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Technical Report
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April 2015

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List of Acronyms

AEO	Annual Energy Outlook
BAU	business as usual
BEV	battery electric vehicle
BITES	Buildings, Industrial, Transportation, and Electricity Scenarios
Btu	British Thermal Units
CAFE	Corporate Average Fuel Economy
CCS	carbon capture and storage
CO_2	carbon dioxide
CTSI	Clean Transportation Sector Initiative
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
eRW	electrified roadway
EV	electric vehicle
FCEV	fuel cell electric vehicle
GHG	greenhouse gas
ICE	internal combustion engine
LDV	light-duty vehicle
mpg	miles per gallon
NREL	National Renewable Energy Laboratory
PEV	plug-in electric vehicle
PHEV	plug-in hybrid electric vehicle
$PM_{2.5}$	2.5 micrometer or smaller particulate matter
TEF	Transportation Energy Futures
TOU	time of use
VMT	vehicle miles traveled
WTW	well-to-wheel
ZEV	zero-emission vehicle

Executive Summary

Reaching deep reductions in greenhouse gas emissions from the U.S. transportation sector will require diverse system and technology development strategies targeting energy intensity, carbon intensity, and demand for transportation services. Technological, economic, demographic, and social trends shape the likelihood of reaching a reduction threshold consistent with what climate scientists report is needed by 2050. This report summarizes work for the U.S. Department of Transportation's Clean Transportation Sector Initiative and builds upon the U.S. Department of Energy's Transportation Energy Futures review of opportunities for reductions in petroleum use and GHG emissions. It contributes to the literature by summarizing the potential of emerging consumer preferences and emissions-reducing technologies and strategies, including vehicle electrification through plug-in or fuel cell vehicles, connected and automated vehicles, biofuel pathways, vehicle efficiency, and transportation demand reduction. The potential of these and other emerging technologies and strategies was explored at a Clean Transportation Sector Initiative workshop. Key findings from this workshop are incorporated into this report, and the event details are summarized in Appendix C.

The transportation sector is changing, influenced by concurrent, ongoing, dynamic trends that could dramatically affect the future energy landscape, including effects on the potential for greenhouse gas emissions reductions. Battery cost reductions and improved performance coupled with a growing number of electric vehicle model offerings are enabling greater battery electric vehicle market penetration, and advances in fuel cell technology and decreases in hydrogen production costs are leading to initial fuel cell vehicle offerings. Radically more efficient vehicles based on both conventional and new drivetrain technologies reduce greenhouse gas emissions per vehicle-mile. Net impacts also depend on the energy sources used for propulsion, and these are changing with increased use of renewable energy and unconventional fossil fuel resources. Connected and automated vehicles are emerging for personal and freight transportation systems and could increase use of low- or non-emitting technologies and systems; however, the net effects of automation on greenhouse gas emissions are uncertain. The long-standing trend of an annual increase in transportation demand has reversed for personal vehicle miles traveled in recent years, demonstrating the possibility of lower-travel future scenarios. Finally, advanced biofuel pathways have continued to develop, highlighting low-carbon and in some cases carbon-negative fuel pathways. We discuss the potential for transformative reductions in petroleum use and greenhouse gas emissions through these emerging transportation-sector technologies and trends and present a Clean Transportation Sector Initiative scenario for such reductions, which are summarized in Table ES-1.

The Clean Transportation Sector Initiative scenario constructed in this report shows the potential for an additional 15% reduction in greenhouse gas emissions over the Transportation Energy Futures 2050 scenario estimates. Although this is not a forecast, exploration of such a transformative goal is valuable in challenging diverse stakeholders from research, development, deployment, policy, and industrial communities to envision a set of possibilities that, while perhaps not likely in the near-term, could shape longer-term strategic interests. Thinking beyond incremental reductions of greenhouse gas emissions enables the assessment of options for transformative change, possibly distinguishing pathways toward deep emissions reductions from those with less transformative potential. Future analytic work could include the periodic re-assessment of the status of greenhouse gas reductions in the transportation sector, as well as

assessment of technological and strategic options for further reduction, with continual refinement in the definition and quantification of metrics, the objectives of the selected portfolios of options, the selection of policy scenarios, and the quantification of interactions among options.

