1% shift away from automobile use to various modes of public transport, assuming current average vehicle occupancies (AVOs) are held constant (i.e., transit service rises in proportion to demand). While rail is more efficient per passenger mile (pax-mi) than automobile use, average bus AVO values are presently too low in the U.S. (9 passengers per vehicle) to provide GHG benefits (Davis and Diegel 2007, APTA 2007). 11 passengers per vehicle are needed to make an average bus ride equivalent to typical automobile travel (assuming the average 1.6-persons per automobile AVO), based purely on fuel use. Such occupancies may be achievable via elimination of lower-demand routes, privatization, on-demand services, higher gasoline prices, and other strategies.

Of course, 9 passengers per vehicle is far below the standard 40-foot bus capacity of 54 passengers (TCRP 2004a), and many new transit users would be rather easily accommodated within existing services. If transit supply is held constant in the face of rising demand, then all personal-vehicle VMT reductions result in un-offset GHG savings (assuming added stops and such have only negligible impacts on bus fuel use). GHG savings can then be quite striking. Table 11 shows the same comparison of LDV and transit modes, assuming *maximum vehicle occupancies*. Although it is highly unlikely that maximum vehicle occupancy rates can be achieved on average, this table provides a sense of maximum attainable efficiencies for each mode (including LDVs), assuming current technologies and fuels. This table also considers the scenario where 1% of LDV travel is shifted to transit without adding new transit service (i.e., emissions from 1% overall reduction in LDV travel).

Moreover, to the extent that bus use encourages walking and shorter trips (in order to access bus stops and reduce bus travel times) and more clustered land use patterns (to reduce access costs and trip distances), a one-to-one passenger-mile comparison is imperfect. In a world of bus-based travel, American motorized trip distances may well fall by nearly one-half, allowing for significant GHG emissions reductions (assuming bus occupancies of 6 or more). Furthermore, bus technology is somewhat similar to light-duty vehicle technology, and alternative designs and fuel sources may be more easily adopted in a bus fleet, allowing for more significant and rapid reduction of GHGs.

Human-powered transportation, such as *walking and biking*, is an important mode alternative for relatively short trips. At an average speed of 12 mph, travelers can bike a 5-mile trip in less than 30 minutes, on par with the average work commute time (Ulrich 2006). A shift from driving to biking offers obvious and significant GHG emissions savings. However, additional exercise requires an increase in food calorie intake (while potentially increasing human lifespan and lifetime energy use).

Coley (1998) found that powering a bicycle at 12 mph requires 26 BTU per mile from the cyclist, who requires 117 BTU/mile from food, which requires 675 BTU/mile for average food production[22] (Coley 1998). In contrast, 5500 BTU/mile is required by the average U.S. automobile. Ulrich (2006) estimates that, after accounting for increased food consumption and longevity[23], shifting from car to cycling 6 miles per day saves just 1.7 million BTU/year per

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[22] Just to be clear, these figures do not include sunlight's substantial energy contribution to food production.

[23] Ulrich (2006) cites rigorous studies that anticipate another 11 days of life per year that a sedentary individual shifts to biking 6 miles per weekday, or 30 miles per week. Over 40 years of biking, for example, one is expected to add a year of life, and a significant amount of food consumption (to maintain weight after forgoing the sedentary lifestyle). Of course, those biking may shorten their travel distances, give up a household vehicle and shift to other

person, or less than 1 percent of a person's yearly energy use. Of course, the energy required for food production varies. On average, Pimentel and Pimentel (2003) estimate that beef requires 54 kcal per consumable kcal, while chicken requires just 4 kcal, and grain requires 3 kcal. The emissions savings from biking could be higher or lower depending on the carbon intensity of food production and electricity sources, relative to automobiles.

Air travel was responsible for 9% of all U.S. transportation GHG emissions in 2003, with commercial air travel contributing 72% of that share (EPA 2006). While air travel presently tends to be more efficient than driving solo (FAA 2005 and WRI 2006), actual numbers depend on aircraft occupancy, trip length, and vehicle fuel economy (which varies greatly by make and model). The average commercial aircraft's emissions intensity is 0.79 lbs CO2e/pax-mi according to the FAA (2005), or just 0.4 to 0.53 lbs/pax-mi (for longer versus shorter flights) according to the World Resources Institute (WRI 2006). In contrast, the average American car (20 mpg) emits 1.3 lbs/pax-mi when driven solo. However, as the number of vehicle occupants increases, the automobile can become gradually more efficient than flying, per passenger mile (0.3 lbs/pax-mi with four passengers).

The percentage of occupied seats on domestic air carriers has increased from 60.4% in 1990 to 72.4% in 2002 (EPA 2006a), but aircraft take-offs and landings require more energy per mile traveled than flying at a constant elevation. Thus, longer trips tend to produce fewer GHGs per mile than short trips. Figure 7 compares short-, medium-, and long-haul aircraft trips with other modes, in terms of carbon-emissions intensities.

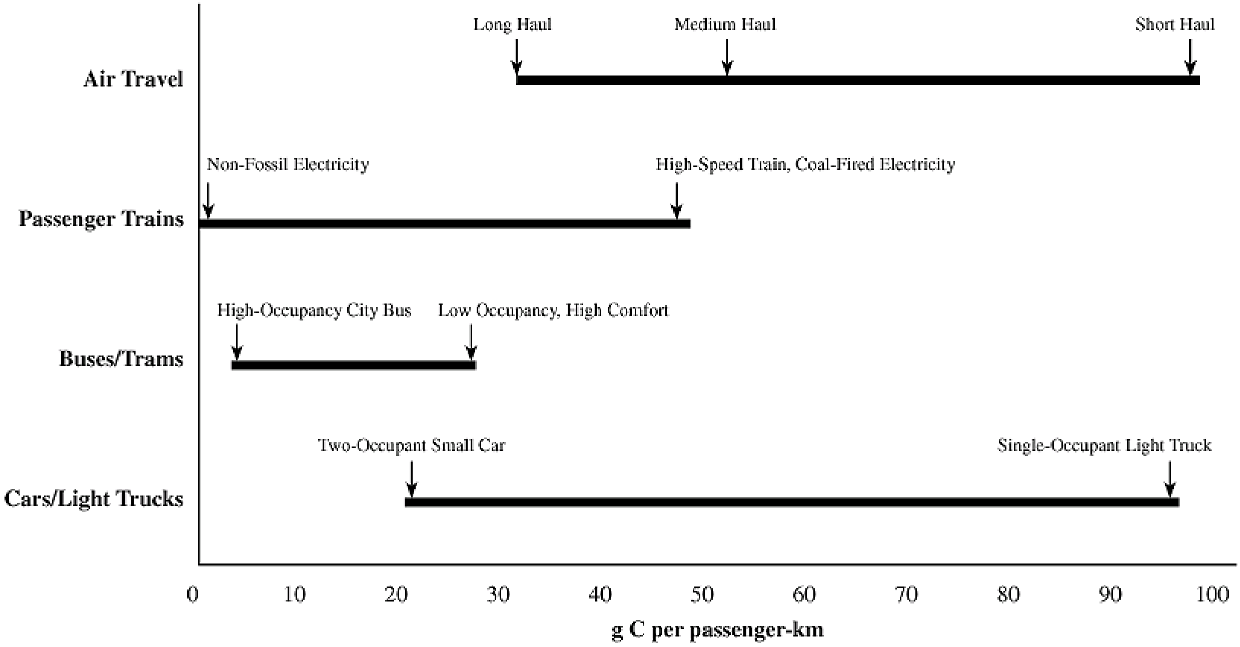

FIGURE 7 Carbon intensity of passenger transport modes (source: IPCC 1999, Fig 8-4).

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modes, make less unanticipated use of automobiles during the day, choose to eat less meat, and pursue other activities that also save energy. Either way, it is interesting that the energy implications of a shift to biking are not clear cut.

The contrails produced by aircraft exhaust may also be contributing to global warming. The extent of this effect is uncertain. Recent studies estimate that contrails could increase radiative forcing by 0.2 to 0.6%, in addition to all other human activities (IPCC 1999, FAA 2005, Fahey 2007).

Of course, the ***embodied energy*** of vehicle and travelway infrastructure provision, transit system administration, and vehicle maintenance should also be considered. Recent life-cycle analyses by Chester and Horvath (2009) suggest striking ratios of total energy to use energy for various modes of transport. Unlike buildings, where lifetime use energy demands (and thus GHG emissions) dominate (as discussed later in this report), most transport systems face high total-to-use energy ratios. Chester and Horvath's (2009) full-cost accounting bumps energy and GHG use-based emissions totals up by 47% for on-road transport (based on three vehicle models and two bus types), 121% for rail transit (based on San Francisco Bay Area Rapid Transit [BART], Caltrain and Muni Metro systems, plus Boston's Green Line), and 24% for air travel (based on small, mid-size and large aircraft). In other words, air transport begins to look more competitive, while non-bus transit modes look less competitive.

Freight Transportation

Freight transport currently contributes 38% of transportation's GHG emissions, and 11% of all U.S. GHG emissions (EPA 2006). Five freight modes exist: truck, rail, air, water and pipeline; and these constitute 60, 6, 5, 13, and 16 percent of freight GHG emissions, respectively (Frey and Kuo 2007). Rail is generally the most fuel efficient among these: in 2001 air-carriers required 7.5 times more energy to carry a ton-mile than the average truck, 17 times more than ships, and 83 times more than rail (EPA 2006). Figure 8 illustrates recent trends in freight mode shifts.

Trucking is gaining mode share due to its significant scheduling and routing flexibility. The U.S. and world economies are shipping higher-value goods, like electronics, pharmaceuticals, and food, and are switching to just-in-time delivery, which requires smaller and more frequent shipments (EPA 2006). These changes have contributed to the increase in truck

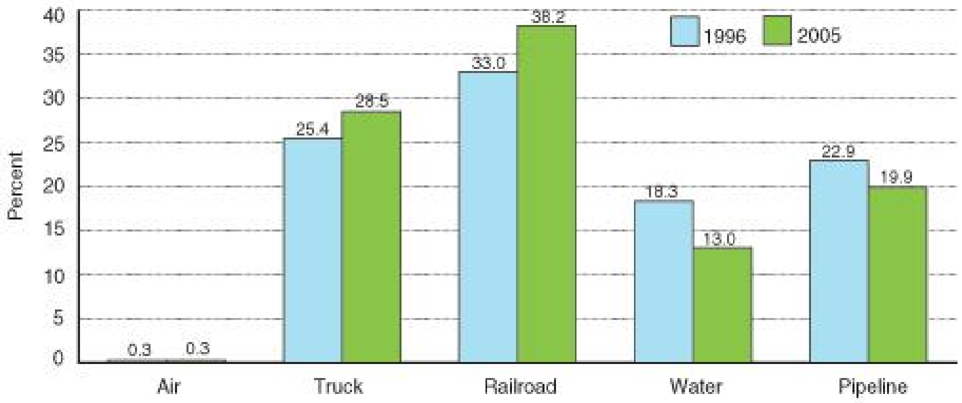

FIGURE 8 Freight mode shares and ton-miles in 1996 and 2005 (source: BTS 2007b, Figure 3).

freight VMT. Over the last 15 to 20 years, truck's share of ton-miles has increased from 26% to 32% (EPA 2006), while mode energy efficiency has fallen 10% (in terms of ton-miles per pound of CO2) (Davies et al. 2007). It can be assumed that this drop in energy efficiency is due to decreases in operational efficiency (e.g., more miles where trucks are traveling empty, or "dead heading"), since HDT fuel economy has remained constant or increased over the same time period (FHWA 2007, Davies et al. 2006, Bertram et al. 2008).

Ton-miles shipped by rail have risen by 59% since 1990, as a result of increased intermodal shipping, growth in international trade, and double-stack rail services (Davies et al. 2007). In addition to being less fuel-intensive, rail also is about 60% cheaper per ton-mile shipped, but obviously more limited in terms of delivery scheduling and site access (Davies et al. 2007).

Aviation is the fastest growing freight transportation mode, with a 63% increase in ton-miles observed between 1990 and 2003 (EPA 2006). However, aviation presently carries less than 1 percent of total U.S. ton-miles, as shown in Figure 8.

With rising trade, truck's rising mode share, and lower ton-miles-per-gallon by trucks overall, it is not too suprising that freight-based GHG emissions have increased by over 50% between 1990 and 2005, nearly twice the rate of increase from passenger transport (Davies et al. 2007). Table 12 shows potential CO2e emissions savings from a one percent mode-shift away from trucks to rail or water. (Aviation is not included in these modal comparisons, because available data does not distinguish between passenger and freight energy use. Pipelines also were excluded, due to a lack of appropriate data.) Moreover, with increased shipping of higher value goods and rising demand for just-in-time deliveries, a shift to rail transport appears impractical for many shippers. In such cases, an obvious option for reducing truck freight emissions is to increase trucking energy efficiency through technological and operational strategies. These include improvements in vehicle aerodynamics (via side skirts and airfoils, for example), reduced idling and dead-heading (i.e., running empty), better speed choices (including reduced congestion at ports of entry), reduced rolling resistance and single wide-based tires, alternative fuels, and increases in vehicle payloads and capacity. (Note: Many of these topics are touched on at http://www.afdc.energy.gov/afdc/vehicles/fuel_economy_heavy.html.)

Idling Reductions

Several strategies target idling reductions, and these include auxiliary power units (APUs), truck-stop electrification (TSE), direct-fire heaters, and automated engine idle systems. APUs are portable units attached to the truck, and generally diesel powered; these can provide climate control and power other cabin devices. Direct-fire heaters are similar to APUs. These external units provide in-cabin (and engine) heat, but do not provide air conditioning and cannot be used to power other cabin devices. It is estimated that use of APUs and direct-fire heaters could reduce fuel use by 9% and 3.4% per truck, respectively (Ang-Olson and Schroeer 2002). Typical units range in price from $1,500 (direct-fire) to $7,000 (APU) (DoE 2007).

Automated engine idle systems are used to sense cabin temperature and turn the engine on and off, as needed for climate control. These have the potential to reduce fuel use by nearly 6% per truck (Ang-Olson and Schroeer 2002). Typical pricing for a retrofit starts at $1,200 (DoE 2007).

TSE systems externally provide climate control and/or power to truck cabins. Single-system electrification consists of an external climate control unit with a hose that delivers the warm or cold air to the truck cabin, and requires no on-board equipment. Shore power systems are simply stations with electrical outlets used to power on-board climate control systems and other devices while the truck engine is off. The truck must be equipped with an electrical plug and an electric HVAC system. These systems typically accept on-site payment by the hour, and, currently, there are 130 TSE locations across the U.S. (DoE 2007).

Of these four idle reduction strategies, APUs offer the most energy savings, but also cost the most up-front. However, DOE (2007) estimates that associated gas savings should cover APU costs within just two years. Table 13 shows the potential U.S. transportation CO2e emissions savings to result from such systems, assuming that 1% of truck miles are driven by vehicles equipped with an idle reduction unit.

Shortening Supply Chains

In addition to improvements in freight vehicle technology and fuels, operational strategies may offer substantial GHG savings. One possibility is reduction in travel distances via more local purchases. For example, it is estimated that the average distance traveled by most produce and processed food in the U.S. (from farm to plate) is about 1500 miles (ATTRA 2008)[24]. Distances traveled, as well as the fraction of imported foodstuffs, have increased steadily over the last 50 years (Pirog & Benjamin 2003, ATTRA 2008). The average fuel economy of a truck carrying foodstuffs is 5.85 mpg (BTS 2003). Thus, assuming a payload of 19 tons (Pirog et al. 2001), the average pound of food consumed in the U.S. may generate 0.17 pounds of transportation-related CO2 emissions.

Pirog et al.'s (2001) Iowa-based study compared three food sources (conventional, averaging 1500 miles; regional, from within the state; and local, within 50 miles), and estimated the difference in fuel use and GHG emissions for 10% of Iowa produce (28 items). They found that annual CO2 emissions could be reduced by 3.5 thousand tons if 10% of Iowa's produce were obtained from local or regional sources. While this savings may seem minor, the food items considered represent only 1% of Iowa's food consumption, so the potential savings is much greater. The authors estimated an annual CO2 reduction of nearly 100 thousand tons using a five-state effort (involving Iowa, Minnesota, Wisconsin, Indiana, Illinois and Michigan), thereby reducing average travel distances by 273 miles (to an average of 1,981 miles), still only considering the same 28 produce items. Nevertheless, Weber and Matthews (2008) find that only 11% of the roughly 8 metric tons of CO2e that the average U.S. households generates annually from its food consumption comes from transport of that food, and food accounts for only 13% of the average U.S. household's total CO2e contributions.

In addition, production emissions vary by food source. Per calorie of energy provided to the final consumer, red meat has been recently estimated to be roughly twice as GHG-emitting as dairy, and three times that of chicken, fish, eggs, fruit and vegetables (Weber and Matthews 2008). Evidently, the methane that cows release and the N_20 released by soil bacteria in producing the cows' feed are the key GHG contributors from raising livestock (Engelhaupt 2008, citing Weber and Matthews 2008). Interestingly, Pimentel and Pimentel's (2003) somewhat earlier work suggests much higher ratios, for red meat to poultry and grains (on the order of 10 or more). Both studies were conducted rather differently, with Weber and Matthews (2008) focused on an input-output analysis of agricultural production, and allocating emissions according to sales volumes, while Pimentel and Pimentel (2003) evaluated energy demands from

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[24] As an example, the average "locally produced" food item in Iowa travels just 50 miles (Pirog & Benjamin 2003).

a much more biological perspective[25]. Either way, much greater savings are thus expected to accrue by small shifts in one's diet rather than buying local. For a household to consume a completely local diet (which is highly unlikely), the savings would be equivalent to driving 700 miles less per year (assuming a 20 mpg vehicle). Weber and Matthews (2008) estimate that shifting a household's diet from red meat to chicken, fish, eggs, vegetables and/or fruit just one day a week will yield a similar GHG savings[26]. Table 14 shows the GHG savings estimate resulting from 1-percent of U.S. households eliminating red meat consumption from their diets 1 day a week and 7 days a week, along with savings estimates due to the purchase of local food (as described by Weber and Matthews [2008]).

Of course, buying used items – instead of new items – offers similar benefits from transport emissions, as well as significant savings in other forms of embodied energy (by avoiding new production). A well-known, web-based program for re-sale of used goods is www.craigslist.org, offering free access to information on a variety of personal items for sale (and for free) in 450 cities worldwide. Freecycle.org also operates in nearly all major U.S. regions, alerting locals to others' unneeded, and free, items.

3. BUILDING DESIGN

Buildings use two-thirds of the nation's electricity for operations and maintenance, and the housing sector alone is responsible for 21% of the nation's total energy use (EIA 2000). A home's energy demands can easily outweigh its associated transport demands: Walker and Rees (1997) estimate that 44% of the average British Columbia's household's GHG emissions come from motorized transport (assuming a single-family detached residence) versus 53% for operation of the home itself. Similar numbers were found in a compact development study in Helsinki by Harmaajarvi et al. (2002).[27]

59 percent of U.S. households live in single-family detached units, representing significant potential for energy savings (Brown et al. 2005). In even broader terms, O'Neill and Chen (2002) examined EIA data to determine which demographic factors most influence a household's residential energy consumption. Most notable are age and number of household members, but household income also plays a key role. While average residential energy use steadily rises with income, per capita energy use falls with increasing household size. O'Neill and Chen (2002) also find that energy use tends to fall as household members age, suggesting that an aging Baby Boomer generation may offer the U.S. some savings. However, Tables C3 through C6 in Appendix C of this report present regression results based on the RECS data set described earlier, and these suggest that adults over 65 years of age use, on average, 165 kWh more electricity and 27 ccf more natural gas per year (221.1 and 32.6 lbs of CO2e per year, respectively) than the average household member in a single-family home. In multifamily

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[25] For example, a newborn calf's mother must be supported for an entire year, while a hen can lay 300 eggs during the same period. (D. Pimentel, email communication on 16 October 2008)

[26] It is interesting to note that the U.S. maintains 9 billion livestock animals (including chickens, pigs, cattle, sheep and so forth) to meet the nation's demand for animal protein. These billions of animals outweigh the U.S. human population by a factor of five and consume seven times more grain than Americans consume. (Pimentel and Pimentel 2003)

[27] These authors estimate the remaining 3 to 4% of energy to be required for provision of municipal infrastructure. Home heating needs will be less in more temperate climates, rendering transportation (and infrastructure) a higher share of associated energy use.

homes, however, this regression coefficient is negative, so other factors may be at play (such as household size, health, and income).

Many experts agree that advances in transport technology and building design will not be enough to offset emissions from rising demand (ORNL 2000, Brown et al. 2005). While refrigeration energy demands are predicted to fall from 9% in 2005 to 4% in 2020, energy demand for commercial office equipment is expected to rise from 9% to 12%, over the same time period. (ORNL 2005) In order to institute meaningful changes, the report recommends a range of policy options geared toward manufacturers, consumers, designers and officials. Through Smart Growth initiatives, based on zoning and mixed-use ordinances, policymakers can reduce various "leap frog", heat-island, and other effects caused by poor growth management. Location Efficient Mortgages (LEMs) and Smart Growth Tax Credits (SGTCs) are examples of how policy can influence the building sector while benefiting both builders and consumers. The SGTC is designed to encourage developers to invest in "locationally efficient residential and mixed-use construction projects that minimize land and water consumption, are pedestrian friendly, and facilitate use of public transit" (Brown et al. 2005, p. 45). Such programs were actually the catalyst for creating LEED standards for neighborhood development (LEED_ND). While savings from efficiency improvements in buildings typically more than offset costs, such improvements appear unlikely without extensive policy changes. (Brown et al. 2005)

New buildings account for 2 to 3% of existing building stock each year, and the square footage of U.S. building stock[28] is expected to increase by 70% by 2035 (Brown et al. 2005). While the impact of new construction practices will have a rising impact over time, renovations to existing buildings may prove more valuable, since more than half of today's stock will still be standing in 2050 (Brown et al. 2005). The following subsections examine different aspects of residential and commercial building design that have an impact on energy consumption.

Embodied Energy

A building's embodied energy comes from the energy required to produce its materials, as well as construct, renovate and demolish it, and has been quantified in several Australian studies (Thormark 2002, Cole and Kernan 1996, Nithraratne et al. 2004, and Adalberth 1997). In most cases, the energy required for building production accounts for only 10-15% of the building's lifetime energy needs (Guggemos and Horvath 2005, Thormark 2002, Adalberth 1997, Björklund et al. 1996), over a roughly 50-year lifespan (Brown 2005), with building operations accounting for the other 85%. As operating energy requirements fall, due to rising efficiency, the fraction of embodied energy will rise, up to 40 to 60%[29] of the total. Furthermore, since most of the embodied CO_2 in building materials is a result of the combustion of fossil fuel in their production, the importance of the electricity grid and advances in technology are magnified (Alcorn 2003).

Due to lack of detail in what is included in some embodied energy studies, it can be difficult to compare them (Cole and Kernan 1996). Most estimates include transport of materials, and Thormark (2002) reports that 75% are transported 200 miles or more, a significant figure. Thormark (2002) also found that operating energy is mostly impacted by insulation thickness in

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[28] U.S. building stock in 2001 was approximately 265,000 million SF, and 200 million SF of this was in residential use (EIA 2001).

[29] 40% assumes a 50-year life span, which is rather typical (Brown 2005), while 60% assumes a shorter building life span.

Sweden's most efficient building in 2002. This single-family home had nearly 500 mm of combined mineral wool and expanded polystyrene (EPS) insulation throughout (Thormark 2002). Alcorn (2003) improved upon a comprehensive database of embodied energy coefficients, and concluded that the first step to reducing design impact could be improved insulation, due to its significant effects on operating energy over time.

Cole and Kernan (1996) note that the embodied energy of building and other materials continues to fall as the technology to produce them becomes more efficient. For example, between 1971 and 1986, energy intensity for steel and cement decreased by 20.5%, 20% and 33%, respectively. As technology improves, the differences in embodied energy across materials will not matter as much as the quantity of materials. Alcorn (2003) determined embodied energy coefficients for hundreds of building materials and found that four forms of aluminum had the highest embodied energy and embodied CO_2. And eight timber products actually had negative values, indicating a net absorption on CO_2 (Alcorn 2003). While some forested regions may not be considered a significant carbon sink (due to their latitude and type of vegetation), the fact that timber is renewable, embodies less CO_2 in its production, and can actually absorb carbon over its lifetime makes it the cleanest option among construction materials[30]. Again, however, these material distinctions become less important over a 50 or more year life time.