Table ES-1. Transportation Energy Scenario Assumptions and Results

Factor (in 2050)	Business as Usual	Transportation Energy Futures (2013)	Clean Transportation Sector Initiative Scenario
VMT Per Vehicle	13,500	18% below business as usual	25% below business as usual
"Eco Driving"	No improvement	5% improved mpg	40% improved mpg
Efficiency Factors	Varies by vehicle type	Varies by vehicle type	50% reduced fuel use
Percent of Plug-in Hybrid Electric Vehicle Drive on Electric		33%	45%
Heavy Duty Freight Efficiency	8.2 MPG	50% improved efficiency	60% improved efficiency
Percentage of the LDV fleet composed of advanced drivetrains	14%	92%	92%
Output Metric (2050)			
Transportation CO_2 Emissions (includes transportation electricity use) (million metric tons CO_2)[a]	1,584	112 (93% reduction)	-88 (106% reduction)
Net Transportation Petroleum Use [b] (quadrillion Btu)	21.3	-2.0	-4.4

[a] CO_2 = carbon dioxide; Btu = British thermal unit. Advanced drivetrains refers to HEVs, PEVs and FCEVs.

[b] Negative values for petroleum use indicate more liquids production (from biofuels) than consumption in the sector. Negative values for CO_2 emissions include CO_2 reductions from net liquids production, essentially assuming they are used in other sectors or exported and displace the relevant fuel (such as diesel) in other sectors. Alternatively, this can be viewed as additional technical potential beyond that required to reach zero emissions in the transportation sector directly.

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Introduction

Transportation represents approximately 10% of U.S. gross domestic product (Research and Innovative Technology Administration 2012, 3–3) and is essential to many aspects of the U.S. economy—including transportation of people to reach employment, commercial districts, or other destinations; commercial transportation to deliver services; and freight transportation to supply the commercial and manufacturing sectors. Transportation represented 28% of U.S. greenhouse gas (GHG) emissions in 2012 (U.S. Environmental Protection Agency 2013). Figure 1 illustrates the importance of the sector in meeting broader GHG reduction targets. Transportation also accounted for 70% of U.S. petroleum consumption (Energy Information Administration 2014), distributed across various uses, as shown in Figure 2. Leadership of efforts to reduce GHG emissions in the transportation sector is a responsibility that transects the mission of both the U.S. Department of Transportation (DOT) and the U.S. Department of Energy (DOE).

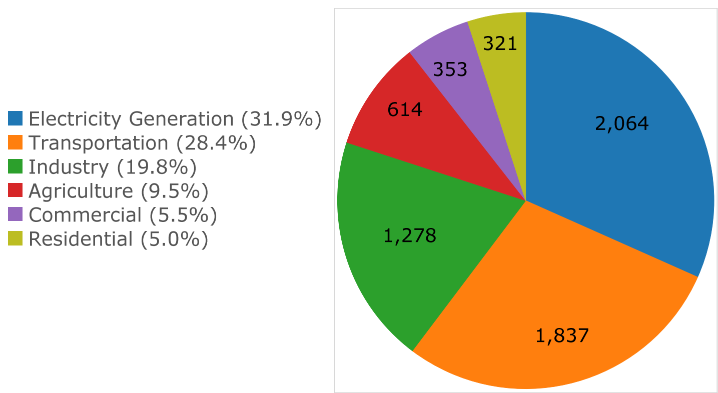

Figure 1. GHG emissions (in million metric tons CO_2 equivalent) by sector in the United States in 2012 (U.S. Environmental Protection Agency 2013)

Note: Carbon dioxide (CO_2) is the predominant GHG emitted in the transportation sector and accounted for in this chart, with smaller shares from methane, nitrous oxide, and fluorinated gases. Short-lived GHGs such as aerosols and black carbon are especially important to transportation-sector emissions, are not accounted for in this data, and are discussed further in the "Emissions" section. These emissions could increase transportation's relative share of emissions above the 28% shown here.

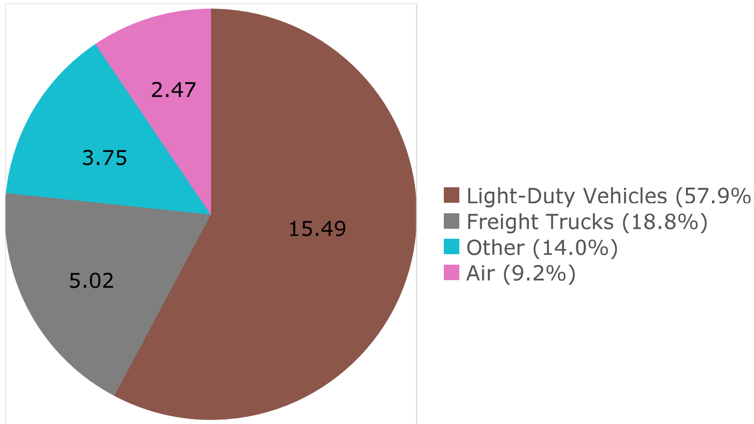

Figure 2. Transportation energy use (in quadrillion British thermal units) by category in the United States in 2012 (U.S. Energy Information Administration 2014)

Note: "Light-duty vehicles" includes cars and light trucks; "freight trucks" are considered to be those over 10,000 pounds; "other" includes pipeline fuel, military use, international shipping, commercial light trucks, freight rail, recreational boats, buses, lubricants, domestic shipping, and passenger rail (in order from most to least energy use); "air" consists of narrow body, wide body and regional jets for passenger and cargo.

To explore strategies that could lead to near-100% reductions in emissions and petroleum use in U.S. on-road transportation by 2050, DOT and DOE's National Renewable Energy Laboratory (NREL) launched the Clean Transportation Sector Initiative (CTSI). This inter-agency initiative addresses the critical challenge of enabling future GHG reductions in the transportation sector, which will rely upon leveraging the capabilities and authority of both departments and engaging with a diverse set of stakeholders. In general, these departments focus on separate but complementary contributions toward promoting GHG reductions in transportation, with DOT focusing on transportation system optimization through infrastructure and transportation mode use and DOE investing in efficient vehicle technologies and sustainable fuel production pathways. CTSI provides an opportunity to leverage the input of the diverse group of stakeholders associated with both departments to identify crosscutting solutions that span across technologies and infrastructure to enable significant GHG reductions in the transportation sector.

CTSI builds upon opportunities identified in DOE's Transportation Energy Futures (TEF) project ("Energy Analysis: Transportation Energy Futures Study" 2014) and opportunities that were identified through a CTSI workshop and expert input. The central goal of CTSI is to provide a set of solutions that could, in combination, achieve an 80%–100% reduction in GHGs by mid-century with related reduction in petroleum use. The value of exploring such a transformative goal is in challenging stakeholders from research, development, deployment, policy, and industrial communities to envision a set of possibilities that, while not likely in the near term, could begin to prompt longer-term strategic directions and guide investments and agency attention. Thinking beyond incremental reduction enables the assessment of options that may lead to transformative change, possibly distinguishing pathways toward deep GHG reductions from those with less potential. This report summarizes some of the opportunities identified in CTSI with the objective of describing a portfolio of choices that could lead to greater than an 80% reduction in transportation GHG emissions and warming aerosols[1] with a capstone goal of their near to complete elimination by mid-century. The opportunities assessed are not intended as a prediction or forecast but represent options that could warrant further investigation, especially when considering scenarios for near-100% GHG reduction (see Figure 3). Pursuing a large set of options may increase the likelihood of reaching emissions targets if the risks associated with the options are discrete but also may decrease investments to individual solutions or technology pathways. This report outlines possible steps toward periodic, continuously improving assessment of the options, with the purpose of increasing the effectiveness of efforts to transform the transportation sector towards greater than 80% GHG emissions reduction.