Of course, recycling of building materials can mean great reductions in embodied energy through all stages of a building's life cycle. Thormark (2002) estimates that up to 37% to 43% of a building's embodied energy can be recovered through recycling of its materials. That is, various building materials ultimately can be re-used elsewhere, effectively having a zero impact during their first life-cycle. For example, some materials, like clay brick, can be reused in the same fashion. Other materials, like gypsum plasterboard and concrete blocks, can be used as fertilizer or aggregate in concrete production (Thromark 2002).

Cost Considerations

Is the cost of upgrading one's home design covered by energy savings? Tables C8 and C9 provide estimates of attic and wall insulation costs. Basic calculations and the literature suggest that attic insulation is almost always worth the investment, and is simple to install. In terms of wall insulation, new-building codes should require a minimum of R21 insulation during construction, at least in the colder U.S. climate zones, and standards should be raised on renovations.

Window costs depend on manufacturer and quality. One double-pane window can cost from $500 to $900, but will cost 20 to 30 percent less when buying in bulk (e.g., 20 or more windows). For a single, high-quality, triple-pane window, one can expect to pay $700 to $1000. (FHI Windows 2007) Given the high cost of upgrading existing windows, it is hard to imagine these covering their cost based on energy savings alone (unless losses around the frame are significant, for example). A single- to triple-pane upgrade throughout a home in Boston, Massachusetts, for example, with low emissivity and an insulated frame would generally save at most $800 per year, which is the price of just one window. In Phoenix, Arizona, home owners may expect to save just $200 annually, when upgrading all windows from single pane to double pane design. (See, e.g., http://www.efficientwindows.org/index.cfm.) Nevertheless, if one's windows already need replacing, the added cost of an energy-efficient window is often worth the

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[30] Cole (1996) also examined embodied energy of building materials, and estimated that wood, concrete, and steel framed structural alternatives represent 3.7, 5.6, and 6.6 GJ of energy per square meter of built area, respectively.

investment in the coldest climates. In the southern U.S., however, simply applying window treatments (including screens, better blinds and curtains) is a wise choice, to prevent solar heat gain during the summer months.

In general, Mithraratne et al.'s (2004) investigations lead them to conclude that, while the initial costs of improvements in home energy efficiency may have long pay-back periods, such benefits will be realized over time, particularly as energy prices continue to rise.

LEED Building Standards

The U.S. Green Building Council (USGBC) has created a series of Leadership in Energy and Environmental Design (LEED) Standards to guide development in a more economically and environmentally sustainable direction (USGBC 2008). Standards exist for various projects, including schools, homes, retail businesses, and healthcare establishments, but for the purposes of this report, focus is placed on LEED for New Construction and Major Renovations and LEED for Existing Buildings: Operations and Maintenance. A total of 69 points are possible, with certified, silver, gold and platinum status being achieved at 29, 33, 39, and 52 points, respectively. The guidelines offer many opportunities for CO_2e savings via infill development and new construction. For example, 1 point can be earned by constructing or renovating on a previously developed site and with a minimum building density of 60,000 SF per net acre. Another point can be earned by placing a site within one-half mile of existing or planned commuter rail, or one-quarter mile of public bus lines. Similarly, 1 point is awarded for providing adjacent vegetated open space equal in size to the building's footprint. Points also can be earned by moderating urban heat island effects: e.g., 1 point if 50% or more of the building's rooftop is vegetated. (USGBC 2008) Unfortunately, points are not awarded on actual building performance (e.g., kWh of electricity used per square foot per year), and LEED-rated buildings can perform poorly relative to their non-LEED counterparts. (Lstiburek 2008, Turner and Frankel 2008)

Parking provision can significantly impact travel mode and thus destination choices, and LEED standards do recognize this, to some extent. One point is awarded for residential development that hits minimum local parking requirements while facilitating shared vehicle use (via infrastructure and programs). In a redevelopment zone, this parking point is awarded when developers provide no new parking. Ideally, such point levels should be tied to use and impact, especially since the same point can be earned by providing bicycle storage for just 5% of building users. Furthermore, the impact fees developers may have to pay for parking reductions can be significant (Shoup 1997). Finally, only 1 point is awarded for providing "ongoing accountability of building energy consumption over time" (USGBC 2005), which seems a lost opportunity for long-term energy management.

While LEED standards for new buildings exhibit several limitations (Lstiburek 2008, Turner and Frankel 2008), LEED standards for existing buildings appear highly progressive and much more challenging to meet. A maximum of 92 credits are available, and certified, silver, gold, and platinum status levels are achieved at 32, 43, 51, and 68 points, respectively. While some points are similar to those previously mentioned (e.g., heat island credits), an existing building can earn 4 to 5 points for accounting for building energy consumption for the previous five years or length of building occupancy, as well as having systems in place to monitor future energy consumption. There also is 1 point for sustainable food purchases, when at least 25% of foods served on the premises are grown within 100 miles of the site, and/or are certified as having fair trade or organic origins. And 1 to 4 points are awarded for 10% to 75% reductions in conventional commute trips. The baseline case assumes all trips are single-occupancy-vehicle (SOV) commute trips in conventional automobiles. Such points will require meaningful collaboration among planners and building owners to guide future development, but may prove difficult to measure.

Residential Cooling and Heating Loads

The Energy Information Administration (EIA) makes available detailed energy-use data for samples of U.S. households and businesses. Using ordinary least squares regression techniques, one can estimate the marginal impacts of various building design features, user attributes, and appliance information on energy demands. The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE 2001) lists the average number of heating degree days (HDDs) and cooling degree days (CDDs) for most U.S. cities. Using these values, one can anticipate marginal differences in heating and cooling demands between and within cities.

The EIA's 2001 Residential Energy Consumption Survey (RECS) includes data for 4,822 U.S. households (out of nearly 110 million), and Table C2 provides RECS-based averages of various variables of interest. In the case of single-family dwelling units (SFDUs), these statistics indicate an annual electricity demand of 4,239 kWh and 183.5 ccf in natural gas per household member and 4.64 kWh and 0.20 ccf per square foot of housing. For multi-family dwelling units (MFDUs) the per-person averages fall dramatically, while square foot averages increase: the numbers are 2,958 kWh and 129.4 ccf per household member and 6.00 kWh and 0.26 ccf per square foot. However, RECS data do not provide information on communal energy demands of MFDUs (e.g., heated pools and laundry facilities, elevator operations and lighted parking lots). Those may add another 10 percent of apartment complex energy needs (Siegel 2009, Stone 2009). Table 15 provides regression results of home and apartment energy use as a function of various dwelling and household attributes, based on the RECS data set. For the full regression results, readers may refer to Appendix C.

To compare CO_2 emissions from residential energy use, 20 sample cities were selected from all U.S. census regions and nearly all 20 climate zones as defined by the EIA's Energy Consumption Survey methods. Based on average CDDs in each region, one can approximate the cooling loads for typical housing configurations using methods employed in the LBL Home Energy Saver, adapted from ASHRAE standards (LBL 2007, ASHRAE 2001).

A highly accurate estimate of home heating loads requires very detailed data (including window size and placement, for example) and more time than this work permits. Variables in the RECS data set include information on heating methods and home size, but lack several other details. The commercial-building data includes more variables, such as presence of ductwork and recent renovations, but most of these variables are provided as yes/no responses, and so are not as helpful in quantifying relative effects as are more continuous control variables.

Total home cooling loads are most easily determined from the hours per year of air conditioner (A/C) operation. Fifty-nine percent of all U.S. homes and 90 percent of all *new* U.S. homes now employ central air (RECS 2005), versus 34% of new homes back in 1970. The associated CO2 emissions per kilowatt-hour vary for the climate zones, and the base case assumes a 2,400+ square foot (SF) home (NAHB 2007). For a 2,000-2,500 SF home, Energy Star recommends an A/C unit with 34,000 BTU/hr capacity (Energy Star 2008). However, if the home is well shaded, one can purchase a unit with a capacity of only 30,000 BTU/hr. This is equivalent to downsizing the home by 500 square feet. Additionally, buying a new A/C unit could reduce energy demands by a third, and thus result in varying degrees of CO2 emissions reductions. The highest cooling loads are in Climate Zone 5 (Miami, Austin, Atlanta, and Las Vegas). In this region, such simple changes can have significant energy savings. Reducing the time that an A/C is operating during peak summer months by just one hour per day can significantly impact national CO2 emissions, in the range of 8,000-10,000 lbs per household. If all 40 million households in the southern United States did this, the CO2e reduction would be equal to approximately 180 million tons, or 7% of current U.S. transportation GHG emissions and 2.25% of total US emissions. Table 16 summarizes these savings for a variety of cities of different sizes and climates.

By the same reasoning, it will be important for consumers to ensure that they are matching the capacity of their home's heating, ventilation and air-conditioning (HVAC) systems to their needs. Over-sizing an A/C causes a unit to cycle on and off more frequently, resulting in greater energy consumption (Brown et al. 2005).

It is also important to note that 1 unit of energy from electricity delivered to the home is almost always more carbon intensive than relying on natural gas at the home, due to different loss rates in the energy production and provision process. Natural gas burns roughly 50-percent cleaner than coal at the power plant, but losses in power generation mean that electricity to heat one's home, even if natural gas is the sole power feedstock, cannot compete with burning natural gas directly. Natural gas burning on site is 90% efficient, while electricity is roughly 27% efficient (implying an approximately 3 to 1 ratio).[31]

Average new-home size in the U.S. is approximately 2400 square feet, and new-home sizes have been rising at a rate of roughly 30 SF per year over the past decade (NAHB 2007)[32]. For a SFDU, the total CO2 emissions from electricity and natural gas consumption per square foot per year is estimated to be 10.29 pounds. For MFDUs, the average unit is estimated to be responsible for 7.44 pounds CO2e per square foot per year (from electricity and natural gas), all else equal[33]. For every household in a SFDU that downsizes from 2400 SF to 2000 SF, the total annual emissions reduction is estimated to be just 770 pounds. This sort of change in housing stock requires a relatively long term. If 1% of the 126 million US households were to do so (e.g., if the majority of this year's new housing stock was sized at 2,000 SF or less, per unit), the nation's total emissions of CO2e are predicted to fall by 0.006%. Of course, larger homes are generally associated with larger lot sizes, lower densities, and potentially more driving. There also are significant embodied energy impacts that should be considered for a comprehensive, life-cycle perspective (see, e.g., Guggemos and Horvath 2005). In general, MFDUs are associated with lower embodied energy requirements (along with lower maintenance-energy [and water] requirements), thanks to economies of scale and shared walls and ceilings/floors, as well as smaller parcel requirements and smaller units. (Siegel 2009) MFDUs do depend more on electricity than on natural gas than do SFDUs (thanks in large part due to the higher cost of individual-unit gas delivery and metering), and on-site burning of natural gas offers a significant

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[31] See, e.g., http://www.fuelingthefuture.org/contents/MoreThanEnergy.asp.

[32] The average new home size in 1990 was 2050 SF; in 2004, it was 2450 SF. (NAHB 2007) According to RECS (2001), there were 107 million dwelling units in the U.S. in 2001, with roughly two million new units constructed every year, and another 7 million existing units being sold each year.

[33] The average interior area of all SFDUs represented in the 2001 RECS data base is 2540 square feet, while the average MFDU measured 1078 square feet. The (weighted) average of all such dwelling units is 2096 square feet (RECS 2001).

GHG savings. As the grid becomes cleaner over time, MFUDs are expected to fare even better, relative to SFDUs.

While home size is of some interest, home design appears to be more important in the energy debate. Insulation thickness is the considered the single most effective way to reduce a home's energy demands; and, as insulation gets thicker, home down-sizing emissions benefits fall. (Essentially, as the building envelope becomes more efficient, size is less important.) Overall, the CO2e savings one may expect by moving to a smaller home are not found to be nearly as significant as the savings one could have by switching to a PHEV or driving a vehicle that runs on biodiesel. Yet rehabilitating and upgrading existing structures can be very helpful. For example, data on non-residential buildings (from the Commercial Businesses Energy Consumption Survey [CBECS], as detailed in Table 17 and Appendix C) suggest that replacing insulation that has been in place for approximately 20 years will save a building owner 3 kWh per square foot per year and approximately 9 MBTU/sqft/year of major fuel (typically natural gas). This is a combined savings of about 14 lbs CO2e per square foot per year. For a 2,400 square foot home, this is 33,600 pounds of CO2e per year, or 2,800 pounds per month, on average. Of course, the savings are greater in colder, northern climates than in the southern United States. If 1% of households were to upgrade their unit's insulation, such as moving from R11 (90 mm) to R60 (500 mm), this is estimated to result in a total savings of 0.243% of current US emissions.

As exposed surface area increases, the amount of heat transferred either into or out of a building increases. Shorter buildings tend to be more efficient than taller buildings, in general, because more of their volume relies on the ground/soil, which offers excellent insulation. Similarly, more square footprints (approaching a half-sphere design, in theory) should perform better, by maximizing interior volume to exposed (wall and rooftop) area. And, as base-floor area increases, ASHRAE data (and spherical theory) suggest that building up should become more energy-efficient, as in the case of multi-family dwelling units. Regressions of the RECS data (Appendix C) suggest that each additional floor in a single-family dwelling unit results in an average added energy demand of 7.48 hundred cubic feet (ccf) of natural gas per year, everything else constant (including interior square footage). In multi-family dwelling units, each added building floor is estimated to increase each household's consumption by 1.25 ccf/year (but decrease electricity consumption by 29 kWh/year); however, as the number of apartments increases, this number (per dwelling unit) falls such that the energy savings of increased units is greater than the added energy demand from additional floors.

This last result is due to the fact that shared walls reduce heating and cooling needs of individual units. For example, the average household in a single-family dwelling unit (SFDU) is estimated to require approximately 395 ccf of natural gas and 14,980 kWh each year, while the same household in a multi-family dwelling unit requires only 196 ccf natural gas and 11,608 kWh. As noted in Appendix C's regression results, this finding suggests that CO2e savings in moving from a 2400 sf SFDU to a same-sized MFDU is approximately 2.85 pounds CO2e per square foot. This equates to an annual savings of 6,847 pounds of CO2e per unit. If 1% of US households made such a move, the aggregate savings is estimated to be 3.66 million tons, or 0.055% of current U.S. emissions[34]. Further, based on regression results, each additional unit in an apartment building is estimated to reduce all other units' energy consumption by 4.4 kWh and

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[34] If one conservatively assumes that RECS is missing 10 percent of energy expenditures by MFDUs (thanks to communal uses) and ignores the benefits of embodied energy savings (from MFDU construction practices), this percentage savings falls to 0.0407%.

7.95 ccf each year. This translates to roughly 15 lbs of CO2e reductions annually, per household and per added unit in the building. When the effect of added floors is factored in, annual CO2e savings is estimated to be around 55 pounds per unit. For example, households in a 5-story, 10-unit building are predicted to have energy demands that produce 273 pounds less CO2 each year than households in a 2-story, 4-unit apartment building, all else equal (see Appendix C). A one-percent increase in households residing in such high-rise MFDUs (versus low-rise MFDUs) is expected to then result in a 0.00216% reduction in aggregate US emissions. If the average household went a step further, relocating from a 2400 sf SFDU to a 2000 sf MFDU, the total CO2 emissions savings would be approximately 7,375 lbs. A one-percent shift of this sort could result in an aggregate savings of 3.95 million tons of CO2e, or 0.059% of US emissions[35].

Before continuing, it should be mentioned that these estimates do not recognize the material and other embodied energy savings that are likely to emerge from large-scale building practices (typical of MFDU construction). However, the RECS data also generally cannot account for communal energy uses that should be ascribed to many MFDUs, such as heating and cooling of shared hallways, pools, apartment complex offices, parking lot lights, and so forth – along with outdoor watering. Thus, the energy savings resulting from a move to MFDUs, away from SFDUs, could be higher or lower, depending on how these two effects compare. Experts expect that MFDUs are more energy (and water) efficient, even at the same interior square footage as SFDUs. (Siegel 2009) More benefits could emerge if unit residents were metered separated and able to select building upgrades (e.g., added insulation); the principal-agent problem tends to result in energy inefficiencies. (See, e.g., Haun 1985.)

Related to all this, the U.S. share of MFDUs has been rising over the past few years, to roughly 40 percent of all residential units built per year, while the share of SFDUs has fallen, to roughly 55 percent, as shown in Appendix Figure C1. There may be opportunities to shift these shares much further, and increase the lifetime of MFDUs, through higher-quality construction practices.

To summarize: In the short term, substantial energy savings can be realized by adding wall and roof insulation to one's home. Longer term savings can be achieved via downsizing and sharing walls, particularly via a move towards multi-unit building types. Just as heating becomes more efficient as one downsizes and/or introduces shared walls, cooling load calculations yield similar results. While it is not easy to account for solar convection and radiance, heat gained through windows (a form of solar radiance) can be important in cooling load calculations, and ideally would be included in such calculations. Finally, energy embodied in the construction and maintenance of buildings of different size and complexity is important and should be included for more comprehensive energy and GHG emissions estimates.

Non-Residential Energy and Emissions

Many companies view climate change as a serious issue because of the many opportunities and risks it presents (Carbon Disclosure Project 2007). Risks relate to increasing regulation as well as rising energy costs, and opportunities involve developing new products and services to meet changing consumer demand (Carbon Disclosure Project 2007). Global companies are recognizing the financial and reputation benefits of GHG reduction, as their businesses become

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[35] If one conservatively assumes that RECS is missing 10 percent of energy expenditures by MFDUs (thanks to communal uses) and ignores the benefits of embodied energy savings (from MFDU construction practices), this percentage savings falls to 0.0453%.

threatened by global warming and they are forced to think of creative solutions to save money in the face of growing costs. Many of the topics addressed in this report illuminate ways that industries can become less energy intensive and carbon-emitting, by improving building and vehicle designs, fleet operations and supply chains.

Missing item responses within the EIA's Commercial Businesses[36] Energy Consumption Survey (CBECS) data make it relatively difficult to calibrate regression models, as compared to the RECS microdata for households. Fortunately, average energy consumption variables are useful in understanding various behaviors, and we are able to evaluate various forms of energy consumption per square foot for year 2000's 5,094 business records[37].

Table 17 summarizes a variety of energy consumption variables for non-residential buildings. These numbers suggest an average building age of 30.9 years, that older buildings (of 50 or more years) are more likely to have undergone renovations within the prior 20 years, and these renovated buildings consume 2 to 4 kWh/square foot per year (versus 17.15 kWh/sq ft average) less than buildings that have not undergone any renovations[38]. Almost 5,000 buildings of all types were again surveyed in 2003, and Table 18 shows ordinary-least-squares regression estimates in a model of annual kilowatt-hours (kWh). It is interesting to note that taller buildings appear to be built with greater energy efficiency than those under 25 floors.

Where natural gas is concerned, primarily for building heating and cooking purposes, those having been renovated consume 10,000 BTU of natural gas less per year per square foot. For the average commercial structure of 100,000 square feet, this equates to 1 billion BTU natural gas energy savings per year, or 1.17 million pounds of CO2e, and 330,000 kWh of electricity savings per year ($29,000 in electric bills, and 0.40 million pounds of CO2e).

The EIA reports a total of 71.7 billion square feet of commercial U.S. buildings in 2001 (not including shopping centers/mall, and translating to roughly 500 sf per U.S. worker or 240 sf per U.S. resident). If just 1 percent of this floor area were made more efficient via renovations, the nation could expect an energy savings of more than 1.4 billion kWh (1.8 billion lbs CO2e) and 71 billion ccf natural gas (838 million lbs CO2e). Still, this is only 0.016% of total US CO2e emissions.

The fact that billions of pounds of CO2e could be saved from electricity reductions underscores the need for cleaner feedstocks at power plants, since such savings are calculated based on a national average of 1.34 lbs CO2e per kWh. If the U.S. grid average fell to 1 lb of CO2e per kWh, then all buildings would immediately be responsible for fewer GHG contributions. Assuming commercial buildings consume 17.15 kWh/sq ft (Table 17), such a reduction in carbon intensity of our national electric grid would mean a 209 million ton reduction in carbon emissions from the nonresidential building sector. Of course, this is still only 2.6% of total US emissions. Clearly, we must manage CO2 emissions on the demand side as well.

Non-residential buildings present interesting design challenges. Restaurants, for example, exhibit very large temperature gradients in small areas – between the kitchen and dining areas, requiring outdoor ventilation of kitchen air and high capacity A/C systems operating throughout

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[36] Commercial buildings are defined as those in which at least half of the floor space is used for a non-residential, non-industrial and non-agricultural purpose.

[37] The CBECS data included 5,215 cases, but 121 were thrown out for insufficient electricity consumption data. Another 1,666 lacked sufficient natural gas consumption data. An explanation for the removal of cases can be found in Appendix C.

[38] In general, older buildings generally consume less energy than newer buildings, per square foot, according to CBECS data. Renovations tend to appear in buildings of roughly 50 or more years age, and these then consume less energy. The average building in the US is essentially operating at a 1970's efficiency.

the building. This may result in much wasted heat in cold climates during the wintertime. Similarly, hospitals and laboratories housing a great deal of equipment will require significant cooling. For such non-residential uses, each building operator must determine what practices will be most efficient. Obviously there are some machines and equipment one just can not turn off, so this is where duct losses and building envelope considerations become important. Since such places can not typically alter the indoor environment for health reasons, many commercial and industrial facilities may seek CO2 reduction through alternative energy source options. Though again, improved insulation could drastically improve energy use and utility bills.

This is also an area where LEED standards – based on building performance measures (rather than simply the presence of certain technologies) – can play a key role. Providing for employee-controlled light adjustment, for example, could save thousands of pounds of CO2e each year, per building. Timing all lights to go off at a certain time while allowing after-hours employees to control a few in their areas tends to be much more economical than leaving all lights on all the time. Much research remains to be done in this area, and valuable information could be obtained from individual business records of energy consumption, particularly if CBECS variable values were provided in more continuous form (rather than respondents selecting categories or bins of overall energy use and such).

Appliances and Home Equipment

The numerous appliances now considered commonplace in many U.S. homes and businesses are another piece of the carbon equation. Consumers have control over the energy demands of these appliances in several ways. When functionally similar and/or smaller appliances exist, consumers can choose more efficient versions (for instance, using a clothesline in place of an electric dryer). And consumers can decrease the amount and intensity of their appliance use (e.g., washing fewer, larger loads of laundry and dimming lights). Finally, consumers can replace older appliances with newer, more efficient ones. In spite of all these options, however, much of an appliance's GHG burden remains outside consumer control, in particular the carbon intensity of the electricity received.

"Phantom loads" are energy consumed by electrical devices when they are not in direct use but still plugged in, and these are estimated to account for 6% of household electricity consumption (Berkeley 2005). This figure is based on a U.S. DOE report (DOE 2008b) which states that 25% of home appliances' energy use occurs while they are turned off. Based on average household energy consumption of 830 kWh per month, plugging appliances (even clothing washers and dryers) into power strips and turning off the power strip when not in use could result in a 2,000-pound (1 ton) CO2e reduction each year, per household. Such GHG emissions estimates depend, of course, on the household's electricity grid's energy sources, as discussed below, in Chapter 4 of this report.

Together, space cooling and heating account for about 26% of U.S. home electricity use (EIA 2001)[39], versus 33% to appliances. Heavy uses include food refrigeration, water heating, and lighting. Table 19 describes potential CO2 emissions savings per month for changes in usage levels (shown in italics) relative to standard choices and use levels. As indicated, changes in

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[39] While many housing units rely on natural gas for heating, many rely on electricity. The breakdown for the 26% is 16% to A/C and 10% to heating (according to http://www.eia.doe.gov/emeu/reps/enduse/er01_us_tab1.html). Of course, in warmer areas of the U.S., A/C use can dominate electricity consumption, particularly during the hottest months of the year.

heating and cooling tend to offer the greatest emissions reduction opportunities for most households.

Water Heating

Tomlinson (2002) estimates that water heating accounts for 12% percent of a U.S. household's energy consumption, in terms of BTU's of natural gas and electricity purchases. Moreover, the average household consumes 64 gallons of water per day, which requires 13.3 kWh of electricity to heat from 63°F to 140°F via a conventional electric-resistance water heater (Tomlinson 2002). Heat-pump water heaters are more efficient and provide the same amount of heat with only 4.9 kWh of electricity. Such heaters can draw some heat from the surrounding air, even when placed in an unconditioned, unheated space. Unheated basements and garages are excellent locations for heat pump water heaters, since the insulation between these spaces and the main house means minimal impact on the home's heating load. (Tomlinson 2002) The potential CO2 emissions reductions for such water heaters are listed Table 19, along with the potential savings for reducing water heater temperature from the standard 140°F to 120°F. (Such calculations rely on the RECS 2001 data, which indicate that 39% of U.S. households use an electric heater, 53% use natural gas for heating, 3.6% use fuel oil, and the remainder use some other form of heating.) Finally, if just one percent of households were to reduce their water heater temperature from 140°F to 120°F, Tomlinson (2002) estimates that 1.027 million tons of CO2e would be saved each year, or 0.013% of US CO2 emissions.