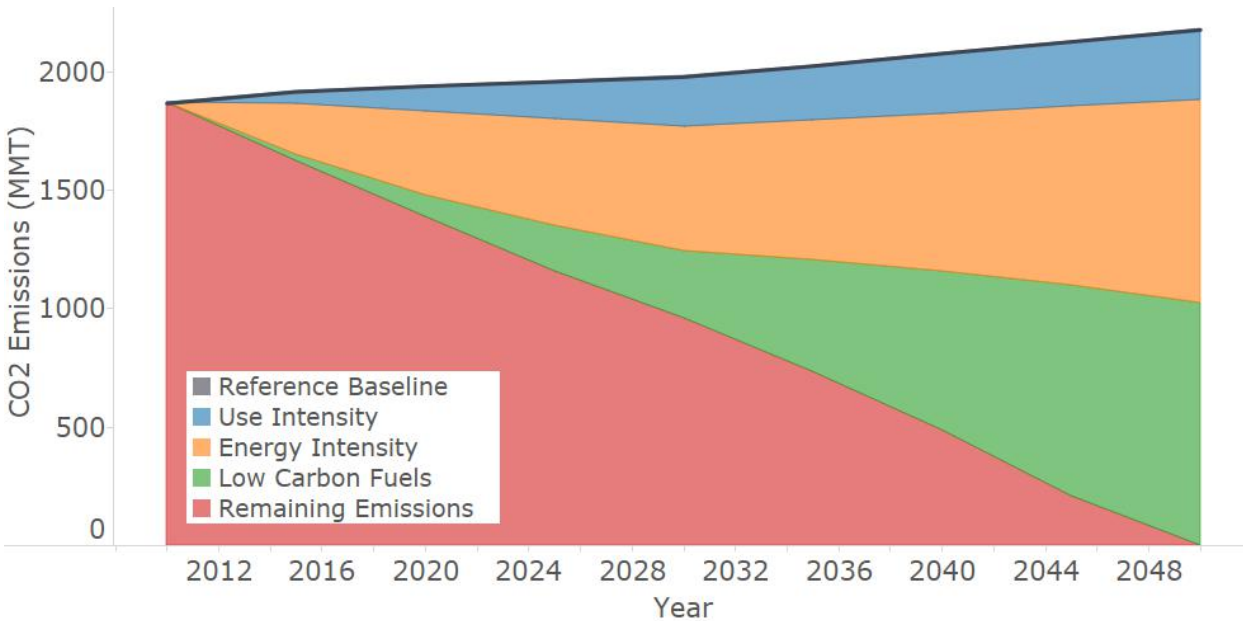

Figure 3. Reductions in use intensity, energy intensity, and carbon intensity all contribute to deep reduction scenarios (as shown in TEF scenario) ("Energy Analysis: Transportation Energy Futures Study" 2014)

The past decade has witnessed significant fundamental changes in the transportation sector compared to previous, relatively stable trends. This report explores some of the changes in national and state policies, markets, travel patterns, and consumer preferences that are increasing energy efficiency, reducing GHG intensity, and reducing travel below previous expectations. At the national level, fuel economy standards for light-duty and heavy-duty vehicles are expected to significantly improve the energy efficiency of over-the-road transportation (*Final Rulemaking to Establish Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles*; U.S. Environmental Protection Agency 2014a; National Highway Traffic Safety Administration 2008), and a new generation of advanced biofuels that addresses both petroleum reduction and climate impacts is beginning to emerge. Meanwhile,

[1] In addition to direct emissions of GHG, the transportation sector also can affect amounts of aerosols, or small particles, in the atmosphere. Some of these aerosols increase atmospheric retention of heat, and these are called warming aerosols (Boucher et al. 2013).

vehicle miles traveled (VMT) in the United States has declined every year between 2007 and 2013, reversing a trend of decades of VMT growth. Broad systemic trends could cause continued VMT stabilization or reduction. Reflecting these trends, the U.S. Energy Information Administration has altered its forecasts over the past decade (see Figure 4), resulting in declines in VMT and transportation-related carbon dioxide (CO_2) emissions forecasts while new vehicle efficiency has increased with successive forecasts (U.S. Energy Information Administration 2014; U.S. Energy Information Administration 2012; U.S. Energy Information Administration 2008; U.S. Energy Information Administration 2004). It is important to note that the latest vehicle efficiency projections plateau after 2025, which is the end year of the current compliance for federal fuel economy standards.

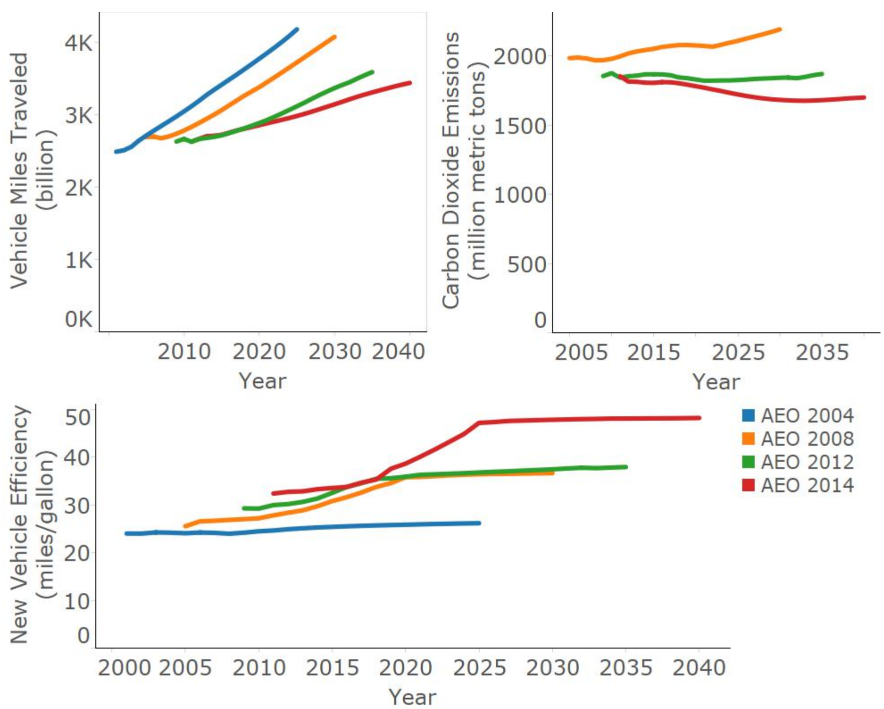

Figure 4. VMT, efficiency, and GHG emissions metrics from different versions of the Annual Energy Outlook (AEO) (U.S. Energy Information Administration 2014; U.S. Energy Information Administration 2012; U.S. Energy Information Administration 2008; U.S. Energy Information Administration 2004)

Despite these changes, the literature indicates that much greater change is necessary to reduce emissions to the levels that the Intergovernmental Panel on Climate Change reports (Edenhofer et al. 2014) are required to mitigate global climate change. Several recent studies identify pathways toward deep reductions in petroleum use and GHG emissions in the U.S. transportation sector ("Energy Analysis: Transportation Energy Futures Study" 2014; Edenhofer et al. 2014; Yang et al. 2008; McCollum and Yang 2009), including studies of reaching an 80% GHG emissions reduction by 2050 for light-duty vehicles (LDVs) (National Research Council 2013) or for the whole transportation sector ("Energy Analysis: Transportation Energy Futures Study" 2014). Studies also address the projected impact of state-level GHG mitigation policies (Edenhofer et al. 2014; California Climate Change Executive Orders 2005), such as those in California (Pavley and Nunez 2006; Bandivadekar et al. 2008).

Studies on economic incentive policies have observed that placing a price on GHGs would result in fewer reductions in the transportation sector than in the electricity sector (California Climate Change Executive Orders 2005; Kahn Ribeiro et al.; McCollum et al. 2012; McKinsey & Company 2011; Showalter, Wood, and Vimmerstedt 2010). In other words, GHG mitigation options in the transportation sector appear to face greater barriers than in the electricity sector. The electric sector has a number of competing low-carbon electricity generation and efficiency options—outlined in the U.S. EPA's proposed Clean Power Plan (U.S. Environmental Protection Agency 2014b)—that yield net benefits even if social costs of carbon emissions are assumed to be relatively low at $13/metric ton CO_2 (the lowest of four costs examined, as compared to $137/metric ton, the highest social cost estimate analyzed) (U.S. Environmental Protection Agency 2014). Transportation fuel costs constitute a greater share of total costs outside of the light-duty vehicle sub-sector, which has a relatively low cost of fuel as compared to the cost of personal vehicle ownership (Nguyen and Ward 2013; Al-Alawi and Bradley 2013). Linking these market dynamics, CTSI explores vehicle electrification pathways, which would connect GHG mitigation in the transportation sector to GHG mitigation in the electricity sector.