Beyond Water Heating

Of course, home and business consumption of unheated water also involves energy inputs, both directly and indirectly. Simply delivering clean water is energy intensive (roughly 5 MWh per million gallons delivered [Koeller 2006]), particularly in regions, like California, that rely on pumping water over long distances (King et al. 2008, Webber 2008). Koeller (2006) finds that a typical city's energy bill comes mostly from wastewater treatment (23%) and water pumping (33%), rather than streetlights (22%), city buildings (12%) and other municipal activities (10%).

Surprisingly, the mining of petroleum also requires a fair amount of water: more per mile traveled than the fuel itself. (Webber 2008) However, this is dwarfed by the "massive" water requirements of electricity production (particularly withdrawal [and return] of water, for cooling purposes). Webber (2008) warns of the "peaking of water", and the rising competition for drinking and electricity generation, resulting in price increases, coupled with potentially crippling climate change-related shortages. He ponders the water impacts of an electrified or biofueled light-duty vehicle fleet, and urges immediate collaboration in energy and water management practices, perhaps via the creation of a U.S. Department of Water. One thing seems clear: water conservation offers multiple benefits, often unexpected.

4. SOURCES OF ENERGY

In 2006, Americans consumed 3.8 billion MWh of electricity, producing 2.7 billion tons of CO2 (EIA 2007)[40]. The peak summer load was 790,000 MW, about 80% of the grid's capacity. Sources of this energy are shown in Figure 9.

According to the EIA (2007), the average retail price of electricity in 2007 was 9 cents per kWh, ranging from 6 cents per kWh for industrial users to 10.4 cents per kWh for residential users.

Currently, hydroelectric is the largest renewable contributor to this mix, and its share continues to increase. Wind power and biomass feedstock also are clearly on the rise. Wind's summertime capacity grew nearly 60% in 2004, from 6,000 MW to 9,500 MW, and Texas now leads the nation in wind power (EIA 2007c). Biomass energy production is rising as well, though mostly for biofuels, in transport; in fact, 74% of biomass energy is used as biofuels (not electricity) (EIA 2007c). Renewable energy investments are likely to continue, thanks to climate change concerns and state energy portfolio standards.

The carbon intensity and price of various renewable and non-renewable energy sources are shown in Table 20.

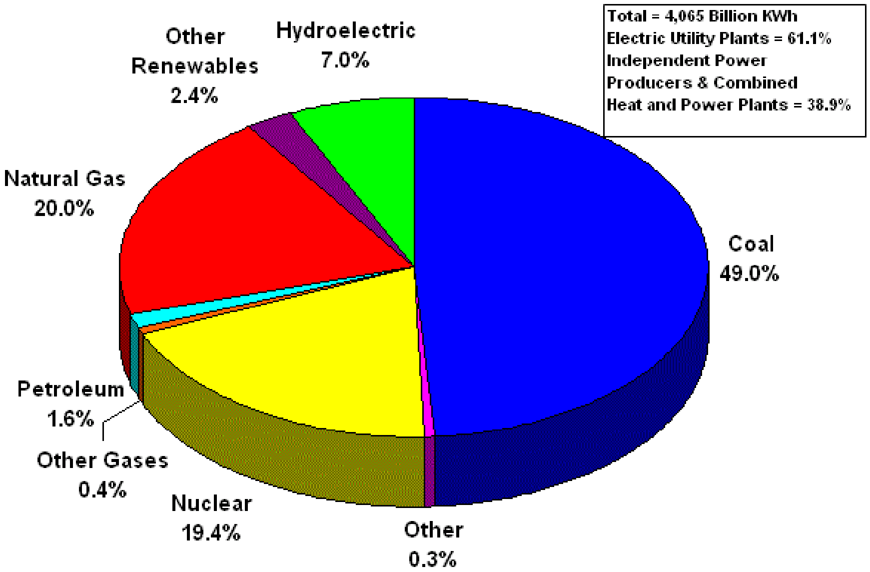

FIGURE 9 U.S. electric power generation (source: EIA 2007b, Figure ES1).

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[40] The U.S. transportation sector is estimate to have emitted 2 billion tons of CO2 in 2003. (EPA 2006)

Non-Renewable Electricity Sources

The majority (90%) of electricity produced in the U.S. is from non-renewable sources, including fossil fuels (coal, natural gas) and nuclear power. It is desirable to reduce our reliance on these sources for a variety of reasons. Fossil fuels, especially coal, are very carbon intensive relative to nuclear power and renewable energy sources. Nuclear power, however, may not enjoy adequate public support.

Fossil Fuels

Fossil fuels are by far the largest share of U.S. energy production, and are also the highest emitting source of electricity per unit energy. Coal itself is used to produce 50% of U.S. electricity (EIA 2007b). Most estimates of future energy production claim that fossil fuels will remain a large portion throughout this century; thus, it is essential to identify ways to use these fuels in a manner that will allow GHG reductions (ASES 2007, MIT 2007).

Carbon capture and sequestration (CCS) is perhaps the most promising method for reducing the carbon emissions intensity of energy production via fossil fuels. At present, coal plants emit 1.5 billion tons of CO2 per year. If these emissions were sequestered, this would be equivalent to one-third the annual volume of natural gas transported by pipeline (MIT 2007). Of course, this new technology will increase the unit cost of energy. To make this technology cost effective, CO2 prices greater than $30 per ton will be needed (MIT 2007). Creyts et al. (2007) suggest that the average marginal cost will be $44 per ton.

This technology is not yet commercially available, and accomplishing such will be necessary for full-scale deployment (MIT 2007). In addition, several sites worldwide should be evaluated, since nearly every potential site poses unique issues. A Massachusetts Institute of Technology (MIT 2007) study suggests that CCS should be demonstrated at three geologically different U.S. locations (and 8 or more globally), at a scale of 1 million metric tons of CO2 per year, before widespread use begins.

Nuclear Energy

As an energy source with low GHG emissions, nuclear power is an alternative to fossil fuels. Currently there are several challenges that must be overcome for nuclear power to increase its share of U.S. (and world) electricity production. It is not currently cost competitive with coal and natural gas, the public generally does not support this source of energy because of safety and national security concerns, and a management plan for increasing radioactive waste production is lacking (MIT 2003). Consequently, forecasts don’t call for large expansions of nuclear power.

In 2002, nuclear power cost 6.7 cents/kWh, while coal was only 4.2 cents/kWh and natural gas (combined cycle gas turbine) was 3.8-5.6 cents/kWh. Including carbon could drive up the price of coal and gas powered energy, making nuclear power increasingly more competitive as the cost of carbon increases. At $50 per ton of carbon, nuclear power is still more expensive. $100 per ton is needed to create a level playing field (for investment in new nuclear plants), and $200 will make nuclear power cheaper than both coal and gas (MIT 2003). The marginal cost of emissions abatement via nuclear energy from existing plants is estimated to be $9 per ton CO2e (Creyts et al. 2007).

Renewable Electricity Sources

As with nuclear power, renewable energy sources emit a small fraction of the GHG emissions associated with fossil fuel energy production. However, unlike nuclear power, safety, national security, and byproduct waste management are not typically concerns associated with renewable sources, thus making them attractive options. It has been estimated that half of the U.S. electricity grid can be produced by renewable sources of energy by 2030 (ASES 2007), resulting in a U.S. emissions savings of approximately 24% (relative to current emissions). In current terms, such a shift (from 9.7% to 50% renewable) is estimated to result in a 17% reduction in U.S. GHG emissions (as shown in Appendix B calculations). A shift from 9.7% reliance to 10.7% reliance on renewable feedstocks (i.e., a 1-percent net shift) for U.S. power generation is estimated to provide a 0.33% reduction in current emissions, making it the single largest GHG-saving strategy for the nation (assuming a 1% adoption rate), as per Table 25 and Figure 10.

Hydroelectric Power

Hydroelectric power is currently the largest source of renewable electricity in the U.S., producing 300 million MWh in 2006, or 7% (EIA 2007). From year to year, production fluctuates with water levels. During periods of drought, the capacity of hydroelectric sources is lower than during wet periods. From 1989 to 2005, the range of production was approximately ±20% of the average, mostly due to changes in water level (EIA 2007c).

While there is estimated to be a potential 30,000 MW of additional capacity, the share in electricity generation of this source is not expected to grow much in the future. Hydroelectric energy production faces many complex environmental issues and regulations, causing its expanded use to be potentially burdensome and expensive (DOE 2008).

Wind Power

Though it is not currently a large source of electricity, wind's capacity has been increasing rapidly in recent years. In 2001 it surpassed U.S. geothermal sources and now offers the second highest share of renewable electricity production in the U.S. (EIA 2007c). At only 4 cents per kWh, this source is very cost competitive with fossil fuels and cheaper than many other renewable sources (DOE 2007, ASES 2007). Creyts et al. (2007) estimate that the marginal cost of emissions reduction is $20 per ton of CO2e. Some forecasts expect wind to be producing 20% of America's electricity by 2030, nearly 30 times its current production (DOE 2007, ASES 2007). Of course, wind power cannot be generated at any time of day or day of the week, unlike burning coal and gas. And windfields lie far from most concentrations of population, requiring some loss of energy in transmission. Energy storage is expensive, though methods are improving. In particular, exciting synergies with PHEVs' batteries for re-charge and storage during off-peak times of day (e.g., nighttime and mid-day) exist, helping smooth the peaking in power-grid demands (thus reducing the risk of brown-outs and black-outs, while reducing energy costs).

Geothermal Energy Plants

U.S. geothermal plants generate an average of 15 billion kWh of electricity per year, or 0.4% of U.S. energy demand (Kagel et al. 2007). These 15 billion kWh effectively avoid the emission of 22 million tons of CO2 each year, when compared to coal production. Sixty new plants were under construction in 2007, and will provide another 18 billion kWh of electricity (Scientific American 2007). Geothermal power presently accounts for less than 1% of the nation's electricity, but could easily meet 20% of the nation's demand U.S. (Kagel et al. 2007). For $1 billion, the full cost of one coal-fired power plant, 10 GW of geothermal energy (10% of current U.S. electricity generation could be produced in the next 40 years (Scientific American 2007). Clearly, geothermal resources exist in the U.S., especially in western states.

A geothermal plant produces only 60 pounds of CO2e for each MWh of electricity, less than 3% of the emissions from a coal-fired power plant (2,191 lbs of CO2) (Kagel et al. 2007). More work remains to be done in the areas of geothermal plant design and evaluation of U.S. resources. The U.S. Geological Survey (USGS) last surveyed geothermal production potential in 1978. The survey only considered depths shallower than 3,000 meters, but the need to drill deeper for oil has produced the technology needed to drill to deeper geothermal reservoirs. Every state in the U.S. has the potential to extract geothermal resources when depths up to 6,000 meters are considered (Fleischmann 2007). Geothermal electricity costs approximately 3 cents per kWh (NREL 2002).

Geothermal Water, for Direct Heating

"Direct use" of geothermal water is a relatively new technology, mainly applied for heating and cooling, but also applicable to many agricultural and industrial uses at a household or local level. Direct use is most effective where the source temperature is between 70°F and 300°F, and researchers have found that resources in this range exist at economic drilling depths (Kagel 2008). A direct use project could be online within a year, and costs are roughly the same as installing a conventional water well, using similar technology. (Kagel 2008)However, the chemistry of geothermal water must be considered, and certain corrosive materials must be removed from the water to prevent system damage. Carbon dioxide can even be extracted from the water in order to heat greenhouses and carbonate beverages. Much like an air conditioner, a pump can concentrate and move heat from a geothermal reservoir to the destination, or from the area to be cooled into an injection well in these direct-use systems. (Kagel 2008)

Geothermal heat pumps, on the other hand, do not require a geothermal reservoir, but rather a source where heat can be extracted from or injected during the appropriate time of year. These heat pumps use 25 to 50% less electricity than conventional home heating and cooling systems, and result in 45 to 70% lower emissions. The average cost for installing a system (including drilling a well down to the water table) at one's home is estimated to be $7,500, as compared to about $4,000 for a typical air conditioning system (EERE 1999). This higher up-front cost is said to be balanced by resulting energy cost[41] savings of $1 to $2, each day.

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[41] For a home of approximately 1,500 square feet, energy costs would be $1 per day. A home of 4,000 square feet may expect a $2 per day energy cost using a geothermal heat pump. With conventional generation practices, average home-electricity costs are $2.50 per day for the average U.S. household. (EERE 1999)

Solar Energy

There is a popular myth that photovoltaics (PV) cannot pay back their energy investment. In fact, the U.S. Department of Energy (2004) reports that rooftop PV systems have an energy payback period of just one to four years, and, assuming a 30 year lifetime, this means 26 to 29 years of zero carbon emissions. This payback period is calculated based on 1,700 kWh/m^2 of energy, while the U.S. average is 1,800 kWh/m^2, so in many southern states with greater solar potential, the energy payback period is even lower (DOE 2004).

The payback period for homeowners is of great concern too, of course, but there are benefits in both energy savings and the added value of one's home. For every $1 decrease in one's annual energy bill total, everything else constant, home value is estimated to increase by $20 (DOE 2004). The average U.S. household uses 830 kWh of electricity each month (DOE 2004). Assuming an average cost of 10 cents/kWh and 50% of one's electricity generation via a rooftop PV, a household could save $500 per month, potentially adding $10,000 to the value of their home (assuming a discount rate of 5 percent and a 60 year return period). Creyts et al. (2007) estimate that the marginal cost of reducing emissions is $29 per ton CO2e. Solar panels can cost between $20,000 and $40,000 to install on one's home, depending on available sunlight and energy needs (Affordable Solar 2008). The expected lifetime of a rooftop PV system is approximately 30 years, and it may take that entire 30 years to realize the direct cost savings of the PV system. For this reason, solar panels are best suited for homes in sunnier climates, which can generate more of their own energy needs via rooftop panels. Even in less sunny climates, a household could meet 100% of its energy requirements using solar panels, it just may need more of them. (Solar potential is estimated using kWh/m^2 of panel area.)

Table 21 shows the CO2e avoided by turning to solar energy. Obviously, CO2e will be eliminated if households use solar panels for 100% of their homes' electricity needs. Regions with the "dirtiest" electricity grid sources will see the greatest reductions in CO2e, from installation of such panels

Biomass Energy

As discussed earlier, in the section on motorized vehicle fuels, biofuels are a form of biomass. And biomass energy can be obtained from lumber and mill waste (wood residue), municipal solid waste (MSW), landfill gas, and agricultural waste (e.g., corn stalks and straw) (EIA 2007c, ASES 2007). Dual- or multi-mix energy plants are able to consume both coal and biomass (in addition to other feedstocks, such as natural gas) in their production of electricity. This is usually done as a means to reduce coal plant emissions without making enhancements in the plant itself (EIA 2007c). In these plants, 36% of their electricity production comes from biomass while the rest comes from non-renewables (EIA 2007c). The Western Governors' Association estimates that 32 GW of capacity could be produced annually by 2015, about half of which would cost consumers 8 cents or less per kWh (ASES 2007).

Typically, biomass is more efficiently used in the production of electricity than in biofuels, which are in liquid form (ASES 2007). However, many other renewable energy sources (wind, geothermal, hydroelectric) cannot be directly utilized by motorized vehicles. Presently, the majority of biomass energy is used for liquid biofuels rather than electricity.

5. LAND USE

The last major piece of a discussion on energy and GHG emissions opportunities lies in land use patterns. This section runs the gamut, from vegetative cover practices to parking polices, and compact development patterns to self-selection in location choice. While land use is relatively slow to change, its relative permanence has a marked impact on long-term concerns, like climate, as well as a variety of transport decisions, as travelers and goods navigate between sites of production and consumption, residence and out-of-home activities.

Vegetative Cover and Urban Forests

Several studies (Nowak et al. 2001, Nowak and Crane 2002, and Nowak 1993, Brack 2002) have examined the feasibility of urban forests to serve as carbon sinks. While the sequestration potential of such forests is indeed significant, the greatest CO2 emissions reductions are likely to come from reduced building energy needs. In a simulated annual planting of 10 million trees[42] in Canberra, Australia over 10 years (1991-2000), Nowak (1993) found that the 100 million trees would store 77 million tons of carbon, and avoid production of 286 million tons over their 50-year lifespan. Of course, when trees die and decay, they release their sequestered carbon back into the atmosphere, so replacement planting is needed to sustain the urban forest benefits.

Most of the benefits of carbon sequestration by vegetation depend on tree size. Larger trees extract and store more CO2, while providing the shade that cuts building energy costs. Natural forests provide a greater carbon sink[43] than urban forests (typically due to their age and size) and a far greater sink than areas with less vegetative cover, like prairie and pasture (Frank, 2002). 70 to 100-percent of North America's terrestrial carbon uptake is estimated to be in the broadleaf (deciduous) forested regions south of 51N latitude (Calgary, Canada) (Fan et al. 1998). A North American forest can store approximately 53.5 tons of carbon per hectare, while an urban forest may store only 25.1 tC/ha. Still, Energy Star (2008) recommends that for a home with significant shade, one may choose a smaller air-conditioning uni than a home of the same square footage and no shade. This would be the equivalent of moving from a 2,400 sq ft home to a 2,000 sq ft home, and Tables 16 and 25 show the savings one could expect from such a move (under "Downsize Home"). In the southern US, this could mean a savings of 1000 pounds of CO2e each year, per home.

The concept of a heat-holding carbon dome over an urban area is known as an *urban heat island*, and is a motivation for urban forests. The average tree cover in U.S. urban areas is about 28% (Rountree and Nowak 1991, Dwyer et al. 2000, Nowak et al. 2001), while pavement materials make up 29 to 45% of urban surfaces (Gui et al. 2007). Due to differences in energy absorption, park settings can be as much as 7°C or 12.6°F cooler (Young-Bae 2005) than developed areas, in what is known as the urban heat island effect.

Gui et al. (2007) concluded that changes in a pavement's reflectivity ("albedo") can generate significant reductions in pavement's maximum temperatures. Reflectivity also can be increased by whitewashing building surfaces, and Sacramento simulations suggest that building peak power demands and energy used for cooling may be reduced by 14% and 19%, respectively, during the hottest months (Gui et al. 2007).

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[42] Over 60 different species of native trees were planted.

[43] While natural forests provide a greater carbon *sink*, urban forests have the potential to shade buildings and reduce cooling loads.

In a study of Tokyo's urban heat island effect, Ihara et al. (2008) considered energy consumption during the entire year, as opposed to just the hottest summer months. Tokyo has made it a point to decrease building energy demand in their urban areas over the last few years, with businesses abandoning wool suits and allowing very casual dress codes during the summers, in order to reduce cooling loads (Time 2007). Taking into account temperature fluctuations, Ihara et al.'s model estimates that reduced air humidity within the building may result in a 3% reduction in energy consumption (Ihara et al. 2008). This study also concluded that increases in building surface reflectivity has substantially reduced the number of hours that urban temperatures lie above 30°C, from 554 hours to 60 hours. Energy savings for vehicles driving through the urban area were also investigated, but not found to be significant. This could be due to the type of vehicles or VMT in Tokyo.

An effective measure for reducing building cooling loads and urban heat island effects is the installation of green roofs. Oberndorfer et al. (2007) found that a 2°C reduction in urban temperature could be realized if 50% of roofs were green roofs versus 0% green roofs. These roofs have many benefits for building maintenance and municipal infrastructure as well: green roofs can reduce storm water runoff by as much as 70%. While green roofs may be more expensive initially to construct, they could be more economical over their lifetime due to the resulting longevity of roof membranes from decreased storm water holding and UV radiation (Oberndorfer et al. 2007). Moreover, while green roofs and urban forests are not a significant carbon sink in and of themselves, existing estimates imply that the electricity consumption and development they avoid can result in significant energy needs and reductions. It is imperative that such vegetative cover make use of native plants, so that annual rainfall will be adequate and no further irrigation will be needed.

Parking Provision

Parking policies can have a significant impact on VMT if enough alternatives to driving are provided. Many cities have created guidelines requiring a minimum number of places per establishment or dwelling unit, but are now finding that an effective way to reduce congestion and pollution is to reduce available parking, or charge premium prices for it. TCRP (2004b) found that by eliminating such requirements and charging market rates for residential spaces could potentially reduce vehicle ownership per household (along with VMT per vehicle, to some extent), enough to reduce household VMT by 30%. This elasticity means that if 1% of households residing in multifamily units were charged $50 per month for parking, one could expect a 0.054% reduction in U.S. transport GHG emissions.

The goal of minimum parking requirements is to meet recurring peak demands. In effect, planners identify the highest number of vehicles parked at an existing location and then require developers to supply at least that many spaces for future parking at similar land use, disabling travel demand management opportunities at the parking stage. Shoup (1997) argues that since these base demands do not account for price, nowhere in the planning stages is cost accounted for, making car ownership more affordable. "Free" parking (along with government subsides of highway facilities) thus has impacts on vehicle trip generation.

Cruising for a parking space can be responsible for a significant portion of a downtown area's traffic. In 2006, studies in Manhattan and Brooklyn found that vehicles looking for an on-street parking space accounted for 28 and 45 percent of traffic, respectively (Shoup 2007). This is because curb parking may cost $1 an hour, while garage parking can cost as much as $20 an hour. When curb parking is underpriced as in most cases, a downtown area may generate as much as 2,000 VMT for each curb space every year. Of course, downtown areas may be exempt from minimum parking requirements, to help deter automobile use. However, such policies can result in cruising, particularly when on-street low-cost metered parking is known to be available but regularly oversubscribed.

In a study of a commercial district near the UCLA campus, Shoup (2007) collected data on vehicles seeking parking and found average cruising distances to be one-half mile. Given a turnover rate of 17 cars per space per day and 470 parking spaces, this half mile of cruising was estimated to contribute 4,000 additional VMT per day in that one neighborhood (or one-half mile per vehicle parked). Shoup (2007) believe that the proper price of parking is the amount that results in approximately one vacant space on each side of a city block. By making a rather heroic assumption that all cruisers would be willing to pay the requisite parking prices, he believes that this level of available parking would virtually eliminate cruising, potentially saving a congested downtown of 20,000 casual parkers per day over 5 tons of CO2e emissions a day, or roughly 2000 tons per year. Time savings from congestion reductions and revenues generated could be used in more productive pursuits.

It should be noted that with a hybrid-electric vehicle, one would use little to no fuel at all during this cruising stage, presenting yet another reason for electric vehicles to be implemented in the short term, rather than building more parking lots to avoid cruising. Of course, pricing of currently free parking may prove very effective in moderating mode and destination choices. The cost of underground parking can easily reach $22,000 or more, per space (Shoup, 1997), sometimes costing more than the car that will be parked in it. Shoup (1997) calculates that a $23,600 parking space effectively costs $91 per month[44]. At this price, providing four parking spaces per 1,000 square feet of office space will make parking costs nearly 40 percent of total building construction costs, including parking. In most cases, individuals do not pay the $91 per month to park, rather their employer or retailers offer such benefits. Shoup (1997) estimates that such parking subsidies exceed a vehicle's operating costs and skew mode choice towards private automobile. If drivers were charged for parking based on the size of their vehicle (projected are) they may be more likely to purchase smaller cars. In fact, the manufacturers of Smart Cars (at smartusa.com) note that two of their vehicles can fit in one conventional parking space.

In most U.S. cities there are few reasonable alternatives to driving for someone who lives more than 10 miles from his/her destination, including places of work. Nevertheless, TCRP (2004B) reviews of the literature find that charging employees for parking can result in a 30% decrease in single-occupancy vehicle (SOV) mode shares. In areas with poor transit service, however, such reductions are on the order of only 10%. This provides a range of 0.004% to 0.013% reduction in U.S. GHG emissions if applied to 1% of the population (depending on quality of transit service). Table 22 summarizes possible CO2 reductions from various parking policies.

Congestion Pricing

Congestion pricing of roadways presents a valuable opportunity to rationalize road networks, by helping ensure that travelers pay for the delay costs they impose on others (essentially those traveling behind them [see, e.g., Kockelman 2004]). A recent study of Seattle travelers with GPS

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[44] This estimate assumes an underground parking structure, zero land cost and property taxes, a 50-year life, and 4% discount rate (Shoup 1997).

vehicle units estimated that variable network pricing (to reflect the congestion impacts of different demand levels over space and time) would reduce regional VMT by 12% and total travel time by 7% with a 6-to-1 benefit-cost ratio (PSRC 2008). Using GPS tolling meters, the study followed participants to establish a baseline tolling routine. Participants were then given a monetary travel budget sufficient to cover the cost of their routine for the duration of the study period, creating an incentive to reduce certain forms of travel to save/make money. This policy approach is very similar to Kockelman and students' credit-based congestion pricing policy proposal, though VMT results differ in their network simulations of the Austin and Dallas-Ft. Worth regions of Texas (Kalmanje and Kockelman 2004, Kockelman and Kalmanje 2005, Gupta and Kockelman 2006, Gulipalli and Kockelman 2008), where marginal social cost pricing of freeways or all links by time of day is rather consistently estimated to result in VMT savings of under 10 percent. Nevertheless, if road pricing of some form were to reduce U.S. VMT by 12 percent for 1 percent of all drivers, the total CO2e emissions savings is estimated to be 1.69 million metric tons, or 0.023% of the US total.

Car Sharing

Another option for consideration is car sharing, where shared vehicles may be available at the worksite and/or home neighborhood for use as needed. Much like a highly accessible form of car rental, such systems provide members with more appropriate vehicle type choices as needed (e.g., a sports utility vehicle for weekend camping trips, a small pickup for moving new furniture, and a small commuter car once or twice a week for work meetings). Such flexibility helps ensure a more efficient fuel-to-passenger ratio and parking space use while encouraging a shift to other modes (see, e.g., Shaheen et al. 2006, Bergmaier et al. 2004). Car sharing membership rates, ease of vehicle availability and adequate presence of other, competitive modes are key to energy and emissions reductions. Moreover, travel distance reductions are not always dramatic (and may actually increase, as previously carless households become members). Nevertheless, the fleet-based nature of this approach, with potentially much more balance in choice and need (by vehicle type, time of day, and location needed) suggests that car sharing is a sound option to promote and pursue, even in the form of multiple simple cooperatives, by friends and neighbors (thus reducing administrative overhead). In this way, ownership rates of pickups, SUVs, and other specialized but relatively inefficient vehicles may fall, along with overall vehicle ownership rates and vehicle sizes, allowing a community's average fuel economy to rise.

Density: Jobs and Population

In the U.S., transport is responsible for 28% of GHG emissions and 33% of energy related CO2 emissions. The U.S. alone accounts for 22% of total emissions worldwide (Ewing et al. 2007a). The U.S. houses only 5% of the Earth's population yet owns 33% of its cars and contributes 45% of global vehicle emissions (Ewing 2007b). It is undoubtedly easier to change travel habits than to change urban form, but many studies suggest important impacts from land use policies and urban planning.

In a broad analysis of factors impacting transit decisions using 1990 National Personal Transportation Survey data, Bento et al. (2005) found that demographic factors (age, employment, household size, household income, and education) are the greatest predictors of a person's travel behavior. Of course, it is quite difficult (and unreasonable) to control these factors in an attempt to curb vehicle travel; so Bento et al. identified several other, lesser factors. Road network and distribution of population throughout the city were the greatest urban form determinants of VMT, while VMT and commute mode were most dependent upon the pattern of residential land use and distribution of employment. Special attention was paid to vehicle ownership, and the probability of owning one or more vehicles. The 2001 National Household Travel Survey results suggest that VMT per vehicle is rather stable across households owning one to three vehicles, ranging from about 9,000 to 10,000 miles per vehicle per year (NHTS 2001). Thus, reducing vehicle ownership may be key to reducing VMT (because VMT per vehicle does not vary much[45]).

Travel Benefits of Compact Development

As mentioned in the section on building design, Walker and Rees (1997) and Harmaajarvi et al. (2002) have estimated transport to account for more than 40-percent of a household's home-based energy requirements. This suggests that significant energy savings may result from more compact development, due to shortened travel distances, for household members, visitors, and deliveries. And there is a fair amount of research to support this argument.

Holtzclaw et al.'s (2002) location efficiency approach attempted to determine which factors most influence home location selection and associated transit use. Using odometer readings from emissions systems inspections in San Francisco, Chicago, and Los Angeles, the author's predicted a household's VMT as a function of home-zone density, transit service and access to jobs by transit, availability of local shopping pedestrian and bicycle "friendliness", that is, the attractiveness of these options as compared to driving, and proximity to jobs (Holtzclaw 2002). The effects of density were estimated to be quite high, but of a similar magnitude to Newman and Kenworthy's. The elasticities for vehicle ownership with respect to density for Chicago, Los Angeles, and San Francisco were -0.33, -0.32, and -0.35. Elasticities for VMT (per capita) with respect to density were -0.350, -0.4, and -0.43. Since these cities enjoy above-average transit systems and the model did not control for costs of parking, income and other relevant variables, applying this model across more cities may not yield such optimistic results. For example, the model does not control for attitudes towards driving and public transit, differences in living or vehicle ownership cost, or the cost and quality of transit. These variables differ significantly in most major U.S. cities. More encouraging, though, is the fact that these three urban areas differ in terrain and climate, yet have high potential for reducing VMT. And higher densities favor smaller, more fuel-efficient cars, resulting in greater carbon savings that is evident in VMT results.

Schimek (1996) examined the argument that income is a better predictor of VMT than residential density by comparing household vehicle ownership to residential density and income. Controlling for income and household size and using data from 1990 National Personal Travel Survey, he found the elasticity of VMT with respect to regional residential density is -0.07, while that with respect to income is +0.3. Further, the VMT effects due to density are mostly a result of reduced vehicle ownership. From this standpoint, income and vehicle ownership are more important than density. Household income is largely responsible for vehicle ownership levels (elasticity of ownership with respect to income of 0.41); next in line are the number of workers

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[45] Data from the 2001 NPTS suggests that a household's first vehicle is used, on average, about 10,000 miles per year, while second and third vehicles are used about 9,000 miles per year. If a household has four or more vehicles, however, average use falls, for a household average annual VMT of 40,000 miles.

(elasticity of ownership with respect to worker count is 0.26), access to transit (-0.20) and number of household members (0.17). Schimek found that U.S. vehicle ownership is projected to fall 11% with a doubling in average population density, due to the higher costs and difficulties of vehicle storage in denser areas, although it should be noted that these elasticities could differ quite a bit at different densities.

Newman and Kenworthy's (2006) estimate of 35 jobs or persons per hectare as a threshold density for per-capita transport energy use has been the source of much debate. Above this density they notice a sharp reduction in walk, bike, and transit. Based on the idea that the average person will spend one hour traveling every day, they estimate that at least 10,000 residents plus jobs need to be provided within a ten-minute walk time radius (approximately 0.8 to 2.0 square miles, based on 3 to5 mph walking speeds) and 100,000 residents plus jobs in a 30 minute walk time radius for adequate amenities to be provided without auto dependence to support them. They suggest that it is unrealistic for cities to simply add a rail line through the center and expect significant distance and mode shifts, but any auto-oriented city could be restructured as smaller, transit-oriented cities. While these numbers are encouraging, some suspect the results may be a result of statistic techniques used and the data sets/contexts analyzed, rather than a fundamental relationship between population/employment densities and VMT (Brindle, 1994). Essentially, different cities around the world enjoy very different histories, cultures, incomes, and transport systems. Moreover, the notion of regional density relationships holding at the local level is quite problematic.

Cervero and Kockelman (1998) examined many features of urban form that may reduce auto dependence. Their gravity-based accessibility measure for access to commercial jobs, was found to have an elasticity of -0.27, suggesting neighborhood retail shops and pedestrian-oriented design are more significant than residential densities in mode choice selection. Integrating aspects of pedestrian oriented design such as four way intersections and vertical mixing of land uses may result in significant VMT reductions. For example, a 10% increase in the number of four-way intersections in a neighborhood was associated with an average reduction in VMT of 384 miles per year per household. Equally important to the understanding of how these factors may reduce VMT is an understanding of what factors individuals most prefer in neo-traditional developments. In Lund's (2006) survey where California residents were asked to identify their top three reasons for choosing to live in a TOD, only 33.9% cited transit accessibility as a top reason (Lund). More often, residents preferred type or quality of housing (60.5%), cost of housing (54%) or quality of neighborhood (51.7%). Lund also found that residents who listed transit as one of their top three reasons were 13 to 40 times more likely to use transit than those who did not, suggesting the effects of self-selection in such developments may be significant.

Table 23 shows potential CO2 emission savings from several types of density increases. A 10% increase in population density based on these estimates in an urban area could yield a reduction of 125 to 537 pounds of CO2e each year, assuming a standard 20 mpg vehicle. Increasing net density and accessibility, or commercial intensity, produces roughly the same CO2e reductions: 573 and 491 pounds annually, respectively. While population and net density do have significant impacts on trip generation, mode, and distance, the density of the urban area and population centrality are two more significant factors of urban form. Population centrality, a measure of distance from the CBD as a proportion of distance from outer edge of the city, may be a proxy for density and land use mix, combining many of the features of urban form that contribute to VMT. Similarly, the elasticity of VMT with respect to population density of urban area could be so high because of the services already in place in such areas.

The advantages of compact development are synergistic in many respects. With more locations closer to home, one may choose to walk or bike to their destination, reducing fuel use. The fact that buildings are closer together also has great impacts on public service infrastructure and a municipality's ability to provide water, electricity, and emergency services. By shifting 60% of new growth to compact patterns, Ewing et al. (2007b) estimate that the U.S. could save 85 million metric tons of CO2 annually by 2030, a savings roughly equivalent to a 28% increase in vehicle efficiency standards by 2020. Such compact development will also slow the growth of urbanized areas which currently are growing three times faster than urban populations and preserve the nation's forest and farmland.

Table 24 shows potential GHG reductions from a variety of compact land use and design strategies. Cervero and Kockelman (1997) examined urban design strategies that could be implemented in the nearer term. A 10% improvement in walking quality (defined on the basis of variables like sidewalk and street light provision, block length, planted strips, lighting distance and flatness of terrain) could yield a 0.09% reduction in SOV travel for non-work trips, corresponding to a reduction of 33 pounds of CO2e per household per year. When the impacts of walking quality on private car use are factored in, a household's annual VMT savings is potentially 819 miles. The reduction in SOV trip by improving land use mixing, through diversity within an area as well as surrounding areas, a household could reduce CO2e by 41 pounds per year. The greatest effect on travel from such urban design strategies is associated with the number of four-way intersections. Such intersections tend to enhance network connectivity, thereby facilitating (via shortening) walk and bike trips. If one accepts these estimates, a 10% increase in four-way intersections with 1% of households in a neighborhood conforming to the expected behavior is associated with annual CO2e reductions of 384 pounds per household.

Related to all of this is the notion of transit-oriented development (TOD), which is defined as an area with moderate to high residential density with employment opportunities and shopping within easy distance to transit stops. Such development resembles "traditional cities" and allows reductions in driving by increasing a neighborhood's "walkability" through higher densities and shares of four way intersections, a more connected grid pattern for streets, and wider sidewalks. Nevertheless, some (e.g., Brindle 1994, Schimek 1996, Shoup 1997) argue that economic factors (such as income and parking costs) are the primary forces behind transportation choices. And others worry that self-selection has a significant role to play, offsetting many travel-related benefits of compact form.

Self-Selection in Location Choice

Researchers have sought to disentangle the impact of travel preferences and "self-selection" in home location choice, and how this ultimately impacts differences in observed travel patterns across distinct neighborhood designs. While definitive conclusions have not emerged, general neighborhood design distinctions appear responsible for at least half of the observed VMT differences. (Please see Cao et al. [2006], Mokhtarian and Cao [2008], and Zhou and Kockelman [2008] for discussions of literature and results in this area.)

As one example of such work, recent surveys by Frank et al. (2007) in Atlanta reveal that, despite driving preferences, residents living in a "walkable" neighborhood tend to drive far less than those living in auto-oriented neighborhoods. The least walkable neighborhoods generated roughly 45.5 miles of travel per worker per day while the most walkable generated only 28.3 miles. Furthermore, those who prefer an auto-oriented neighborhood but happen to live in a walkable neighborhood tend to drive significantly less (just 25.7 miles per day per worker) than their counterparts in auto-oriented neighborhoods (42 miles), despite their stated preference. Of those who prefer walkable neighborhoods, the VMT values average 25.8 miles and 36.6 vehicle miles per day per worker. Thus, while someone may prefer to live in a different neighborhood, it appears that he/she will still "conform" to the travel opportunities of the home neighborhood. It also merits mention that households residing in suburban settings (versus more "traditional" neighborhoods) tend to be older and have more members. As expected (by VMT patterns), they also own more vehicles per household member (see, e.g., Bento et al. 2005 and O'Neill 2002). The neighborhoods in the study had similar densities, though they differed in household size and income.

Beyond VMT distinctions, of course, vehicle choices and travel speeds are to some extent impacted by neighborhood setting (see, e.g., Kockelman and Zhao [2000]), further distinguishing energy demands. More research would be useful in this and many other important areas for energy and climate policy.

6. CONCLUSIONS AND RECOMMENDATIONS

Policymakers interested in reducing U.S. GHG emissions have at their disposal a wide variety of options. These differ in a number of ways, including potential savings offered, initial costs, timeframe, and policy challenges. The sheer magnitude and complexity of actors involved in the problem of GHG emissions undoubtedly means that effective abatement policies will be comprehensive and multifaceted, employing a variety of options to some extent. It is important to know where the biggest GHG reductions can be made in the near and longer terms. To this end, this report anticipates emissions reductions one can expect from a wide variety of policies, behaviors, technologies, and design strategies. These include vehicle size and design, transport modes, fuel types, energy generation processes, food consumption, appliance technologies, home and building design, and land use patterns. The CO2e and energy (in BTUs) impacts of most of the important and interesting strategies covered here are summarized in Table 25 (assuming a 1-percent adoption rate), including a column suggesting how difficult it may be to implement various measures. Figure 10 (below) illustrates the relative benefits of key options.

Passenger travel accounts for 20% of total U.S. GHG emissions (of anthropogenic origin) and presents multiple opportunities for relatively near-term savings, thanks to a variety of reasonable vehicle and fuel substitutes. Information gathered towards this report suggests that current policy should emphasize **much higher fuel economy standards**, which ultimately will harness **improvements in fuel economy available in conventional and hybrid vehicles** while reducing fleet size and weight, without impacting safety in any significant way. In particular, technologies available in some current models (such as direct injection and continuous variable valve transmission) as well as **vehicle-mass reductions** offer significant fuel economy gains. Use of **biofuels** in place of gasoline or diesel can reduce direct GHG emissions, depending on the method of production. When production requires land use changes, net emissions actually

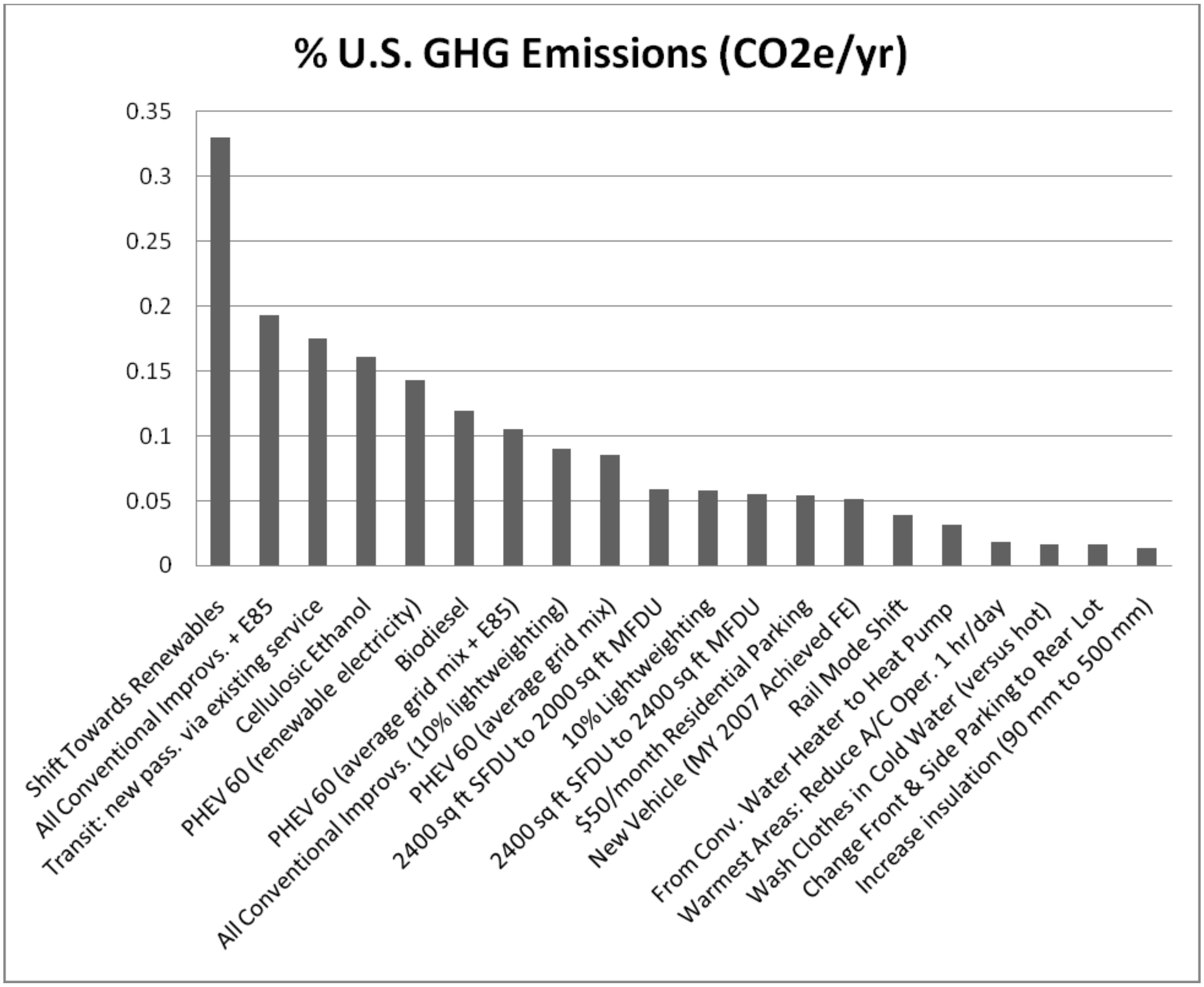

FIGURE 10 Percentage changes in GHG emissions across 1-percent adoption strategies.

could increase – substantially. For biofuels to be effective in reducing emissions, they must be produced with little or no land-use-related carbon debt (by coming from biomass waste, algae, or feedstocks planted on abandoned agricultural land). If this can be done, then corn ethanol may represent a useful near-term (but not long-term[46]) strategy, to help prepare the nation's infrastructure for cellulosic fuel distribution (but without affecting GHG emissions to any significant extent).

Such shifts should be cost-effective for consumers, even under high discounting rates and rather low fuel prices. However, few consumers exhibit the style of rational decision-making that allows such choices to emerge naturally; stronger fuel economy policy[47] (i.e., **higher CAFE**-style standards – on the order of 40 mpg or more, ideally before 2020) will be needed, as

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[46] Most experts now agree that corn ethanol should not have a significant long-term future in this country, for various reasons. (Webber 2008)

[47] While long-term U.S. CAFE standards were raised recently, they continue to lag the rest of the developed world and do not require much technical innovation. In fact, an average vehicle with all conventional improvements currently available and 10% downsizing achieves the 2020 CAFE goal of 35 mpg.

well as higher gas taxes, feebate policies, consumer-targeted **information campaigns** relating lifetime fuel expenditure savings of different vehicle models, and perhaps additional incentives designed to help consumers overcome the higher up-front cost of fuel economy.

Hybrid and diesel engines also exhibit significant potential, but at a greater incremental cost. Consensus is emerging for pursuit of **plug-in hybrid electric vehicles** (PHEVs), particularly over the longer term, as demand for VMT shows no signs of abating. PHEVs can greatly improve upon the efficiency constraints inherent in combustive technologies as well as largely centralizing passenger travel GHG emissions in a few locations, thus enabling carbon sequestration. PHEV success will depend on improvements in battery technology (for cost-effectiveness and technical feasibility) and the utility industry (both in terms of dispatch management, to handle new demand, and power plant "cleanliness", in GHGs as well as other emissions). Nevertheless, it seems likely that diesel engines will continue to serve as high-torque-requiring work vehicles (for light- and heavy-duty vehicles), hybrid engine designs will best suit urban drivers (i.e., congested driving conditions), and PHEVs will work well for those with consistent highway-based travel patterns, such as suburban commuters.

Beyond vehicle design and fuels, **speed choices, mode choices and trip lengths** are important considerations. Ideally, light-duty vehicle speeds would remain between 30 and 55 mph and passenger travel would evolve away from private single-occupant automobiles, towards higher occupancy or human-powered modes. Of course, transit modes face a number of challenges, including dispersed travel patterns and entrenched traveler habits and preferences. Moreover, the savings from a shift to transit may increase carbon emissions, at current occupancy levels. While biking appears very beneficial in direct fuel and energy savings, increased food consumption and life expectancies can offset much of this savings.

Vehicle design, fuel shifts, increased passenger car occupancies and direct reductions in trip distances (particularly those flown) promise the greatest energy impacts. Strategies that favor **trip elimination and shorter trips** (e.g., video conferencing and satellite offices) and promote **car sharing and car-pooling** should be encouraged. **Congestion pricing** of roadways has the potential to tackle the emissions (and congestion) issue from multiple dimensions: by shortening trip distances, raising vehicle occupancies, while greatly reducing recurring congestion (on tolled corridors) and the associated stop-and-go style driving conditions, Without targeted, behaviorally based models of travel demand, it is difficult to anticipate how likely such behavioral changes are, but energy taxation, roadway tolls and other pricing policies may spur such transitions.

Freight travel accounts for 7 percent of the nation's GHG emissions, and offers several opportunities for relatively near-term emissions savings. **Reduced idling** (via technology or behavioral shifts) and a **shift to rail and water** transport will reduce such emissions, though the feasibility of such shifts will differ greatly across businesses. And freight rail is nearing its capacity. As an alternative, improving fuel economy of trucking is an option. However, even a 9% fuel savings results in rather low emissions savings for the U.S., since trucking represents a relatively small portion of total emissions.

Interestingly, a **shift away from red meat and dairy products** appears to provide dramatic GHG savings[48]. **Local purchases** of food and other consumables, to shorten distances of freight travel, also warrant some attention.

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[48] Red meat production is found to be very energy intensive and GHG-emitting. Eating less red meat or adopting a vegetarian diet is estimated to dramatically reduce GHG emissions. However, quantifying this savings is challenging, and study results differ in methodologies used and overall impact estimates.

All these behaviors are difficult to regulate, however, and may only emerge in the face of significant energy taxes and/or high oil costs[49]. Ideally, very effective public campaigns could also be waged, if top leaders and regular individuals from all walks of life were willing and able to persuasively communicate the importance of such lifestyle and other shifts to members of the public at large.

In terms of land use decisions and related policies, the most substantial GHG reductions are likely to emerge from **parking supply policies**. Residential parking space pricing (in multi-family units, for example) impacts vehicle ownership, and commercial parking policies (including caps, pricing, and cash-outs to employees) impacts mode choices. Certainly, in the near term such policies are easier to adopt than those that involve construction of new and renovation of existing infrastructure. Many neighborhoods already charge much more than $50 per month for parking, a policy that could reduce transport-related GHG emissions by 16%, due to mode choice shifts (away from SOVs) and reduced vehicle ownership (particularly if applied at the residence). And $90/month may be closer to the true cost of such parking, resulting in further savings. Charging higher rates for curb parking also may reduce trip generation and cruising time, helping relieve downtown congestion while reducing VMT.

As a proxy for a variety of relevant neighborhood attributes (including parking availability and price) **population density** has consistently proven a strong indicator of travel behaviors, relative to most other attributes of urban form. Of course, pockets of density may bear little fruit; overall, regional densification is most associated with energy conservation, but obviously harder to achieve in existing, developed areas. Attention to the relative positioning of jobs, housing, and other activity locations can be helpful in reducing longer-term GHG emissions, by impacting trip distances, vehicle ownership decisions (both number and type), transit's competitiveness, mode choices, and building size.