Key metrics for assessing deep reduction scenarios include the quantities of different types of transportation supply and demand as they develop over time; life cycle GHG emissions and other environmental impacts across various infrastructure, fuel, and vehicle options; and full costs of infrastructure, fuel, and vehicle options. This report includes estimates from the literature for GHG and fine particulate matter emissions from biofuels, plug-in electric vehicles (PEVs), and hydrogen fuel cell electric vehicles (FCEV) but does not develop environmental impact estimate comparisons across different pathway scenarios. The literature includes cost estimates for some of the options considered in this report, generally showing a broad range of estimates. For example, Melaina et al. (2013) summarizes alternative fuel infrastructure costs, NAS (2013) estimates future costs of vehicles, and the Transparent Cost Database ("Transparent Cost Database" 2014) summarizes ranges of costs for specific fuels and vehicle technologies by collecting current and projected estimates from many publicly available studies in one database. This report notes the importance of defining sets of cost or environmental metrics for evaluating scenarios for transportation sector development and highlights some of this literature but does not comprehensively address these issues. In general, studies find significant uncertainty in long-term costs for advanced technologies. In many cases, the uncertainty range in future costs is larger than the expected differences between competing technologies, which implies that projections for adoption of both combustion and electric drivetrain technologies are likely to be inaccurate.

This report highlights emerging trends, technologies, systems, and strategies that may help enhance responses to energy and environmental issues while seeking to preserve or improve upon the services that the current transportation system provides. The literature on options for reducing transportation-sector GHG emissions does not conclusively define which pathway(s) to take if emissions are to be most effectively reduced and generally finds that very deep cuts are challenging with known options. The literature also does not establish a comprehensive methodology that could be used to assess known options. Accordingly, this report builds upon previous analyses by (1) focusing on emissions reductions beyond 80% by 2050; (2) considering transportation sector options in greater focus relative to the many studies that examine emissions reductions across the entire economy; (3) including recent developments for novel technologies and strategies; and (4) identifying actions that might improve future assessments. While previously published literature addresses all of these areas individually, this report seeks to provide an additional contribution through a unified summary that includes considerable detail on selected emissions reduction options that include less-considered technologies or strategies.

CTSI seeks to improve the understanding of potentially transformative and disruptive transportation sector options to achieve near-zero sector GHG emissions. Transformative refers to a possible role in a greater than 80% reduction in GHGs emitted by the sector. Disruptive refers to the effects on incumbent systems and has been defined elsewhere as meeting two of the following three criteria: (1) produced by different manufacturers from the incumbent; (2) used in different ways; and (3) requires different infrastructure (Hardman et al. 2013). Estimates of reduction opportunities in the literature are generally based on the deployment of transportation technologies that have functioning prototypes with quantifiable performance. This report explores additional technologies—connected and automated vehicles and roadway electrification for PEV charging—that may not have received as much attention in previous studies because they were not as close to commercialization or their effects were less well quantified. In addition to these novel technologies, this report considers transportation demand trends, biofuel pathways, and radically more efficient vehicles. Each of these options can be correlated to functions of the DOT. The effects of these advances are summarized in a new, integrated scenario with dramatically reduced GHG emissions and petroleum consumption.

Each of these advances applies to on-road transportation, including light-, medium-, and heavy-duty vehicles, and some of them apply to other transportation modes. The report is organized around these emerging technology options or strategies rather than around optimizing transportation modes. Examples of applications of these options in LDVs are emphasized because these vehicles dominate transportation energy use, as shown earlier in Figure 2. Within the LDV category, the majority of vehicles (~90%) are owned and operated by consumers (Polk 2015). Applications beyond LDVs are also important to the goals of CTSI and may present an increasing portion of growth in fuel consumption.