Of course, urban form is slow to change, and estimated impacts appear relatively weak, in terms of transportation effects. Policies requiring more efficient **appliances, temperature settings**, **insulation practices, vegetative shading, and technologies for cooling and heating** residential and commercial structures demonstrate meaningful potential for reducing energy demands and CO2 emissions in the near- to medium-term. Over the longer term, requirements for **better building design, particularly high R-value insulation**, a shift toward **multi-family structures** and smaller dwelling units, **use and re-use of lower-energy building materials**, and **more compact urban arrangements** will bear more significant and enduring savings. Again, these sort of changes will probably require dramatic changes in building codes and zoning regulations (in cities and in unincoporated areas), particularly in colder climates. Finally, the notion of **reducing, reusing, and recycling** merits mention here. Simply extending the useful life of various consumer items, along with reduced packaging, can bear multiple benefits (including substantial cost savings). Water-use reductions and recycling of grey water also offer important energy benefits, which often go neglected in the literature (most likely due to data and other information limitations).

While all of these activities applied across the board, without demolishing existing structures and scrapping vehicles before their standard life spans, can take us a long way, the question remains: Can we achieve a 80-percent or even a 50-percent reduction in the nation's energy demands and GHG emissions over the coming decades, as populations and incomes rise, and as consumer preferences and global supply chains expand? It appears that such reductions

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[49] Given the relatively low price-elasticity of vehicle fuel sales, energy taxation policies may best include credits for lower-income populations and others facing excessive cost burden.

will require tremendous behavioral shifts, motivated by policies that introduce significant energy taxes, household-level carbon budgets, and cooperative local and international behavior in the interest of the global community.

Tables 1 through 26 provide a suite of estimates for CO2e reductions, petroleum impacts, energy intensities of different fuels, and other details of interest here, for most of the topics studied in this report. These metrics provide for a relatively rigorous comparison of the impacts of various changes in behavior and technologies – and sense of what is attainable in each carbon-producing, energy-consuming facet of American life, following minor shifts (on the order of 1 percent adoption) or far more dramatic shifts in behavior. While Table 1 suggests that a $2 per gallon tax on gasoline could reduce petroleum imports by nearly 3 percent (the maximum impact in that table's set of policies and practices), Table 2 suggests that a complete shift toward PHEVs (with 60 mile ranges) could induce a much greater petroleum savings for the nation, on the order of 60 percent. Of course, petroleum is just one source of energy and carbon emissions, and the energy stored in a PHEV's battery must come from somewhere, so the CO2e emissions impacts of such a strategy are much lower: on the order of 8 percent (if 100 percent of light-duty vehicles were to make the switch), according to Table 3. If the U.S. could "simply" follow the EU's lead on fuel economy standards, and switch to a 44.3 mpg (EPA test-rated) average, Table 7 suggests a 12.6% reduction in CO2e emissions. The least carbon-intensive fuel is cellulosic ethanol, and a complete shift to it among the light-duty vehicle fleet (which is impossible, and not necessarily carbon saving, depending on land use implications) would generate about a 16% CO2e savings. It is interesting to note how much dirtier conventional coal technologies for energy production are than natural gas, its closest competitor (among distinct feedstocks), according to Table 20 (in terms of CO2e per BTU), with a ratio approaching 4 to 1. As noted above, shifts in electricity generation consistently offer the greatest savings, with an impossible 100-percent immediate shift to renewable feedstocks estimated to provide a 33-percent near-term CO2e savings. Over the longer term, impacts are greater and a 50-percent shift toward renewable feedstocks may be feasible.

Such estimates provide a window on the potential reductions in CO2e over time: 15 percent or more from electricity generation processes and 12 percent or more from fuel economy improvements on par with other developed countries. Unfortunately, this is nowhere near the 50 to 80-percent cuts assumed needed by 2050, of course, and the nation's population is rising in the meantime. Table 10 suggests that a complete shift to rapid rail at average occupancies may provide for nearly 10-percent reductions in CO2e. If buses could be used at maximum occupancy, the 100-percent mode-shift estimate climbs to 25 percent. Of course, such a shift is hardly likely, under any circumstances, given Americans' reliance on the private automobile. But it gives one a sense of whether such policies are worth pursuing.

In terms of building designs and land use patterns, Table 16 suggests significant opportunities for saving energy on cooling in places like Miami, Austin and Las Vegas exist, by updating/weatherizing and downsizing homes (up to 10,000 lbs of CO2e per year). In contrast, the best places to reduce CO2e emissions from a shift to solar at the home are in places like Montana, Colorado and Missouri (Table 21), where the electricity grid is relatively carbon-intensive. Unfortunately, parking, land use, and urban design strategies do not appear to compete with other policies and practices, when evaluated on the basis of travel demand impacts: only at 100-percent adoption levels do these begin to approach a one-percentage point reduction in overall carbon emissions levels (Tables 22, 23, 24, and 25). For a clear picture of this, Figure 10 illustrates the relative implications of Table 25's top 20 strategies. Of course, other, less direct energy and emissions impacts can and do emerge, in the design of buildings, vehicle type choice, and so on. These are not so well studied, but a move to MFDUs and shared walls offer important energy-savings opportunities, as discussed earlier[50].

Given the lack of "silver bullets", the public and its policymakers have to anticipate significant shifts in behavior and lifestyles in order to reach carbon targets. These will be affected by contextual changes, as incomes rise, preferences shift, fossil fuels peak and changing weather systems provoke population migrations. Extreme climate is expected to accelerate conditions of drought as well as flooding, temperature shifts, loss in arable lands, and water supply limitations. Very high energy prices will lead to related shifts, in how we live and conduct business. Such transitions "will not be temporary but generational" (Peterson 2008). How well and how quickly we anticipate these and adapt is a critical question, with a highly uncertain answer. Unfortunately, a "simple extrapolation or extensions of the present modeling paradigms are wholly inadequate to capture the extent of possible effects." (Peterson 2008)

Fortunately, assuming that the willpower to establish the appropriate conservation mechanisms materializes, many of the opportunities for energy savings and carbon emissions reductions will likely pay for themselves. McKinsey & Co. (2007) estimates that **40 percent of carbon reductions can be had at "negative costs"**, representing a savings over the (discounted) lifetime of the required investments. It seems that many near- and long-term opportunities exist for direction consumption and production practices towards the target. Current and future generations hope that the nation, and indeed the entire human race, rise to the challenge, soon.

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[50] As mentioned (and footnoted) earlier, MFDUs carry some communal energy demands that RECS data do not cover. If these add 10 percent to a MFDU's energy demands, the standing of MFDU options in Figure 10 shifts, from 10th and 12th places, to 13th and 14th places. So this option remains a top contender, but with a roughly 52 percent lower impact (per 1-percent adoption rate).

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TABLE 1 GHG Emission and Petroleum Consumption Savings from 1 Percent Adoption of Speed Limit, Tire Pressure and Gas Price Policies

Speed Limits	**Speed (mph)**	**FE Loss (%)**	**Fuel Economy (mpg)**	**1 Percent GHG Emissions (MMTCE)**	**GHG Emissions Saved (MMTCE)**	**Percent U.S. GHG Emissions**	**1 Percent Petroleum Consumed (mbd)**	**Daily Petroleum Savings (mbd)**	**Percent of U.S. Petroleum Consumption**	**Percent of U.S. Petroleum Imports**
Base Urban Interstate (65 mph)	65	9.7	18.5	0.865	Vs. Base Urban		0.019	Vs. Base Urban		
Lower Urban Interstate (55 mph)	55	--	20.5	0.781	0.084	4.35E-03	0.017	1.80E-03	8.69E-03	1.80E-02
Base Rural Interstate (70 mph)	70	17.1	17.0	0.509	Vs. Base Rural		0.011	Vs. Base Rural		
Lower Rural 1 (65 mph)	65	9.7	18.5	0.467	0.042	2.16E-03	0.010	8.95E-04	4.32E-03	8.95E-03
Lower Rural 2 (55 mph)	55	--	20.5	0.422	0.087	4.51E-03	0.009	1.87E-03	9.02E-03	1.87E-02
Combined Urban and Rural 1				1.248	0.126	6.51E-03	0.027	2.69E-03	1.30E-02	2.69E-02
Combined Urban and Rural 2				1.203	0.171	8.86E-03	0.026	3.67E-03	1.77E-02	3.67E-02
Tires	**Tire Pressure (psi)**	**FE Change (%)**	**Fuel Economy (mpg)**	**1 Percent GHG Emissions (MMTCE)**	**GHG Emissions Saved (MMTCE)**	**Percent U.S. GHG Emissions**	**1 Percent Petroleum Consumed (mbd)**	**Daily Petroleum Savings (mbd)**	**Percent of U.S. Petroleum Consumption**	**Percent of U.S. Petroleum Imports**
Underinflated Tire	24	-2.2	20.1	4.639	Vs. Underinflated/Non-RR		0.099	Vs. Underinflated/Non-RR		
Maintained Tire Pressure	32	--	20.5	4.535	0.104	5.39E-03	0.097	2.23E-03	1.08E-02	2.22E-02
Low Rolling Resistance Tires	32	2.5	21.1	4.425	0.111	5.73E-03	0.095	2.37E-03	1.15E-02	2.37E-02
Gas taxes	**Price with Tax**	**Percent Price Increase**	**Gasoline Consumption Saved (mbd)**	**1 Percent GHG Emissions (MMTCE)**	**GHG Emissions Saved (MMTCE)**	**Percent U.S. GHG Emissions**	**1 Percent Petroleum Consumed (mbd)**	**Daily Petroleum Savings (mbd)**	**Percent of U.S. Petroleum Consumption**	**Percent of U.S. Petroleum Imports**
No Tax Increase	4.00	0.0	0.00	4.677	Vs. Present Tax		0.100	Vs. Present Tax		
$0.50/gal Gas Tax Increase	4.50	12.5	83.88	4.644	0.032	1.68E-03	0.100	6.96E-04	3.36E-03	6.94E-03
$1.00/gal Gas Tax Increase	5.00	25.0	167.77	4.612	0.065	3.36E-03	0.099	1.39E-03	6.72E-03	1.39E-02
$1.50/gal Gas Tax Increase	5.50	37.5	251.65	4.579	0.097	5.04E-03	0.098	2.09E-03	1.01E-02	2.08E-02
$2.00/gal Gas Tax Increase	6.00	50.0	335.54	4.547	0.130	6.73E-03	0.097	2.78E-03	1.34E-02	2.78E-02

Note: The "1 Percent GHG Emissions" column provides the total GHG emissions expected from U.S. light-duty vehicles at the given fuel economy or gas tax level. MMTCE stands for million metric tons of carbon equivalent (CO2e), where one metric ton is 1000 kg, or 2205 lbs.

TABLE 2 Potential Petroleum Savings from Improvements in Vehicle Technology

Technology	FE Benefit (%)		Fuel Econ. (mpg)	Daily Petroleum Savings (mbd)	Percent of U.S. Petroleum Consumption	Percent of U.S. Petroleum Imports	Daily Petroleum Savings (mbd)	Percent of U.S. Petroleum Consumption	Percent of U.S. Petroleum Imports
	Low	High							
Base Vehicle (2007 fleet average)	--	--	20.5	versus Average Vehicle			versus New MY 2007 Vehicle		
Base Vehicle (MY 2007 achieved)	--	--	26.7	0.021	0.103	0.212			
Engine Technology	0	0	0.0	0.000	0.000	0.000			
Cylinder Deactivation	3	8	28.2	0.025	0.120	0.249	0.004	0.018	0.037
Direct Injection	1	3	27.2	0.023	0.109	0.226	0.001	0.007	0.014
Turbocharging	3	7	28.0	0.025	0.119	0.245	0.003	0.016	0.033
Valve Event Manipulation (VEM)	1	7	27.8	0.024	0.116	0.239	0.003	0.013	0.027
Transmission Technology									
Automatic or Continuously Variable	1	8	27.9	0.024	0.117	0.242	0.003	0.015	0.030
Aggressive Shift Logic	1	5	27.5	0.023	0.113	0.233	0.002	0.010	0.020
Vehicle Design									
10% Mass Reduction	4	10	28.6	0.026	0.125	0.258	0.005	0.022	0.046
Improved Aerodynamics	1	2	27.1	0.022	0.108	0.222	0.001	0.005	0.010
Accessory Electrification	1	5	27.5	0.023	0.113	0.233	0.002	0.010	0.020
Low Rolling Resistance Tires	1	2	27.1	0.022	0.108	0.222	0.001	0.005	0.010
All Conventional Technologies	17	57	36.6	0.040	0.194	0.401	0.019	0.092	0.189
Diesel	20	40	34.7	0.043	0.207	0.427	0.022	0.104	0.215
Diesel with Conventional Technologies	29	72	40.2	0.049	0.239	0.493	0.028	0.136	0.281
HEV	17	30	33.0	0.035	0.167	0.346	0.013	0.065	0.133
HEV with Conventional Technologies	34	87	42.9	0.048	0.231	0.476	0.026	0.128	0.264
PHEV 40	34	87	42.9	0.070	0.336	0.695	0.048	0.234	0.483
PHEV 60	34	87	42.9	0.081	0.389	0.804	0.059	0.287	0.592

Note: The mid-point of the Low and High FE Benefit percentages was assumed in each case. These low and high percentages come from NRC (2008). “All Conventional Technologies” includes all Engine, Transmission, and Vehicle Design Technologies listed above.

TABLE 3 Potential CO_2 Emissions Savings from 1 Percent Adoption of Various Improvements in Vehicle Technology

	Technology	FE Benefit (%)		Fuel Economy (mpg)	1 Percent GHG Emissions (MMTCE)	Annual Savings (MMTCE)	Percent of U.S. GHG Emissions	Annual Savings (MMTCE)	Percent of U.S. GHG Emissions
		Low	High						
	Base Vehicle (2007 fleet average)	--	--	20.5	4.27	Vs. Average Vehicles		Vs. New Vehicles	
	Base Vehicle (MY 2007 acheived)	--	--	26.7	3.28	0.991	0.051		
Conventional Technologies	*Engine Technology*								
	Cylinder Deactivation	3	8	28.2	3.18	1.087	0.056	0.095	0.005
	Direct Injection	1	3	27.2	3.24	1.024	0.053	0.032	0.002
	Turbocharging	3	7	28.0	3.18	1.087	0.056	0.095	0.005
	Valve Event Manipulation (VEM)	1	7	27.8	3.24	1.024	0.053	0.032	0.002
	Transmission Technology								
	Automatic or Continously Variable	1	8	27.9	3.24	1.024	0.053	0.032	0.002
	Aggressive Shift Logic	1	5	27.5	3.24	1.024	0.053	0.032	0.002
	Vehicle Design								
	10% Mass Reduction	4	10	28.6	3.15	1.117	0.058	0.126	0.007
	Improved Aerodynamics	1	2	27.1	3.24	1.024	0.053	0.032	0.002
	Accessory Electrification	1	5	27.5	3.24	1.024	0.053	0.032	0.002
	Low RR Tires	1	2	27.1	3.24	1.024	0.053	0.032	0.002
	All Conventional Technologies	17	57	36.6	2.39	1.876	0.097	0.885	0.046
Advanced Drivetrain Technologies	Diesel	20	40	34.7	2.74	1.524	0.079	0.532	0.028
	Diesel w/ Conventional Technologies	29	72	40.2	2.37	1.897	0.098	0.906	0.047
	HEV	17	30	33.0	2.65	1.615	0.084	0.624	0.032
	HEV w/ Conventional Technologies	34	87	42.9	2.04	2.226	0.115	1.235	0.064
	PHEV 40 (Coal-fired)	34	87	42.9	2.24	2.029	0.105	1.037	0.054
	PHEV 40 (Renewable)	34	87	42.9	1.02	3.247	0.168	2.256	0.117
	PHEV 40 (Grid Average)	34	87	42.9	1.78	2.491	0.129	1.500	0.078
	PHEV 40 (Clean Grid)	34	87	42.9	1.55	2.718	0.141	1.727	0.090
	PHEV 40 (Clean Grid and CCS)	34	87	42.9	1.19	3.081	0.160	2.090	0.108
	PHEV 60 (Coal-fired)	34	87	42.9	2.34	1.930	0.100	0.939	0.049
	PHEV 60 (Renewable)	34	87	42.9	0.51	3.758	0.195	2.767	0.143
	PHEV 60 (Grid Average)	34	87	42.9	1.64	2.623	0.136	1.632	0.085
	PHEV 60 (Clean Grid)	34	87	42.9	1.30	2.964	0.154	1.973	0.102
	PHEV 60 (Clean Grid and CCS)	34	87	42.9	0.76	3.508	0.182	2.517	0.130

TABLE 4 Lifetime Savings (or Cost) from Advanced Materials in a Typical Passenger Car (in present dollars)

Gas Price	Payback Period	4 Percent Discount Rate				12 Percent Discount Rate			
		Steel	Plastics	Aluminum	Magnesium	Steel	Plastics	Aluminum	Magnesium
$3.00 per Gallon	3 Years	$14.26	(30.59)	(897.42)	(929.58)	(9.70)	(52.92)	(887.12)	(927.24)
	4 Years	66.52	25.27	(774.83)	(783.66)	26.38	(14.36)	(802.49)	(826.50)
	5 Years	114.50	76.56	(662.26)	(649.67)	57.14	18.52	(730.33)	(740.60)
	14 Years	403.37	385.33	15.35	156.92	192.77	163.49	(412.19)	(361.90)
$3.50 per Gallon	3 Years	45.32	2.61	(824.55)	(842.85)	15.32	(26.18)	(828.43)	(857.37)
	4 Years	106.29	67.78	(681.53)	(672.61)	57.41	18.81	(729.70)	(739.84)
	5 Years	162.28	127.63	(550.20)	(516.28)	93.30	57.17	(645.51)	(639.63)
	14 Years	499.28	487.85	231.63	424.74	251.53	226.31	(274.34)	(197.81)
$4.00 per Gallon	3 Years	76.38	35.82	(751.68)	(756.11)	40.34	0.57	(769.74)	(787.50)
	4 Years	146.06	110.30	(588.23)	(561.55)	88.45	51.98	(656.90)	(653.19)
	5 Years	210.05	178.69	(438.14)	(382.89)	129.46	95.83	(560.68)	(538.66)
	14 Years	595.19	590.38	465.34	692.56	310.30	289.12	(136.49)	(33.72)

Note: New vehicles are assumed to be driven 15,600 miles each year, declining at a rate of 4.5 percent annually. Lightweighting enabled by materials from EEA (2007). An assumed fuel economy benefit of 6 percent is achieved for every 10 percent mass reduction.

TABLE 5 Lifetime Savings (or Cost) from HEV Ownership Assuming Moderate Return Expectations (in present dollars)

Comparison	**Toyota Prius vs. Toyota Corolla**	**Honda Civic Hybrid vs. Toyota Corolla**	**Toyota Prius vs. Ford Focus**	**Honda Civic Hybrid vs. Ford Focus**	**Toyota Prius vs. Toyota Camry**	**Honda Civic Hybrid vs. Toyota Camry**	**Ford Escape Hybrid vs. Ford Escape**	**Ford Escape Hybrid vs. Toyota RAV4**	**Ford Escape Hybrid vs. Ford Explorer**	**Ford Escape Hybrid vs. Honda Pilot**
Price Difference	$6250	7350	6745	7845	2580	3680	7500	5140	445	(955)
Gas at $3.00 per gallon										
NPV (3 yrs)	(4815.72)	(6120.80)	(3827.67)	(5132.75)	(298.82)	(1603.90)	(6678)	(4409)	106	1452
NPV (4 yrs)	(4347.51)	(5721.95)	(3215.87)	(4590.31)	312.98	(1061.47)	(6529)	(4259)	255	1601
NPV (5 yrs)	(3917.56)	(5355.70)	(2654.07)	(4092.21)	874.78	(563.36)	(6391)	(4122)	392	1739
NPV (Lifetime)	(1329.46)	(3151.02)	727.72	(1093.85)	4256.56	2435.00	(5564)	(3295)	1219	2565
Gas at $3.50 per gallon										
NPV (3 yrs)	(4537.41)	(5883.72)	(3464.01)	(4810.32)	64.83	(1281.48)	(6589)	(4320)	194	1541
NPV (4 yrs)	(3991.16)	(5418.40)	(2750.24)	(4177.48)	778.60	(648.63)	(6415)	(4145)	369	1715
NPV (5 yrs)	(3489.55)	(4991.10)	(2094.81)	(3596.36)	1434.03	(67.51)	(6254)	(3985)	529	1875
NPV (Lifetime)	(470.10)	(2418.98)	1850.60	(98.27)	5379.45	3430.58	(5290)	(3021)	1494	2840
Gas at $4.00 per gallon										
NPV (3 yrs)	(4259.10)	(5646.64)	(3100.36)	(4487.90)	428.49	(959.05)	(6500)	(4231)	283	1630
NPV (4 yrs)	(3634.82)	(5114.84)	(2284.62)	(3764.65)	1244.23	(235.80)	(6301)	(4032)	483	1829
NPV (5 yrs)	(3061.55)	(4626.51)	(1535.56)	(3100.51)	1993.29	428.34	(6118)	(3849)	666	2012
NPV (Lifetime)	389.25	(1686.93)	2973.49	897.31	6502.34	4426.15	(5015)	(2746)	1768	3114
Gas at $4.50 per gallon										
NPV (3 yrs)	(3980.79)	(5409.56)	(2736.70)	(4165.47)	792.15	(636.62)	(6411)	(4142)	372	1718
NPV (4 yrs)	(3278.47)	(4811.29)	(1819.00)	(3351.82)	1709.85	177.03	(6187)	(3918)	597	1943
NPV (5 yrs)	(2633.55)	(4261.91)	(976.30)	(2604.66)	2552.55	924.19	(5981)	(3712)	803	2149
NPV (Lifetime)	1248.60	(954.89)	4096.38	1892.88	7625.23	5421.73	(4741)	(2472)	2043	3389
Gas at $5.00 per gallon										
NPV (3 yrs)	(3702.48)	(5172.49)	(2373.04)	(3843.04)	1155.81	(314.20)	(6322)	(4053)	461	1807
NPV (4 yrs)	(2922.12)	(4507.74)	(1353.37)	(2938.98)	2175.47	589.86	(6073)	(3804)	710	2057
NPV (5 yrs)	(2205.54)	(3897.32)	(417.04)	(2108.81)	3111.81	1420.03	(5844)	(3575)	939	2286
NPV (Lifetime)	2107.96	(222.85)	5219.27	2888.46	8748.12	6417.31	(4466)	(2197)	2317	3663

TABLE 6 Lifetime Savings (or Cost) from HEV Ownership Assuming High Return Expectations (in present dollars)

Comparison	**Toyota Prius vs. Toyota Corolla**	**Honda Civic Hybrid vs. Toyota Corolla**	**Toyota Prius vs. Ford Focus**	**Honda Civic Hybrid vs. Ford Focus**	**Toyota Prius vs. Toyota Camry**	**Honda Civic Hybrid vs. Toyota Camry**	**Ford Escape Hybrid vs. Ford Escape**	**Ford Escape Hybrid vs. Toyota RAV4**	**Ford Escape Hybrid vs. Ford Explorer**	**Ford Escape Hybrid vs. Honda Pilot**
Price Difference	$6250	7350	6745	7845	2580	3680	7500	5140	445	(955)
Gas at $3.00 per gallon										
NPV (3 yrs)	(4677.26)	(5858.67)	(3822.81)	(5004.22)	(546.02)	(1727.44)	(6266.76)	(4159.61)	32.35	1282.35
NPV (4 yrs)	(4354.02)	(5583.32)	(3400.45)	(4629.74)	(123.66)	(1352.96)	(6163.50)	(4056.36)	135.61	1385.61
NPV (5 yrs)	(4078.40)	(5348.53)	(3040.30)	(4310.43)	236.48	(1033.65)	(6075.45)	(3968.31)	223.65	1473.65
NPV (Lifetime)	(2863.26)	(4313.41)	(1452.51)	(2902.66)	1824.27	374.12	(5687.28)	(3580.14)	611.82	1861.82
Gas at $3.50 per gallon										
NPV (3 yrs)	(4453.08)	(5667.71)	(3529.88)	(4744.51)	(253.10)	(1467.72)	(6195.14)	(4088.00)	103.96	1353.96
NPV (4 yrs)	(4075.97)	(5346.46)	(3037.13)	(4307.62)	239.66	(1030.83)	(6074.68)	(3967.54)	224.43	1474.43
NPV (5 yrs)	(3754.42)	(5072.55)	(2616.96)	(3935.09)	659.82	(658.30)	(5971.96)	(3864.82)	327.15	1577.15
NPV (Lifetime)	(2336.75)	(3864.90)	(764.54)	(2292.69)	2512.25	984.09	(5519.09)	(3411.95)	780.02	2030.02
Gas at $4.00 per gallon										
NPV (3 yrs)	(4228.91)	(5476.74)	(3236.96)	(4484.79)	39.83	(1208.01)	(6123.53)	(4016.39)	175.58	1425.58
NPV (4 yrs)	(3797.92)	(5109.61)	(2673.81)	(3985.49)	602.98	(708.71)	(5985.86)	(3878.71)	313.25	1563.25
NPV (5 yrs)	(3430.43)	(4796.56)	(2193.62)	(3559.75)	1083.17	(282.96)	(5868.46)	(3761.32)	430.64	1680.64
NPV (Lifetime)	(1810.23)	(3416.39)	(76.56)	(1682.72)	3200.22	1594.07	(5350.90)	(3243.76)	948.21	2198.21
Gas at $4.50 per gallon										
NPV (3 yrs)	(4004.73)	(5285.77)	(2944.04)	(4225.08)	332.75	(948.30)	(6051.92)	(3944.78)	247.19	1497.19
NPV (4 yrs)	(3519.87)	(4872.75)	(2310.49)	(3663.37)	966.30	(386.58)	(5897.03)	(3789.89)	402.07	1652.07
NPV (5 yrs)	(3106.44)	(4520.57)	(1770.28)	(3184.40)	1506.51	92.38	(5764.97)	(3657.82)	534.14	1784.14
NPV (Lifetime)	(1283.72)	(2967.88)	611.41	(1072.75)	3888.20	2204.04	(5182.71)	(3075.57)	1116.40	2366.40
Gas at $5.00 per gallon										
NPV (3 yrs)	(3780.55)	(5094.81)	(2651.11)	(3965.37)	625.67	(688.58)	(5980.31)	(3873.16)	318.80	1568.80
NPV (4 yrs)	(3241.82)	(4635.89)	(1947.17)	(3341.24)	1329.62	(64.45)	(5808.21)	(3701.07)	490.89	1740.89
NPV (5 yrs)	(2782.46)	(4244.58)	(1346.94)	(2809.06)	1929.85	467.73	(5661.47)	(3554.33)	637.63	1887.63
NPV (Lifetime)	(757.21)	(2519.37)	1299.38	(462.77)	4576.17	2814.01	(5014.52)	(2907.38)	1284.59	2534.59

TABLE 7 Potential Petroleum Consumption Reduction and GHG Emissions Savings from 1% Adoption of Fuel Economy Standards

Fuel Economy Standard	Fuel Economy	U.S. Petroleum Consumption Savings (mbd)	Percent of U.S. Petroleum Consumption	U.S. GHG Emission Savings (MMTCE)	Percent of U.S. GHG Emissions
2008 Fleet Average	20.5	versus 2008 Fleet Average FE			
Passenger Cars	22.4				
Vans, SUVs, and Pickups	18.0				
2008 CAFE Standards	25.4	0.018	0.089	3.175	0.045
Passenger Cars	27.5	0.010	0.048	1.717	0.024
Vans, SUVs, and Pickups	22.5	0.009	0.042	1.491	0.021
CA 2012 Standards	32.5	0.036	0.172	6.118	0.086
Passenger Cars	38.2	0.022	0.108	3.829	0.054
Vans, SUVs, and Pickups	24.7	0.012	0.057	2.023	0.029
2020 CAFE Standards	35.0	0.040	0.193	6.870	0.097
CA 2016 Standards	36.4	0.042	0.204	7.242	0.102
Passenger Cars	43.4	0.026	0.126	4.480	0.063
Vans, SUVs, and Pickups	26.8	0.014	0.069	2.448	0.035
EU 2008 Standards	44.2	0.052	0.250	8.902	0.126
$500 per 0.01 GPM Feebate	23.8	0.013	0.065	1.766	0.025
$1000 per 0.01 GPM Feebate	26.5	0.022	0.105	2.789	0.039

TABLE 8 Potential CO2 Emissions Savings for Alternative Fuels, Following 1% Change in LDV Miles

Alternative Fuels	Lbs CO2e per VMT	Δ CO2e/yr (billion lbs)	% Savings of U.S. Total CO2e Emissions
Cellulosic Ethanol	0.11	25.5	0.16
Biodiesel	0.40	18.9	0.12
Hydrogen	0.72	11.6	0.07
Compressed Natural Gas	0.88	7.9	0.048
Liquefied Natural Gas	0.95	6.4	0.04
Corn Ethanol	0.96	6.1	0.038
Methanol	1.12	2.4	0.015
Gasoline (Base Case)	1.23	0	0

Assumptions:

1. U.S. LDV VMT/yr = 2.27 billion miles (NHTS 2001)
2. 2003 Avg. LDV fuel economy = 20.3 MPG (EPA 2006)
3. 25 lb CO2e/gal gasoline (EPA 2007b)
4. lb CO2e/BTU of alternative fuels derived from Figure 6.
5. Remaining 99% LDV miles fueled by gasoline.
6. Biofuels estimates do not include the potential affects ofincreased emissions from land use changes.

TABLE 9 Carbon and Energy Intensity of Various Vehicle Fuels

Fuel Type (measured in units of gallons, except for Hydrogen)	10^{-4} Lbs CO2e/ BTU	BTU per unit	Lbs CO2e/ kWh	kWh/ unit
Gasoline (gal)	2.2	114,100	0.75	33.4
Diesel (gal)	2.4	129,800	0.82	38.0
E100 Ethanol-Corn (gal)	1.7	76,100	0.58	22.3
E85 Ethanol-Corn (gal)	1.8	81,800	0.61	23.9
E100 Ethanol-Cellulosic (gal)	0.2	76,100	0.07	22.3
E85 Ethanol-Cellulosic (gal)	0.5	81,800	0.17	23.9
Hydrogen (*pounds*)	1.3	52,000	0.44	15.2
Biodiesel (gal)	0.7	129,500	0.24	37.9
M100 Methanol (gal)	2.0	56,800	0.68	16.6
M85 Methanol (gal)	2.1	65,400	0.69	19.1

Assumptions:

1. BTU/unit comes from NAFA (2006) and Bossel and Eliasson (2003).
2. Lbs CO2e/BTU comes from EPA (2007a).
3. Gasoline emissions: 25 lbs CO2e/gallon (EPA 2007b)

TABLE 10 Estimates of CO2 Emissions Savings from a 1% Shift Away from Automobile Mode, Assuming Current Average Vehicle Occupancy and Power Train Technology

Mode	BTU/paxmile	Current Avg. Ridership (pax/veh)	% Savings of Total U.S. CO2e Emissions
Automobile (gasoline)	3448	1.6	-
Bus (diesel)	4160	9	-0.055
Light Rail (electric)	1160	25	0.070
Subway/Rapid Rail (electric)	860	23	0.097
Regional Rail (diesel & electric)	1471	33	0.076

Assumptions:

1. AVO = 1.6 persons (Davis & Diegel 2007)
2. U.S. LDV VMT/yr = 2.27 billion miles (NHTS 2001)
3. Transit yearly energy use, passenger and vehicle mileage (APTA 2007)
4. In APTA 2007, Subway/Rapid Rail is listed as Heavy Rail, and Regional Rail is listed as Commuter Rail.
5. Gasoline Emissions: 0.00022 lbs CO2e/BTU (EPA 2007a)
6. Diesel Emissions: 0.00024 lbs CO2e/BTU (EPA 2007a)
7. Electricity Emissions: 0.00039 lbs CO2e/BTU (EIA 2000)

TABLE 11 Savings from a 1% Shift Away from Automobile Mode, Assuming Maximum Transit Vehicle Occupancy

Mode	BTU/pax mile	Ridership (pax/veh)	% Savings of Total U.S. CO2e Emissions
Automobile (gasoline)	3448	1.6	-
Lose 1% Automobile Trips (gasoline)	3448	1.6	0.175
Automobile (gasoline)	1379	4	0.105
Bus (diesel)	705	54	0.136
Light Rail (electric)	291	100	0.148
Subway/Rap Rail (electric)	237	82	0.153
Regional Rail (diesel & electric)	425	114	0.146

Assumptions:

1. AVO = 1.6 persons (Davis & Diegel 2007)
2. U.S. LDV VMT/yr = 2.27 billion miles (NHTS 2001)
3. Transit yearly energy use, passenger and vehicle mileage (APTA 2007)
4. In APTA 2007, Subway/Rapid Rail is listed as Heavy Rail, and Regional Rail is listed as Commuter Rail.
5. Gasoline Emissions: 0.00022 lbs CO2e/BTU (EPA 2007a)
6. Diesel Emissions: 0.00024 lbs CO2e/BTU (EPA 2007a)
7. Electricity Emissions: 0.00039 lbs CO2e/BTU (EIA 2000)
8. Maximum transit vehicle occupancy from TRB TCRP (2004a)

TABLE 12 Potential CO2e Emissions Savings from a 1% Mode-Shift Away fromTruck to Rail or Water

Freight Mode	BTU/ton-mi	Billion Ton-mi/yr	% Savings of Total U.S. CO2e Emissions
Truck	2380	1,200	–
Rail	340	1,700	0.038
Water	510	621	0.035

Assumptions:

1. Diesel Emissions: 0.00024 lbs CO2e/BTU (EPA 2007a)
2. BTU/ton-mi (Davis & Diegel 2007; FHWA 2007)
3. Ton-mi/yr (Davis & Diegel 2007)

TABLE 13 Potential CO2e Emissions Savings When 1% of Truck VMT Is Driven by Vehicles Using an Idle Reduction Strategy

Strategy	% Fuel Savings	$ Saved per Truck per Year	% Savings of Total U.S. CO2e Emissions
APU	9.0%	$5400	0.0043%
Automated Engine Idle	6.0%	$3600	0.0028%
Direct Fire	3.4%	$2040	0.0015%

Assumptions:

1. % Fuel Savings (Ang-Olson and Schroeer 2002)
2. Truck VMT: 145,624,000,000 (FHWA 2007)
3. Typical Combination Truck Fuel Efficiency: 6 mpg (Ang-Olsen and Schroeer 2002)
4. BTU/gallon Diesel: 129,000 (NAFA 2006)
5. Diesel Emissions: 0.00024 lbs CO2e/BTU (EPA 2007a)
6. $4.00/gallon diesel
7. Average Miles Per Year Per Long Range Truck (>500 mi): 90,000 (FHWA 2007)
8. Maximum Market Penetration is 63% of Truck VMT (FHWA 2007; Ang-Olsen and Schroeer 2002)

TABLE 14 Carbon Implications of Meat Consumption and Non-Local Food Purchases

	GHG Savings (MMTCE/year)	% Savings of Total U.S. GHG
1% of household shift diet from red meat (7 days/week)	3.40	0.18
1% shift diet from red meat (1 day/week)	0.486	0.03
1% shift to purchasing 100% “local” food	0.486	0.03
1% shift to purchasing 10% “local” food	0.049	0.003

TABLE 15 Residential Energy Consumption Survey (RECS) Model Results

		Single Family Dwelling Unit	Multifamily Dwelling Unit
Y = Electricity Use (kWh/year)	Household Size	991	611
	HH Members >65	164	-327
	CDD	2.11	1.49
	Total Square Footage	0.80	0.75
	Number of Floors	-33.88	-29.10
	Number of Apartments	n/a	-4.411
	Town Indicator	1665	763
	Rural Indicator	854	26
	Suburban Indicator	4084	2350
Y = Natural Gas Consumption (ccf/year)	Household Size	27	20
	HH Members >65	-3.02	34
	HDD	0.049	0.022
	Programmable Thermostat	-12	2.5
	Total Square Footage	0.073	0.027
	Number of Floors	7.48	1.26
	Number of Apartments	n/a	-0.795
	Town Indicator	-152	-20.8
	Rural Indicator	-86	22
	Suburban Indicator	-498	-168

Note: Values come from ordinary least squares regression results of RECS 2001 data, as shown in Appendix Tables C3 through C6.

TABLE 16 Cooling-Related CO2 Emission Savings Potentials for Cities of Different Sizes and Climates, Using Various A/C Load Reduction Strategies (Pounds of CO2e per Unit per Year)

City	CDD	Update Unit	Downsize Home	Update & Downsize	Less One Hour A/C Operation per Day
Spokane, WA	684	72	32	96	46
Billings, MT	882	772	348	1029	493
Portland, MA	521	164	74	218	314
Green Bay, WI	665	403	182	538	387
Harrisburg, PA	1225	569	257	759	364
Denver, CO	948	1247	563	1663	683
Chicago, IL	1030	728	329	971	465
Detroit, MI	796	533	241	711	511
Baltimore, MD	1377	817	369	1090	261
Seattle, WA	306	24	11	33	47
New York, NY	1162	488	220	651	312
Kansas City, MO	1714	1527	689	2037	488
Los Angeles, CA	654	60	27	81	26
Atlanta, GA	1784	1359	613	1811	434
Sacramento, CA	1388	346	156	461	132
Raleigh-Durham, NC	1573	934	421	1245	298
Miami, FL	4431	2828	1276	3771	986
Austin, TX	3228	2246	1013	2994	662
Charleston, SC	2200	1317	594	1757	421
Las Vegas, NV	3489	2102	948	2803	672

Note: Values assume current A/C unit installed in 1986, with SEER of 8.87. Updated unit (from 2006) would have a SEER of 12. Downsizing the home from 2000-2500 SF to 1500-2000 SF would allow a capacity reduction from 34,000 BTU/hr to 30,000 BTU/hr. Both strategies would mean a capacity reduction from 34,000 BTU/hr to 30,000 BTU/hr and an increase in efficiency from 8.87 to 12 (SEER value). The final column, less one hour of operation, assumes the household adjusted its thermostat to operate one less hour each day (which may easily be 30 minutes before leaving the home in the morning and 30 minutes after retuning in the afternoon).

TABLE 17 Nonresidential Building Energy Consumption Data

	Criteria	NG consumption (ccf/sq ft)	NG consumption (BTU/sq ft)	Electricity Consumption (kWh/sq ft)	Major Fuel Consumption (MBTU/sq ft)	Average Electricity Expenditures ($/Sq Ft)	Average Age (years)
All Data	Initial	0.57	58.74	17.15	109.41	1.41	30.87
	Renovated since 1980	0.66	67.90	15.48	121.79	1.24	50.97
	Renovated HVAC	0.66	67.80	16.55	127.83	1.27	50.61
	Renovated insulation	0.54	56.16	14.06	109.32	1.13	56.17
Excluding Lab/Hospital	Initial			16.37	100.30	1.37	31.33
	Renovated since 1980			13.85	104.11	1.15	52.53
	Renovated HVAC			14.46	103.56	1.17	52.35
	Renovated insulation			12.84	90.64	1.06	56.82
	Not renovated since 1980			17.18	99.08	1.44	24.55
	Un-renovated HVAC			16.67	99.80	1.41	28.04
	Un-renovated insulation			16.58	100.89	1.39	29.84
Lab/Hospital	Initial			24.73	197.59	1.76	26.53
	Renovated since 1980			25.22	226.90	1.75	42.00
	Renovated HVAC			25.91	236.62	1.72	43.00
	Renovated insulation			21.44	222.27	1.57	53.00
	Not renovated since 1980			25.42	178.52	1.76	16.61
	Un-renovated HVAC			24.32	182.18	1.78	19.74
	Un-renovated insulation			25.06	195.40	1.78	23.96

Note: “Renovations since 1980” refers to any kind of major renovation to the building envelope or operating systems. (EIA 2001)

TABLE 18 Commercial Building Annual Electricity and Natural Gas Consumption Model Results for 2003 CBECS Data

Electricity Consumed (kWh/year)			**Natural Gas Consumption (ccf/year)**		
	Coef.	**t-stat.**		**Coef.**	**t-stat.**
(Constant)	-9.82E04	-4.319	(Constant)	-1653.13	-1.276
Square Footage (SF)	8.012	17.556	Square footage (Sqft)	0.227	7.448
# Workers	2.51E03	19.932	# Workers	23.32	3.894
# Total Hours open/wk.	1.38E03	6.537	# Total hours open/week	42.87	3.337
			# Businesses	-1.17E02	-1.934
Price in $/kWh	-1.11E05	-1.042	Price in $/ccf	-5.61E02	-1.596
CDD*SF (‘000)	3.132	16.414	HDD*SF (‘000)	3.62E-03	7.972
High Rise (>15 Floors)	6.11E05	2.052	High Rise (>15 Floors)	3.74E05	2.489
Age of the Building	-5.30E02	-1.843	Age of the Building	19.201	1.142
SF * Retail Indicator	6.164	5.311	SF * Retail Indicator	-0.148	-2.466
SF * Service Indicator	7.276	12.927	SF * Service Indicator	0.351	13.258
			SF * Basic Indicator	-0.124	10.105
No of observations	**4711**		**No of observations**	**3133**	
R^2	**0.677**		**R^2**	**0.446**	

Note: Other explanatory variables were examined, and statistically insignificant variables were removed from these final model specifications. All variable definitions can be found in Table C11.

TABLE 19 Opportunities for CO2e Savings Based on Changes in Electricity Use Patterns

Type of Electricity Use (before & after energy-saving change)	**Wattage (kW)**	**Usage (hours per day)**	**Potential Savings (Billion kWh/ year)**	**CO2e Savings (MMTCE per year)**	**% Savings of Total U.S. CO2e Emissions**
Clothes Dryer					
electric dryer	1.8-5.5	1	0	0	-
clothesline	0	n/a	0.8-2.5	0.50-1.53	0.007-0.02
Clothes Washer					
hot water	3.5-5	0.86	0	0	0
cold water	0.35-0.5	0.86	1.2-1.8	0.75-1.1	0.01-0.014
Light bulbs					
incandescent	0.06	15	0	0	0
fluorescent	0.015	15	0.3	0.18	0.002
Television (19 inch display)					
25 hrs/week	0.065-0.11	3.6	0	0	0
0 hrs/week	0.065-0.11	0	0.10-0.18	0.64-1.1	0.0009-0.0015
Refrigerator					
energy inefficient (455 kWh/yr top-freezer)	0.0519	24	0	0	0
energy efficient (364 kWh/yr)	0.0416	24	0.11	0.073	0.001
Water Heater					
Conventional Electric, 140 °F setting	13.3	-	0	0	-
Conventional Electric, 120°F setting	9.9	-	1.5	0.91	0.013
Heat Pump	4.9	-	3.8	2.3	0.03
Computer Mode					
full power all day (120 W)	0.12	24	0	0	0
sleep mode part-time (17 hrs at 5 W)	0.03	17	1.1	0.65	0.009
Computer Monitor					
CRT (120 watt)	0.15	7	0	0	-
LCD (40 watt)	0.04	7	0.35	0.21	0.003

Note: Values for TV, washer, dryer, and computer mode come from http://apps1.eere.energy.gov/consumer/your_home/appliances/index.cfm/mytopic=10040. Computer monitor wattages and use level come from http://michaelbluejay.com/electricity/. Average pounds of CO2 per kWh assumed to be 1.341 (EIA 2000). This varies with home location. Clothes dryer assumes 5 kW electric dryer, 8 loads a week, and 45 min. per load. Washer assumes electric water heater, and 8 loads per week. Water heater calculations assume average family's consumption to be 64.3 gallons per day. (Tomlinson 2002) Number of housing units come from the U.S. Census (2007). Heat pump calculation assumes 43% of homes rely on an electric heater while 57% use natural gas, based on RECS 2001 data.[51]

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[51] RECS (2001) data indicate that 39% of U.S. households use an electric heater, 53% use natural gas for heating, 3.6% use fuel oil, and the remainder use some other form of heating.

TABLE 20 Carbon Intensity and Price of Various Energy Sources for Power Generation

Energy Source	**10^{-4} Lbs CO2e/BTU**	**Lbs CO2e/kWh**	**$/kWh**
Coal	6.14	2.08	0.04-0.055
Natural Gas	3.67	1.25	0.04-0.05
Nuclear	0.10	0.03	0.07-0.145
Biomass	0.27	0.09	0.060
Solar PV	0.23	0.08	0.200
Hydro	0.11	0.04	0.05-0.11
Geothermal	0.09	0.03	0.030
Wind	0.08	0.03	0.04-0.06
Sources: Lbs/kWh come from EIA 2000, EPA 2007a, & Meijer 2002. And $/kWh values come from DOE 2007, MIT 2003, NREL 2002, & Cold Energy 2005. Notes: U.S. grid average carbon intensity is 3.93 E-04 CO2e/BTU, as consumed by the end user (thus including transmission losses).			

TABLE 21 Annual GHG Savings due to Residential Use of Solar Energy (annual CO2e in lbs per home)

U.S. City	lb CO2/kWh	50% Electricity Provided By Solar	100% Electricity Provided By Solar
Seattle & Spokane, WA	0.23	1145	2291
Los Angeles & Sacramento, CA	0.48	2390	4781
Portland, MA	0.91	4532	9064
New York, NY & Harrisburg, PA	1.13	5627	11255
Baltimore, MD & Miami FL	1.39	6922	13844
Miami, FL	1.39	6922	13844
Las Vegas, NV	1.46	7271	14542
Austin, TX	1.63	8117	16235
Atlanta, GA	1.69	8416	16832
Green Bay, WI, Detroit, MI, & Chicago IL	1.71	8516	17032
Kansas City, MO	1.90	9462	18924
Billings, MT & Denver, CO	1.98	9860	19721

Note: Table assumes 830 kWh per month per household (DOE 2004). Pounds/kWh values come from ASHRAE (2001).

TABLE 22 Annual CO2 Emission Savings Estimates Resulting from Various Parking Policies, Assuming that 1% of Workers are Affected

Parking Policies	SOV Share Reduction or VMT Reduction	VMT Reduction per Worker or HH (per year)	CO2e Reduction per Worker or HH Affected (lbs/year)	U.S. CO2e Savings if 1% of Workers or HHs Affected (metric tons/year)
Paid employee parking[1a]	10-30% SOV share	451-1352	563-1691	322,188-966,564
$50/month residential parking[1b]	30% VMT	5,378	6,723	3,843,172
Change front and side parking to rear lot[1b]	36% SOV share	1,317	1,646	941,141
Market priced curb parking[2a]	n/a	182.5	228	142,759

Sources: (1) VTPI (2007) & (2) Shoup (1997).

Assumptions: Vehicles average 20 mpg, average number of work trips per person per year is 565, average work trip distance is 12 miles, and average cruising distance is one half mile; Number of affected workers is 1.27 million. (Census 2000)

Note: Curb parking VMT reduction is based only on cruising parking and does not account for reduced trip generation due to higher parking costs. Superscript “a” is for VMT reduction per worker & “b” is for VMT reduction per HH.

TABLE 23 Annual CO2 Emissions Savings Estimates Following 10% Increases in Land Use Variables, Assuming That 1% of All U.S. Households Experience Such Changes

Effect of a 10% Increase in…	Elasticity Estimate	VMT Reduction (miles/HH per year)	CO2e Reduction per Adopting HH (lbs/year)	US CO2e Savings from 1% Adoption (metric tons/year)
Population Density	-.071 to -0.302	125-537	156-671	75,735-325,757
Net (Persons + Jobs) Density	-0.322	573	716	409,471
Accessibility	-0.273	491	614	350,873

Sources: (1) Schimek (2002), (2) Newman and Kenworthy (2006), (3) Cervero and Kockelman (1997).

TABLE 24 Annual CO2 Emissions Savings Resulting from 10-Percent Change in Urban Design Variable Values for 1% of U.S. Households, Assuming Only Non-Work Travel Is Affected

Effect of 10% Increase in …	*Elasticity of Non-SOV Mode Choice for Non-work Travel*	*Elasticity of Non Personal Vehicle Choice*	*Elasticity of PMT by Vehicle for Non-work Travel*	*VMT Reduction (miles/HH per year)*	*CO2e Reduction per Affected HH (lbs/year)*
Walking Quality	0.091	0.183 (non-work), 0.174 (pers. bus.), 0.119 (work)		655	819
Land Use Mixing	0.111			41	51
Vertical Mixing			-0.141	92	114
4-way Intersections			-0.591	384	480
Front & Side Parking	-0.512	-0.121 (non-work)		-339	-423

Assumptions: Average vehicle occupancy for work trips is 1.14, non-work is 1.88, vehicle averages 20 mpg.