The next section, "Selected Transformative and Disruptive Options," summarizes each of these strategies and discusses linkages to the DOT mission, estimated potential contributions to GHG reductions, the trends driving that potential, and barriers and enablers. Following that discussion of selected options, the "Emissions" section examines life cycle emissions estimates available from the literature on biofuels, PEVs, and hydrogen FCEV strategies. In the "CTSI Scenario" section, we present the new, integrated scenario. The "Discussion" section includes potential next steps toward improvements in future assessments, and the "Conclusions" section points toward opportunities and challenges ahead.

Selected Transformative and Disruptive Options

The technology options and strategies presented in this section—vehicle electrification pathways, connected and automated vehicles, reduction in transportation demand, biofuel pathways, and radically more efficient vehicles—were selected through CTSI. Figure 5 summarizes these strategies and categorizes the mechanism of their GHG emissions reduction effect. These options were identified through a literature review and a workshop convened by DOT in February 2014 (see Appendix C for more information on the workshop and http://www.rita.dot.gov/rdt/ for the CTSI workshop presentations). While more options are considered here than in TEF, the analysis may not be comprehensive of all potential options and not all of the selected options will necessarily be pursued by the market. However, these additional strategies may increase the probability of approaching, reaching, or exceeding national GHG and petroleum use reduction goals. The following summary of each strategy discusses potential contributions to GHG reductions, the trends driving that potential, and barriers and enablers.