Sources: (1) Cervero and Kockelman (1997). Walking quality includes sidewalk and street light provision, block length, planted strips, lighting distance and flatness of terrain. Land use mixing is measure of dissimilarity of land use among neighboring hectares as well as how varied the land uses are within each hectare. Vertical mixing is proportion of parcels with more than one land use on site.
(2) TCRP (2004B)

TABLE 25 Comparison of GHG Emissions and Energy Savings Estimates (as a Percentage of Total U.S. GHG Emissions and Energy Use) from 1% Adoption of Various Energy-Saving Strategies

Reduction Strategy	**Difficulty of Implementation** (1 to 4: Most to Least Feasible)	**% U.S. Annual GHG Emissions**	**Energy Saved Per Year** (billion BTU)
Passenger Travel - Shift from Average PC			
New Vehicle (MY 2007 Achieved FE)	1	0.051	36,285
10% Lightweighting	2	0.058	41,265
All Conventional Improvements (includes 10% lightweighting)	2	0.090	64,033
Biodiesel	2	0.119	0
Cellulosic Ethanol	3	0.161	0
All Conventional Improvements + E85 cellulosic ethanol fuel	3	0.193	137,314
PHEV 60 (average grid mix)	2	0.085	60,475
PHEV 60 (renewable electricity)	3	0.143	101,741
PHEV 60 (average grid mix + E85 cellulosic ethanol fuel)	3	0.105	74,705
Transit Mode Shift (with new passengers served by existing service)	2	0.175	127,849
Subway/Rapid Rail - Average occupancy	2	0.096	95,972
Freight Travel - Shift from Average HDV			
Rail Mode Shift	2	0.039	25,677
Idle Reduction (APU)	2	0.005	2,800
Energy Sources - Shift from Average Grid			
Shift Towards Renewables (from 9.7 to 10.7% mix of feedstocks)	n/a	0.33	0
Building Design - 1% Shift from Average SFDU			
Downsize Home, from 2400 to 2000 sq ft	2	0.0060	3,164
2400 sq ft SFDU to 2400 sq ft MFDU	4	0.0546	27,906
2400 sq ft SFDU to 2000 sq ft MFDU	4	0.0588	30,053
Low-rise MFDU to High-rise MFDU (2000 sf)	2	0.0026	1,329
Warmest Climates: Reduce A/C Operation by 1 hour per day	1	0.018	7,145
Increase Insulation 90 mm to 500 mm	3	0.013	17,845
Switch from Conventional Water Heater to Heat Pump	2	0.031	29,546
Reduce Water Heater Temp from 140 to 120°F	1	0.013	5,160

(*continued on next page*)

TABLE 25 (*continued*) Comparison of GHG Emissions and Energy Savings Estimates (as a Percentage of Total U.S. GHG Emissions and Energy Use) from 1% Adoption of Various Energy-Saving Strategies

Reduction Strategy	**Difficulty of Implementation** (1 to 4: Most to Least Feasible)	**% U.S. Annual GHG Emissions**	**Energy Saved Per Year** (billion BTU)
Wash Clothes in Cold Water (versus hot)	1	0.016	6,351
Put Computer on Sleep Mode for 17 hrs/day	1	0.010	3,969
Land Use			
Increase (gross) U.S. Population Density 10%	2	0.001- 0.004	711 - 2,846
Increase Net Density 10%	2	0.006	4,269
Increase Accessibility 10%	3	0.005	3,557
Parking			
Parking to be Paid by Employees	2	0.004 – 0.013	2,850 - 9,250
$50/month Residential Parking	2	0.054	38,400
Change Front & Side Parking to Rear Lot – (from Tables 22 & 24)	2	0.016	11,380
Market Priced Curb Parking Downtown	2	0.002	1,420
Design			
Increase Walking Quality Measure 10%	2	0.007	4,980
Increase Measure of Land Use Mixing 10%	3	0.0004	285
Increase Measure of Vertical Mixing 10%	3	0.001	711
Increase Fraction of Four-way Intersections 10%	3	0.004	2,850

Note: Each of these strategies is described at length in the body of the report. For definition of terms, details of calculations, and sources of parameters, please see respective sections (in the appendix as well). Parking, Land Use and Design strategies are detailed in Tables 22, 23, and 24, respectively. Difficulty of Implementation seeks to represent the cost, cultural, political, and technological challenges in significant level of adoption (e.g., 10% adoption rate), but not full adoption. It is a subjective score (with 1 being thought easiest to adopt, at some scale, and 4 being most difficult), and various arguments can be made for assignment of other levels.

TABLE 26 Petroleum Savings Estimates Arising from 1-Percent Shifts in Fuel, Mode Choice, HDT Design, and Other Strategies

1% Shift from…	Energy Saved Saved Per Year (Trillion BTU)	Gasoline (gas) or Diesel Saved Per Year (Million Gallons)
Gas (LDV) to Alternative Fuel	-	1,100
LDV to Light Rail (avg. ridership)	84.9	1,100 (gas)
LDV to Subway (avg. ridership)	96.0	1,100 (gas)
LDV to Regional Rail (max ridership)	97.5	1,100 (gas), -81(diesel)
LDV to Bus (max ridership)	101.8	1,100 (gas), -201 (diesel)
LDV to LDV (max ridership)	76.7	672 (gas)
LDV to Regional Rail (avg. ridership)	73.3	1,100 (gas), -281 (diesel)
Current Electricity Grid to Renewable Grid (natural gas savings)	-	380
HDT to water	23.5	181
HDT to HDT w/APU	2.8	22
HDT to HDT w/Automated Engine Idle	1.9	14.5
HDT to HDT w/Direct Fire	1.1	8

Assumptions:

1. Gasoline contains 114,100 BTU per gallon, while diesel contains 129,800 BTU per gallon. (NAFA 2006)
2. Fuel savings calculations are based on the energy savings estimated for Tables 8, 10, 11, 12, 13, and 21.
3. Shift to diesel-based modes from passenger vehicles reduces gasoline demand, but adds to diesel demand in many cases. Thus, the negative diesel fuel values.

Appendix A

Details on Calculations Involving Vehicle Technologies and Fuel-Related Policies

This first appendix shows sample calculations of petroleum consumption reductions and GHG emission savings from passenger vehicle technologies and fuel economy regulation. Parameters assumed throughout these calculations are shown below, in Table A1. This appendix begins by outlining intermediate calculations before ultimately showing the form for calculating reductions and savings from 1 percent adoption scenarios.

VOLUMETRIC FUEL GHG INTENSITIES

To find GHG intensity on a per-gallon fuel basis in units of lb CO_2e per gal fuel of various fuels:

$$VolumetricGHGIntensity = EnergyBasisGHGIntensity \times HeatContent \times \frac{lb}{454\ g} \times \frac{MBtu}{10^6\ Btu}$$

ELECTRICITY GHG INTENSITIES

Electricity GHG intensity calculations are simplified by assuming carbon intensity to be equivalent to GHG intensity. Carbon intensities are found on a plant-to-grid basis. To find the carbon intensity on a per-kWh basis in units of lb CO_2 per kWh-grid of various electricity generation technologies:

$$ElectricCarbonIntensity = \frac{FeedstockCarbonIntensity \times PlantHeatRate}{Transmission\&DistributionEfficiency} \times \frac{MBtu}{10^6\ Btu}$$

For the special case of coal power with carbon capture and sequestration:

$$ElectricCarbonIntensity = \frac{FeedstockCarbonIntensity \times PlantHeatRate \times (1 - CCSEfficiency)}{Transmission\&DistributionEfficiency} \times \frac{MBtu}{10^6\ Btu}$$

ELECTRICITY GRID AVERAGING

Weighted averages of different electricity generation technologies are used to assess large-scale impacts of technologies. Grid average electric carbon intensity in units of lb CO_2 per kWh-grid for generation technologies indexed $i = 1$ to N are given by:

$$ElectricCarbonIntensity_{GridAverage} = \sum_{i=1}^{N} \frac{ElectricCarbonIntensity_i \times GridFraction_i}{100}$$

HEAT CONTENT RATIO

A heat content ratio is used to normalize consumption of various liquid fuels as consumption of petroleum. The heat content ratio for a fuel has units of gallons of petroleum per gallons of fuel consumed and is given by:

$$HeatContentRatio = \frac{HeatContent}{HeatContent_{Petroleum}}$$

FUEL ECONOMIES

Fuel economies are adjusted to reflect improvements from vehicle technologies (as well as losses from inefficient operation which are addressed via policies such as lower speed limits and proper tire pressure maintenance). Fuel economy benefits, shown in the first columns of Tables 1, 2 and 3, are used to adjust base fuel economies:

$$FuelEconomy = FuelEconomy_{Base} \times \frac{100 \pm FuelEconomyBenefit/Loss}{100}$$

The fuel economy loss from improper tire maintenance is given by:

$$FELoss_{TireUnderInflation} = 8\ psi \times \frac{1.4\%\ Roll\ Resist\ Increase}{psi\ Underinflation} \times \frac{2\%\ FE\ Loss}{10\%\ Roll\ Resist\ Increase} = 2.2\%$$

where a 1.4 percent increase in rolling resistance per psi underinflation and 2 percent fuel economy loss per 10 percent rolling resistance increase are assumed based on TRB (2006). An average underinflation of 8 psi (25 percent of an assumed average tire pressure of 32 psi) is chosen based on an NHTSA (2004) finding that 26 percent of passenger cars and 29 percent of light duty trucks have at least one tire 25 percent or more underinflated.

The fuel economy losses avoided by lowering speed limits are based on empirical testing of the fuel economy–speed relationship in passenger vehicles by West et al. (1997). The fuel economy losses from vehicle technologies are midpoints of values given by NRC (2008).

Fuel economies from more stringent fuel economy standards, shown in Table 8, are taken from An and Sauer (2004). Finally, fuel economies expected from feebates are computed using percent fuel economy increases from Greene et al. (2005).

Base fuel economies are found using weighted averages of passenger car fleet and SUV, pickup truck, and van fleet fuel economies. The fleet average is weighted by percent of fleet and the new vehicle average is weighted by percent of sales:

$$FuelEconomy_{FleetAvg} = \frac{NumPassCars \times AvgPassCarFE + NumLDTs \times AvgLDTFE}{NumPassVehs}$$

$$FuelEconomy_{NewVehAvg} = \frac{PassCarSalesShare \times AvgNewPassCarFE + LDTSalesShare \times AvgNewLDTFE}{100}$$

1-PERCENT ADOPTION PETROLEUM REDUCTIONS

To calculate petroleum saved in units of million barrels per day (mbd) from various vehicle technology strategies:

$$PetroleumConsumed = \frac{\frac{NumVeh}{100} \times AnnualVMT \times HeatContentRatio}{FuelEconomy} \times \frac{mbd}{42 \times 10^6\ gal \times 365\ days}$$

$$PetroleumSaved = PetroleumConsumed_{Base} - PetroleumConsumed$$

$$PercentConsumption = \frac{PetroleumSaved}{20.7\ mbd} \times 100\%$$

$$PercentImports = \frac{PetroleumSaved}{10.0\ mbd} \times 100\%$$

For the special case of PHEVs:

$$PetroleumConsumed = (1 - ElecFrac) \times \frac{\frac{NumVeh}{100} \times AnnualVMT \times HeatContentRatio}{FuelEconomy} \times \frac{mbd}{42 \times 10^6\ gal \times 365\ days}$$

1-PERCENT ADOPTION GHG SAVINGS

To calculate the GHG emission saved in million metric tons carbon equivalents (MMTCE) from various vehicle technology strategies

$$AnnualGHGEmissions = \frac{\frac{NumVeh}{100} \times AnnualVMT \times VolumetricGHGIntensity}{FuelEconomy} \times \frac{MMTCE}{2204 \times 10^6\ lbs}$$

$$GHGEmissionsSaved = AnnualGHGEmissions_{Base} - AnnualGHGEmissions$$

$$PercentEmissions = \frac{GHGEmissionsSaved}{7075.6\ MMTCE} \times 100\%$$

For the special case of PHEVs:

$$AnnualGHGEmissions = \frac{NumVeh}{100} \times AnnualVMT \times \left[(1 - ElecFrac) \times \frac{VolumetricGHGIntensity}{FuelEconomy} + ElecFrac \times ElectricCarbonIntensity \times ElectricEfficiency\right] \times \frac{MMTCE}{2204 \times 10^6\ lbs}$$

GAS TAXES

The own price elasticity of demand for gasoline is used to compute the reduction in gasoline consumption:

$$GasolineSaved = 9.076\ mbd\ gasoline \times (100 - Elasticity \times TaxIncrease)$$

where *Elasticity* is taken from Hughes et al. (2007). Gasoline savings then give petroleum and GHG emission savings:

$$PetroleumSaved = GasolineSaved \times HeatContentRatio$$

$$GHGEmissionsSaved = GasolineSaved \times \frac{42 \times 10^6\ gal \times 365\ days}{mbd} \times VolumetricGHGIntensity \times \frac{MMTCE}{2204 \times 10^6\ lbs}$$

TABLE A1 Assumed Parameters from Vehicle Technology Calculations

Electric Feedstock Carbon Contents	Coal	lb CO_2/MMBTU	208.6	EIA (2008)
	Natural Gas (Pipeline)	lb CO_2/MMBTU	117.0	
	Petroleum (Residual oil)	lb CO_2/MMBTU	173.1	
	Nuclear	lb CO_2/MMBTU	0.0	
	Renewable	lb CO_2/MMBTU	0.0	
Electric Generation Technology Grid Fractions	Coal	%	50	
	Natural gas	%	20	
	Petroleum	%	1	
	Nuclear	%	20	
	Renewables	%	9	
	Coal (Clean Grid)	%	35	
	Natural Gas (Clean Grid)	%	15	
	Nuclear/Renewables (Clean Grid)	%	50	
Power Generation Heat Rates and Efficiencies	Fossil Fueled Steam-Electric	BTU/kWh	10,107	Aabakken (2006)
	Nuclear Steam-Electric	BTU/kWh	10,439	
	Geothermal Energy Plant	BTU/kWh	21,017	
	CCS Overall Efficiency	g CO_2e-saved/g CO_2e-base	0.85	IPCC (2005)
	Electric Transmission and Distribution	kWh-Grid/kWh	0.93	US Climate Change Technology Program (2005)
Fuel Carbon Intensity (Energy Basis)	Gasoline (weighted mix)	g CO_2e per MMBTU (WTW)	99450	EPA (2007)
	Corn ethanol	g CO_2e per MMBTU (WTW)	77815	
	Corn ethanol (biomass fuel)	g CO_2e per MMBTU (WTW)	45639	

(*continued on next page*)

TABLE A1 (*continued*) Assumed Parameters from Vehicle Technology Calculations

	Cellulosic ethanol	g CO_2e per MMBTU (WTW)	9023	
	E85 (Corn-based)	g CO_2e per MMBTU (WTW)	81060.25	Calculated from EPA (2007)
	E85 (Cellulosic)	g CO_2e per MMBTU (WTW)	22587.05	
	L S Diesel	g CO_2e per MMBTU (WTW)	96803	EPA (2007)
	Biodiesel	g CO_2e per MMBTU (WTW)	31292	
	B20	g CO_2e per MMBTU (WTW)	83700.8	Calculated from EPA (2007)
Fuel Heat Contents (HHV)	Petroleum	BTU/gal petroleum	138,095	EIA (2008)
	Motor Gasoline	BTU/gal motor gas	124,000	
	Diesel	BTU/gal diesel	139,000	
	Natural Gas	BTU/cf natural gas	1,026	
	Coal	BTU/short ton coal	20,681,000	
	Electricity	BTU/kWh	3,412	
	Ethanol	BTU/gal ethanol	83,333	
	E85	BTU/gal E85	94,190	Calculated from EIA (2003)
	Biodiesel	BTU/gal biodiesel	126,206	Wright et al. (2008)
	B20	BTU/gal B20	136,441	Calculated from EIA (2008) and Wright et al. (2008)
Passenger Vehicle Fleet Characteristics	Number of Passenger Cars	Thousands of vehicles	135,400	Davis and Diegel (2008)
	Number of SUVs, Vans, and Pickups	Thousands of vehicles	99,125	
	Number of Light-duty Vehicles	Thousands of vehicles	234,525	
	Average Annual Passenger Vehicle Mileage	VMT	11,100	
	Passenger Car Total Annual Vehicle Mileage	Million VMT	1,682,671	
	SUV, Van, and Pickup Total Annual Vehicle Mileage	Million VMT	1,089,013	
	Light-duty vehicle Total Annual Vehicle Mileage	Million VMT	2,771,684	
	U.S. Passenger Car Percent of Light Vehicle Fleet, 2006	%	57.7	
	U.S. SUV, Van, and Pickup Percent of Light Vehicle Fleet, 2006	%	42.3	
	U.S. Passenger Car Percent of Light Vehicle Sales, 2006	%	47.1	

(*continued on next page*)

TABLE A1 (*continued*) **Assumed Parameters from Vehicle Technology Calculations**

	U.S. SUV, Van, and Pickup Percent of Light Vehicle Sales, 2006	%	52.9	
Vehicle Fuel Economies	U.S. Passenger Car Fleet Average, 2006	mpg	22.4	
	U.S. SUV, Van, and Pickup Fleet Average, 2006	mpg	18.0	
	U.S. Passenger Car New Sale Average, MY 2007	mpg	31.0	
	U.S. SUV, Van, and Pickup New Sale Average, MY 2006	mpg	22.9	
PHEV Parameters	PHEV Electric Efficiency (Mid-Size Passenger Car)	Wh-Grid/mi	333	Gremban (2006)
	PHEV 10 Electric Miles Fraction	Percent Electric Miles	0.5	Santini (2008)
	PHEV 60 Electric Miles Fraction	Percent Electric Miles	0.75	
Macroeconomic Statistics	U.S. Net Daily Motor Gasoline Consumption (2007)	mbd	9.076	EIA (2008)
	U.S. Net Daily Diesel Consumption (2007)	mbd	3.048	
	U.S. Net Daily Jet Fuel Consumption (2007)	mbd	1.623	
	U.S. Net Daily Petroleum Consumption (Oil Equivalent)	mbd	20.7	
	U.S. Net Daily Crude Oil Imports (Oil Equivalent)	mbd	10.0	
	U.S. Net Annual GHG Emissions, 2007	MMTCE	7075.6	

Notes: Columns (from left to right) represent topic, fuel type, measurement units, assumed constant, and source of constant. MMBTU is million BTUs (as opposed to MBTU, which traditionally signifies “mil” or 1,000 BTUs).

Appendix B

Details On Calculations Involving Alternative Fuels, Modes, Freight, and Electricity Generation

The following are example calculations for tables (as numbered below) on energy and modes found in the main body of this report.

Table 9. Potential CO2 Emissions Savings for Alternative Fuels, following 1% Change in LDV Miles.

Assumptions:
1. U.S. LDV VMT/yr = 2.27 billion miles (NHTS 2001)
2. 2003 Avg. LDV fuel economy = 20.3 MPG (EPA 2006)
3. 25 lb CO2e/gal gasoline (EPA 2007b)
4. lb CO2e/BTU of alternative fuels derived from Figure 6.
5. Remaining 99% LDV miles fueled by gasoline.

Cellulosic ethanol is used in this example:
1. Current LDV Emissions = 2.27 billion VMT * 1.23 lbs CO2e/VMT
   = 2.8 trillion lbs CO2e
2. Post shift LDV emissions = (0.99*2.27 bill VMT)*1.23 lbs CO2e/VMT
   <u>+ (0.01*2.27 bill VMT)*0.11 lbs CO2e/VMT</u>
   = 2.77 trillion lbs CO2e
3. % Savings of total U.S. emissions = (Step 1 – Step 2) / 15.8 trillion lbs CO2e
   = 0.62%

Table 11. Savings from a 1% Shift Away from Automobile Mode, Assuming Current Average Vehicle Occupancy

Assumptions:
1. AVO = 1.6 persons (Davis and Diegel 2007)
2. U.S. LDV VMT/yr = 2.27 trillion miles (NHTS 2001)
3. Bus Regional Rail (listed as Commuter rail in APTA 2007) yearly energy use, passenger and vehicle mileage (Davis and Diegel 2007)
4. Subway/Rapid Rail (listed as heavy rail in APTA 2007) & Light Rail yearly energy use, passenger and vehicle mileage (APTA 2007)
5. Gasoline Emissions: 0.00022 lbs CO2e/BTU (EPA 2007a)
6. Diesel Emissions: 0.00024 lbs CO2e/BTU (EPA 2007a)
7. Electricity Emissions: 0.00039 lbs CO2e/BTU (EIA 2000)

Ridership values are national averages per vehicle (LDV, bus, rail car).
Total U.S. emissions were obtained from EPA Emissions and Sinks.
This HH transportation mode comparison excludes air and water travel.
Lifecycle emissions for each fuel type were used (rather than tailpipe emissions).

Bus data is used in this example:

1. Current Bus Energy Use/year = BTU/pax-mi * Yearly pax-mi
   = 4160 BTU/pax-mi * 22.821 billion pax-mi/yr
   = 94,925 billion BTU/yr
2. Current Annual Bus Emissions = Step 1 * lbs CO2e/Diesel BTU
   = 94,925 billion BTU/yr * 0.00024 lbs CO2e/BTU
   = 22,782 billion lbs CO2e/yr
3. Total HH Travel Yearly Emissions = ∑Modal Yearly Emissions
   = 2.81 trill lbs (LDV)
   + Step 2 (Bus)
   + 849,000,000 lbs (Light Rail)
   + 4,970,000,000 (Subway)
   + 4,429,000,000 (Regional Rail)
   = 2.845 trillion lbs
4. Current LDV pax-mi = Current LDVMT * avg. LDV ridership
   = 2,270 billion VMT * 1.6 pax/veh
   = 3,710 billion pax-mi
5. Post Shift Yearly LDV pax-mi = Step 4 – (0.01* Step 4)
   = 3.71 trillion pax-mi – (0.01*3.71 trillion pax-mi)
   =3.67 trillion pax-mi
6. Post Shift Yearly Bus pax-mi = Current Bus pax-mi + (0.01*Step 4)
   = 22.821 billion pax-mi/yr + (0.01*3.71 trillion pax-mi)
   = 60 billion pax-mi/yr
7. Post Shift Bus Yearly Energy Use = BTU/pax-mi * Step 6
   = 4230 BTU/pax-mi * 60 billion pax-mi/yr
   = 249 trillion BTU/yr
8. Post Shift Bus Yearly Emissions = Step 7 * lbs CO2e/Diesel BTU
   = 249 trillion BTU/pax-mi * 0.00024 lbs CO2e/BTU
   = 59.8 billion lbs CO2e/BTU
9. Total Post Shift HH Travel Yearly Emissions = ∑Modal Post Shift Yearly Emissions
   = 2.78 trill lbs (Post shift LDV)
   + Step 8 (Post shift Bus)
   + 5 thous lbs (current Light Rail)
   + 5 thous lbs (current Subway)
   + 7 thous lbs (current Regional Rail)
   = 2.854 trillion lbs
10. % Savings of Total U.S. Emissions from 1% LDV miles shift to Bus
   = (Step 3 – Step 9) / Total U.S. Emissions
   = (2.845 trill lbs – 2.854 trill lbs) / 15.8 trillion lbs
   = -0.06%

Table 12. Savings from a 1% Shift Away from Automobile Mode, Assuming Maximum Transit Vehicle Occupancy

Calculations and assumptions are the same as for Table 7, except in the assumed maximum possible ridership for each vehicle. This maximum ridership is impossible to obtain continuously. The max ridership shown is for the average vehicle (LDV, bus, rail car) used in U.S. systems for each mode.

Table 13. Potential CO2e Emissions Savings from a 1% Mode-shift Away from Truck to Rail or Water

Assumptions:

1. Diesel Emissions: 0.00024 lbs CO2e/BTU (EPA 2007a)
2. BTU/ton-mi (Davis and Diegel 2007; FHWA 2007)
3. Ton-mi/yr (Davis and Diegel 2007)

Rail mode used for example:

1. Rail Yearly Energy Use = BTU/ton-mi * ton-mi/year
   = 340 BTU/ton-mi * 1,700 billion BTU/yr
   =573 trillion BTU/yr
2. Total freight yearly energy use = ∑ Modal Yearly energy use
   = 2,990 trill BTU/yr (HDT)
   + 573 trill BTU/yr (rail)
   + 317 trill BTU/yr (water)
   = 3,880 trill BTU/yr
3. Post-shift yearly HDT ton-mi = 0.99 * 1,250 billion ton-mi
   = 1,240 billion ton-mi
4. Post-shift yearly HDT Energy use = Step 3 * BTU/ton-mi
   = 1,240 billion ton-mi * 2380 BTU/ton-mi
   = 2,961 trillion BTU
5. Post-shift yearly rail ton-mi = rail ton-mi/yr + (0.01* HDT ton-mi/year)
   = 1,700 billion ton-mi/yr + (0.01 * 1,250 billion ton-mi/yr)
   = 1,710 billion ton-mi/yr
6. Post-shift yearly rail Energy use = Step 5 * BTU/ton-mi
   = 1,710 billion ton-mi/yr * 337 BTU/ton-mi
   = 577 trillion BTU/yr
7. Total Post-shift yearly Energy use = ∑ Modal Post-shift yearly Energy use
   = Step 4 (HDT)
   + Step 5 (rail)
   + 317 trillion BTU/yr (water)
   = 3,854 trillion BTU/yr
8. Emissions Savings when 1% HDT ton-mi shift to rail
   = (Step 2 – Step 7) * Emissions/Unit Energy
   = (3,880 trill BTU – 3,854 trill BTU) * 0.00024 lbs CO2e/BTU
   = 6.1 billion lbs CO2e

9. % Total U.S. Emissions saved = Step 8 / Total U.S. Emissions
   = 6.1 billion lbs CO2e / 15.8 trillion lbs CO2e
   = 0.04%

Table 14. Potential CO2e Emissions Savings when 1% of Truck VMT Driven by Vehicles Using an Idle Reduction Strategy

Assumptions:

1. % Fuel Savings (Ang-Olson and Schroeer 2002)
2. Truck VMT: 145,624,000,000 (FHWA 2007)
3. Typical Combination Truck Fuel Efficiency: 6 mpg (Ang-Olsen and Schroeer 2002)
4. BTU/gallon Diesel: 129,000 (NAFA 2006)
5. Diesel Emissions: 0.00024 lbs CO2e/BTU (EPA 2007a)
6. $4.00/gallon diesel
7. Average Miles Per Year Per Long Range Truck (>500 mi): 90,000 (FHWA 2007)
8. Maximum Market Penetration is 63% of Truck VMT (FHWA 2007; Ang-Olsen and Schroeer 2002)

APU used for example:

1. 145,624,000,000 mi/year * 0.01 = 1,456,240,000 mi/year adopt strategy
2. 1,456,240,000 mi/year / 6 mpg = 242,706,667 gal/year without strategy
3. To obtain gallons saved per year: 242,706,667 gal/year *0.09 = 21,843,600 gal/year
4. $ saved per year per truck: 90,000 mi / 6 mpg *0.09 * $4/gal = $5,400/yr/truck
5. Energy saved per year: 21,843,600 gal/year * 129,000 BTU/gal = 2.8 Trillion BTU
6. Emissions saved per year: 2.8 Trillion BTU * 0.00024 lbs CO2/BTU = 680,000,000 lbs
7. % Total U.S. Emissions saved per year: 680,000,000 lbs / 4,107,000,000,000 lbs * 100 = 0.005%

Table 21. Emissions Savings When Shifting to a Cleaner Electricity Grid.

Assumptions

1. Electricity demand in 2006 was 3.8 billion MWh (EIA 2007).
2. CO2 emissions from electricity production in 2006 was 2.7 billion tons (EIA 2007).
3. Electricity demand growth rate is assumed to be 1.5% per year (EIA 2007d).
4. Total U.S. Emissions projections for 2030 and 2050 are derived from 1990-2005 trend (EPA 2007c).

Average Grid: 2006 average emissions = 2.7 billion tons / 3.8 billion MWh = 0.71 tons/MWh
Renewables: 3% of average grid emissions = 0.03 * 0.71 tons/MWh = 0.02 tons/MWh
Total U.S. Emissions 2006: 7.9 billion tons

2006 reduction in GHG due to using 50% renewables as feedstock:

1. Emissions: (0.5*3.8 billion MWh*0.71 tons/MWh) + (0.5*3.8 billion MWh*0.02 tons/MWh) = 1.4 billion tons
2. % Emissions Savings: (2.7 billion tons – Step 1) / 7.9 billion tons = 17%

2006 reduction in GHG due to using 1% renewables as feedstock:

1. Emissions: (0.99*3.8 billion MWh*0.71 tons/MWh) + (0.01*3.8 billion MWh*0.02 tons/MWh) = 2.67 billion tons
2. % Emissions Savings: (2.7 billion tons – 2.67 billion tons) / 7.9 billion tons = 0.33%

Appendix C

Details on Calculations Involving Land Use and Building Design

LAND USE AND TRIP-MAKING DETAILS

The VMT reduction due to elasticities of work, non-work, and total VMT with respect to any feature is calculated as follows:

Elasticity x Percentage Change in Feature x VMT / 100 = estimated VMT reduction

All calculations assume 20 mpg fuel economy (average for entire US vehicle fleet), and thus 1.25 lbs of CO2e per mile traveled. One hundred cubic feet (ccf) of natural gas emits 11.7 pounds of CO2e when burned. The national average for carbon emissions from power production is 1.34 lbs CO2e per kWh.

BUILDING DESIGN

Important Unit Conversions: 100 MBTU [52] = 1 therm = 10^5 BTU = 29.3 kWh = 11.7 lbs CO2e = 1.03 ccf ng (where 1 ccf ng = 100 cubic feet of natural gas)

TABLE C1 Average Personal Travel Information (from NHTS 2001)

Trip Type	Average #Person Trips (trips/yr)	Avg person Trip Length [$d_{\text{person trip}}$]	Avg Veh Trips per Year	Avg Veh trip length [$d_{\text{veh trip}}$]	Avg Total Annual VMT/HH	Hwy mi/veh trip	Average Veh Occup.
Work Commute	565	12.11	479	12.08	5724	6.64	1.14
Shopping	707	7.02	459	6.74	3062	3.71	1.79
Personal/Family Business	863	7.84	537	7.45	3956	4.10	1.83
Social and Recreational	952	11.36	441	11.91	5186	6.55	2.03

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[52] The acronym MBTU is problematic, since many use it to mean mega or million (10^6) BTUs, but tradition suggests that it means 1,000 BTUs (thanks to Roman numerals [http://en.wikipedia.org/wiki/BTU]). Care must be taken when converting this unit, to ensure consistency with author intent.

Residential

The Energy Information Administration makes detailed energy microdata available at both the household and commercial level. Using simple regressions in SPSS, one may calculate the coefficient effects of various household/housing unit characteristics on energy consumption. For this report, electricity consumption (kWh) and natural gas consumption (ccf) are determined for households.

ASHRAE (2001) lists Heating Degree Days (HDD) and Cooling Degree Days (CDD) for most cities in the United States and for major cities. With these values, we can determine the marginal difference in heating and cooling loads between two cities, as well as their relative impact on overall energy consumption.

The 2001 Residential Energy Consumption Survey (RECS) includes data for 4822 households. According to the 2000 Census, the actual number of households in the US was 107 million. The number of workers was 138.8 million. The survey permits simple averages of energy consumption (detailed in Table C2). In the regressions of this RECS data, an addition household member or square foot of home did not yield as great a result as the simple averages of the data: 4017 kWh per household member and 5 kWh per square foot of housing. Further, the averages for natural gas were 13706 ccf per household member and 17 ccf per square foot of housing.

In 2006, the number of households had risen to 126 million, and the number of workers was 152.2 million.

Single family detached cases were selected because this housing type makes up 60.9% of the US housing stock, and apartments make up another 25.0%. All cases assume the base unit is located in a city. All values noted in the residential building section make use of the coefficient in Tables C3 to C6 calculate marginal differences in energy consumption as home and household characteristics change.

Values considered most notable from the residential data were household size (marginal increase in energy consumption per household member), household members older than 65 years-old, cooling degree days, heating degree days, home location and home size (square footage). Table C3 provides a summary of these characteristics' coefficients.

TABLE C2 Residential Energy Consumption Averages (using EIA's 2001 RECS data)

			Electricity Consumption (kWh per year)		Natural Gas Consumption (ccf per year)	
Home Type	Average HH Size	Avg. Home Size (SF)	Per HH Member	Per SF	Per HH Member	Per SF
Mobile Home	2.63	1064	4666	11.54	77.06	0.19
MFDU	2.19	1079	2958	6.00	129.40	0.26
SFDU	2.78	2540	4239	4.64	183.49	0.20

Note: Mobile homes represent 325 cases, and 6.8 million dwelling units across the U.S. MFDUs represent 1136 cases and 26.5 million homes. SFDUs account for 3361 cases and 73.7 million homes across the U.S.

Example Calculations:

		Single Family		Multifamily	
		KWH	CCFNG	KWH	CCFNG
	x	B * x	B * x	B * x	B * x
Household Size	2.630	2603.70	71.32	1606.93	53.37
Laundry Drier	Yes	2377.00		1332.00	
Building Age	4.460	200.27	1.78	1290.50	0.89
Income	5.520	673.44	16.28	1159.20	24.74
AC present	Yes	2280.00		844.00	
Water Heater	Yes	1050.00		528.00	
HDD all	4223.800	1072.85	206.97	1068.62	92.92
CDD all	1326.460	2802.81	-75.61	1979.08	-39.79
Square Footage	2400 sq ft	1920.00	175.20	1800.00	64.80
Totals		*14980.07*	*395.94*	*11608.33*	*196.92*
CO2e		24705.83		17859.18	
Difference		6846.65			

The associated savings for a relocation of 1% of all US households from a low-rise MFDU to a high-rise MFDU (assuming 2 units per floor) can be computed as follows:

Electricity: $-29.10\frac{kWh}{floor} - 2\times 4.411\frac{kWh}{unit} = -37.922\ kWh/floor$

Natural Gas: $1.26\frac{ccf}{floor} + 2\times -0.795\frac{ccf}{unit} = -0.33\ ccf/floor$

$$-37.922\frac{kWh}{floor}\times 1.34\frac{lbs\ CO2e}{kwh} + -0.33\frac{ccf}{floor}\times 11.7\frac{lbs\ CO2e}{ccf}$$
$$= -54.676\ lbs\frac{CO2e}{floor * unit}$$

$$54.676\ \frac{lbs\ CO2e}{floor * unit} * 5\ floors = 273.38\ \frac{lbs}{unit}$$

$$273.38\ lbs \times 126{,}000{,}000\ households \times 1\%\ adoption + 15.8\ trillion\ lbs = .00216\%$$

TABLE C3 Results of Model of Electricity Consumption (kWh) in Single-Family Detached Units as a Function of Housing Unit Characteristics

	Unstandardized Coefficients		**Standardized Coefficients**	**t-stats.**	**P-values**
Variable	B	Std. Error	Beta		
(Constant)	-8110.770	1153.834		-7.029	.000
CDD65	2.113	.179	.268	11.806	.000
HDD65	.254	.092	.066	2.765	.006
HHSize	990.965	87.044	.191	11.385	.000
Adults >65	163.584	176.261	.014	.928	.353
Infants <1 year old	-2013.783	572.834	-.052	-3.515	.000
Income	122.787	61.608	.037	1.993	.046
Number of Stories	-33.883	19.636	-.028	-1.726	.085
Basement Present	-1087.623	293.079	-.071	-3.711	.000
Attic Present	64.963	246.316	.004	.264	.792
Garage Size (1,2,3 car)	124.381	34.985	.058	3.555	.000
Building Age	44.904	47.458	.016	.946	.344
Air Conditioning Present	2280.337	419.561	-.067	-3.056	.002
Rooms using AC in Summer	792.484	61.596	.310	12.866	.000
Significant Tree Shade	387.808	229.887	.025	1.687	.092
Lights on Longer than 12 hours	670.760	103.952	.096	6.453	.000
Number of windows	198.404	158.446	.021	1.252	.211
Washing Machine Loads	286.122	83.312	.057	3.434	.001
Own a Dryer	2377.559	460.849	.088	5.159	.000
Number of Color TVs	410.153	97.927	.067	4.188	.000
Number of PCs	348.615	146.499	.041	2.380	.017
Total Square Footage	.798	.109	.147	7.338	.000
Town Indicator	1665.925	315.431	.084	5.281	.000
Suburb Indicator	853.892	309.414	.046	2.760	.006
Rural Indicator	4084.906	308.432	.216	13.244	.000
Water Heater Less than 30 Gallons	77.942	547.545	.003	.142	.887
Water Heater More than 30 Gallons	1052.717	426.685	.051	2.467	.014

Note: Dependent variable = kWh/year, weighted least squares regression (using expansion factors), only cases of Single Family Detached DUs (n= 2,935), & adj. R square = 0.411.

TABLE C4 Results of Model of Natural Gas (ccf) Consumption in Single-Family Detached Units as a Function of Housing Unit Characteristics

	Unstandardized Coefficients		**Standardized Coefficients**	**t-stats.**	**P-values**
Variable	B	Std. Error	Beta		
(Constant)	181.551	58.954		3.080	.002
CDD65	-.057	.013	-.104	-4.274	.000
HDD65	.049	.007	.184	7.455	.000
HHSize	27.117	6.245	.075	4.342	.000
Adults >65	-3.023	13.410	-.004	-.225	.822
Infants <1 year old	-8.427	43.987	-.003	-.192	.848
Total Square Footage	.073	.007	.194	10.167	.000
Town Indicator	-152.207	24.330	-.110	-6.256	.000
Suburb Indicator	-86.213	23.587	-.067	-3.655	.000
Rural Indicator	-498.479	23.404	-.380	-21.299	.000
Income	-2.954	4.439	-.013	-.665	.506
Number of Stories	7.483	1.500	.089	4.988	.000
Attic present	4.306	18.938	.004	.227	.820
Garage Size (1, 2, 3 cars)	6.285	2.553	.042	2.462	.014
Main heating equipment age	.402	.461	.015	.872	.383
Thermostat for main heating equipment	-2.391	16.791	-.003	-.142	.887
Main thermostat programmable	-11.860	3.535	-.059	-3.355	.001

Note: Dependent variable = ccf of natural gas per year, weighted least squares regression (using expansion factors), only cases of Single Family Detached DUs (n= 2,935), & adj. R square = 0.266.

TABLE C5 Model Results for Electricity Consumption (kWh) per Apartment Unit as a Function of Appliances and Building Characteristics

	Unstandardized Coefficients		**Standardized Coefficients**	**t-stats.**	**P-values**
Variable	B	Std. Error	Beta		
(Constant)	6380.306	3859.448		1.653	.099
CDD65	1.492	.177	.319	8.420	.000
HDD65	.253	.093	.099	2.730	.006
HHSize	611.055	109.411	.158	5.585	.000
Adults >65	-327.325	248.179	-.035	-1.319	.187
Infants <1 year old	-1035.624	796.647	-.033	-1.300	.194
Total Square Feet	.746	.238	.102	3.137	.002
Town Indicator	762.988	357.312	.055	2.135	.033
Suburb Indicator	25.840	363.282	.002	.071	.943
Rural Indicator	2350.492	730.919	.081	3.216	.001
Air Conditioning Present	844.759	308.327	.078	2.740	.006
Number of Windows	-439.216	120.983	-.102	-3.630	.000
Own a dryer	1332.349	586.942	.121	2.270	.023
Number of Ceiling Fans	349.623	130.069	.074	2.688	.007
Number of Color TVs	485.117	145.940	.097	3.324	.001
Number of VCRs/DVD Players	148.594	163.816	.026	.907	.365
Number of PCs	455.112	170.863	.074	2.664	.008
Water Heater Less than 30 Gallons	582.047	412.582	.040	1.411	.159
Water Heater More than 30 Gallons	528.313	295.697	.053	1.787	.074
Building Age	289.350	55.748	.148	5.190	.000
Dishwasher Used	-53.577	298.629	-.005	-.179	.858
Number of Apartments	-4.411	5.256	-.415	-.839	.401
Number of Floors	-29.102	52.053	-.270	-.559	.576

Note: Dependent variable = kWh/year, weighted least squares regression (using expansion factors), only cases of MFDUs (n= 1,136), & adj. R square = 0.314.

TABLE C6 Results of Model of Natural Gas (ccf) Consumption as a Function of Housing Unit Characteristics in Apartments Containing 5 or more Units

	Unstandardized Coefficients		Standardized Coefficients	t-stats.	P-values
Variable	B	Std. Error	Beta		
(Constant)	31.299	41.495		.754	.451
CDD65	-.030	.009	-.167	-3.310	.001
HDD65	.022	.005	.206	4.056	.000
HHSize	20.292	6.541	.122	3.102	.002
Adults >65	33.871	14.160	.092	2.392	.017
Infant <1 year old	60.271	42.907	.051	1.405	.161
Total Square Feet	.027	.021	.051	1.304	.193
Town Indicator	-20.813	22.099	-.035	-.942	.347
Suburb Indicator	22.069	21.286	.038	1.037	.300
Rural Indicator	-168.061	53.738	-.112	-3.127	.002
Income	4.481	3.186	.054	1.406	.160
Main heating equipment age	.196	.172	.042	1.137	.256
Thermostat for main heating equipment	2.018	6.815	.011	.296	.767
Main thermostat programmable	2.499	1.991	.051	1.256	.210
Number of Apartments	-.795	.268	-.142	-2.971	.003
Number of Floors in building	1.259	2.596	.023	.485	.628

Note: Dependent variable = ccf of natural gas per year, weighted least squares regression (using expansion factors), only cases of MFDUs with 5+ units (n= 692), & adj. R square = 0.143.

Air Conditioning:

$$UEC = \frac{hours}{day} x \frac{days}{year} x \frac{Btu}{hour} \div SEER$$

(LBL 2000)

Where UEC= unit electricity consumption, BTU/hr is rated capacity of the unit, and SEER is seasonal energy efficiency ratio.

Hours/day and days/year were obtained from ASHRAE (2001). BTU/hr is determined from housing square footage: e.g., 1500-2000 sq ft requires 30,000 BTU/hr, 2000-2500 sq ft requires 34, 000 BTU/hr. The SEER is a rating assigned each year, stating what the average energy efficiency of all units produced in that year was. Currently, AC units can be produced with a SEER of 15, but due to duct losses and improper installation, most units are operating at only 75% of their rated efficiency. (McKinsey 2007)

Solar Energy Savings:

Based on average consumption of 830 kWh per month (DOE 2004), one can determine what percent of that electricity will come from solar power and multiply by the pounds of CO2e emitted per kWh used (Table 21).

Example- Seattle, WA with 50% energy provided by solar power:
0.23 lbs CO2e/kWh x 50% x 830 kWh/month x 12 months/year = 1145.4 lbs CO2e/year

NON RESIDENTIAL

Missing values in the commercial energy consumption data made it more difficult to run regressions. Instead, average energy consumption variables can aid in the understanding of potential energy reducing behaviors. Using the commercial energy data, we evaluate natural gas consumption (ccf), electricity consumption (kWh), major fuel consumption (MBTU), and electricity expenditures ($kWh) per square foot for 5,094 cases. The data included 5,215 cases, but 121 were thrown out for insufficient electricity consumption data. Another 1,666 lacked sufficient natural gas consumption data. This data is summarized in the following table.

Because lab/medical equipment has large impacts on electricity consumption due to operation and enhanced cooling, primary building activity classification was used to eliminate certain cases. 43 labs, 144 nursing, 217 inpatient healthcare, and 73 outpatient healthcare building uses were excluded in some analysis to determine more accurate energy consumption.

TABLE C7 Measures of Nonresidential Energy Consumption and Number of Cases

Cases	Measure
5,094	Electricity/Major Fuel
4,617	Electricity/Major Fuel, excluding labs, nursing, inpatient and outpatient care
3,428	Natural Gas

ADDED INSULATION'S COST IMPLICATIONS

TABLE C8 Typical Costs for Added Attic Insulation

R-value	Cost ($/sq ft) Wood-framed	Cost ($/sq ft) Metal-framed
11	0.33	0.29
19	0.45	0.41
30	0.6	0.55
38	0.73	0.68
49	0.94	0.83
60	1.11	1.00

Note: Prices include material, labor, and contractor fees. Data source is Oak Ridge National Laboratory's Insulation Factsheet (from February 12, 2008, at http://www.ornl.gov/~roofs/Zip/ZipHome.html; Accessed on August 1, 2008).

TABLE C9 Typical Cost for Adding Cavity Insulation to R11 Walls

R-Value	Cost ($/sq ft) Wood-framed	Cost ($/sq ft) Metal-framed	Cost ($/sq ft) Concrete Masonry
13	0.41	0.41	1.43
15	0.56	0.56	1.71
19	1.56	1.56	-
21	1.58	1.58	-

Note: Prices include material, labor, and contractor fees. Data source is Oak Ridge National Laboratory's Insulation Factsheet (from February 12, 2008, at http://www.ornl.gov/~roofs/Zip/ZipHome.html; Accessed on August 1, 2008).

TABLE C10 Summary Statistics for Table 17's Variables (Commercial Building Annual Electricity and Natural Gas Consumption, Using 2003 CBECS Data)

Variable	Min.	Max.	Mean	Std. Dev.
Annual electricity consumed (kWh)	36.00	194,434,138	2,046,075	6,142,762
Annual natural gas consumed (ccf)	0.00	6,359,230	58,805	226,590
Square footage of the building (SF)	1001	1,600,000	100,185	231,257
# Workers	0	7500	149.07	508.76
# Total hours open in the week (hrs.)		168	76.81	50.15
# Businesses in the building	1	2100	4.78	32.55
Price of electricity ($/kWh)	0.126	74.0	0.949	1.459
Price of natural gas ($/ccf)	0.018	3.047	0.093	0.059
Heating degree days, HDD (base 65^o)	0	11,059	4,489.45	2,260.12
Cooling degree days, CDD (base 65^o)	20	5,904	1,350.73	1,025.10
Age of the building (years)	0	232	33.87	29.66
Electricity consumed in kWh/worker	41.60	5,784,242	24,116	108,889
Electricity consumed in kWh/sqft	0.01	352.17	17.14	19.98
Natural gas consumed in ccf/ worker	0.00	38,110	883.24	1,997.58
Natural gas consumed in kWh /SF	0.00	12.19	0.57	0.81
Educational use (principal activity)	0	1	0.124	0.330
Retail use (principal activity)	0	1	0.214	0.410
Basic industry use (principal activity)	0	1	0.391	0.488
Service use (principal activity)	0	1	0.188	0.391
Other use (principal activity)	0	1	0.083	0.276

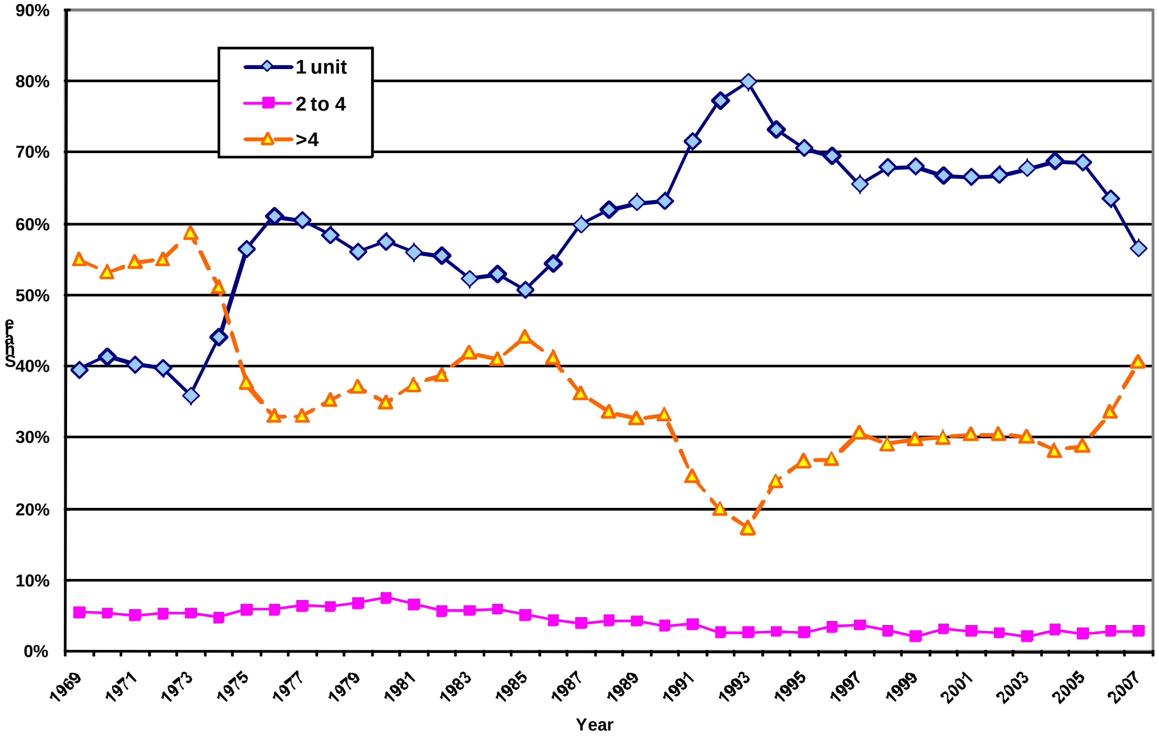

FIGURE C1 Share of housing units under construction, by number of units per building, 1969 through 2007 (source: U.S. Bureau of the Census, Economic Indicators Website).