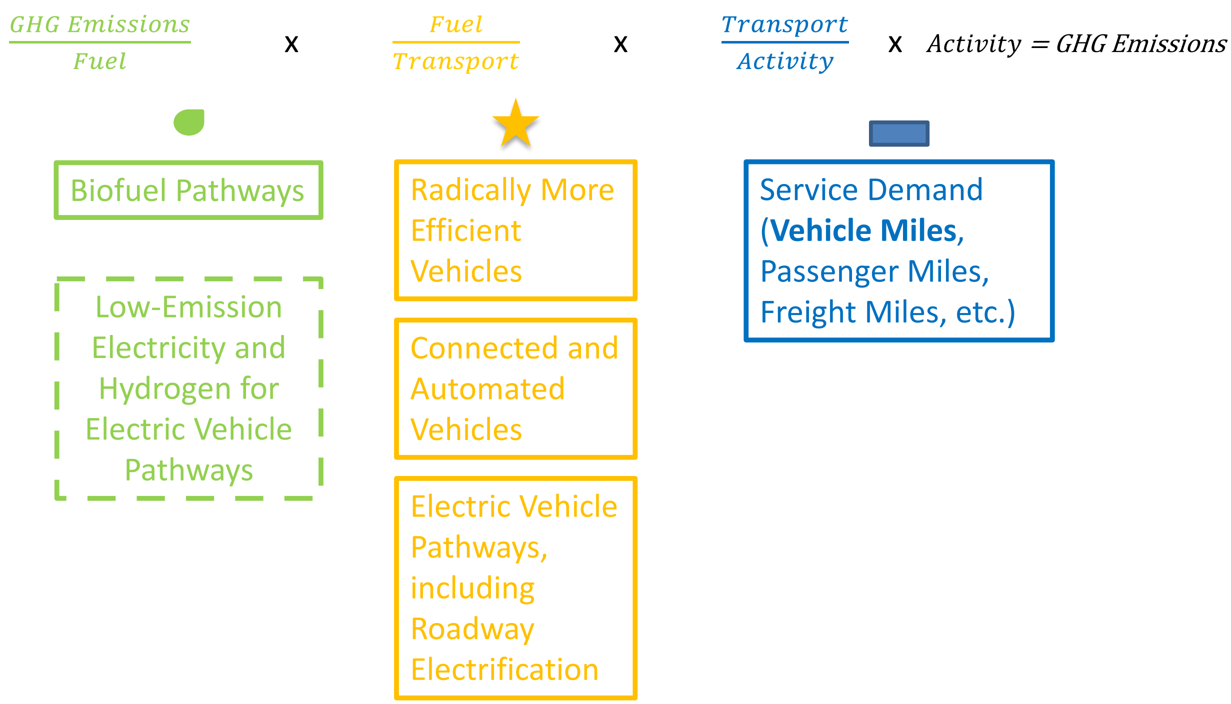

Figure 5. Opportunities for GHG emissions reduction considered, by type

Note: Dashed line indicates that low-emissions electricity and hydrogen supply are discussed in the life cycle assessment section, but these technology trends are not considered in this report. While these analyses are outside of the scope of this report, the implications of the supply of both fuels and electricity are critical to the overall energy and GHG footprint of the transportation sector. Color coded symbols (, ,) appear in each section below to categorize opportunities by type.

Electric Vehicle Pathways

Most studies of the potential for clean energy transportation systems—scenarios that reach 80% or greater emissions reduction—rely heavily on successful deployment of electric drive technologies. Electric vehicle pathways can enable zero tailpipe emissions and take advantage of the efficiency of electric motors to deliver generally lower energy operation. Electric vehicles include plug-in electric vehicles (PEVs) with sub-categories of plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs). Another category of electric drive vehicles is fuel cell electric vehicles (FCEVs) that use electricity from a hydrogen fuel cell to power the electric drivetrain. This section considers each of these vehicle technologies, as well as electrified roadways, which transfer power from infrastructure to vehicles, allowing greater electric range at any battery size. We also summarize supportive policies, barriers, and the role of vehicle electrification in the CTSI scenario.

These strategies are being pursued either singularly or in tandem by all of the major LDV manufacturers and to a lesser extent in certain applications of medium and heavy-duty vehicles (see Figure 2 for transportation energy use amounts used by light-, medium-, and heavy-duty vehicles). Certain characteristics of electric drive vehicles have attributes that present opportunities and challenges for the future energy and emissions landscape that fall within the mission of the DOT: First, they address energy security by changing the fuel supply chain from petroleum-based fuel to emphasize a set of electric-sector fuels. Second, electric drive vehicles are a significant component of a strategy to meet the light-duty corporate average fuel economy (CAFE) standards that are jointly promulgated by DOT and the U.S. Environmental Protection Agency (EPA). Third, hybrid electric vehicles and PEVs could utilize electrified roadways, infrastructures that will require engagement by DOT as well as state and local authorities. Fourth, because they displace liquid fuel sales and the associated fuel tax revenues, electric drive vehicles, and in particular PEVs, reduce payments to the U.S. Highway Trust Fund (administered by the DOT) and further stress other infrastructure funding mechanisms based on fuel taxes.

TEF included a scenario of a high penetration of advanced LDV technologies, including PEVs and FCEVs. This scenario explicitly depended on many factors, including the rapid development of improved technologies, introduction of vehicle models by manufacturers, and consumer acceptance beyond early adopters. Since TEF's release, advanced vehicle technology adoption has followed a trend consistent with the high penetration in TEF, and that scenario is included unchanged as part of CTSI. For each electrification technology, these advances are described below, along with an update on technology status, market impact, factors affecting GHG reduction, and barriers to greater adoption. One change relative to TEF is based on emerging evidence that drivers of PHEVs utilize electricity more than initially estimated for an equivalent vehicle, so this has been adjusted in the CTSI scenario as summarized in Table 1. This trend could either continue and technology advances or also change course as electric vehicles move beyond early adopters into mainstream drivers who may have different charging habits. It is important to note that while this report emphasizes LDV (i.e., passenger) electrification, these technologies can be used in other applications.

Table 1. TEF and CTSI Scenario Factors in 2050 From Electric Vehicle Pathways

Factor (in 2050)	TEF Scenario	CTSI Scenario
Percent of PHEV Drive on Electric	33%	45%

Plug-in Electric Vehicles

Perhaps the most consequential technology for the increased adoption of PEVs is the battery, which has improved in cost, performance, and durability. Battery costs have fallen dramatically in recent years. DOE's estimates for the 2013 cost of high-volume production of current battery technology is $325/kWh, which is down from more than $1,000/kWh in 2008 (U.S. Department of Energy 2014b). In practice, the decline in the price of batteries in the market is likely to lag behind these modeled cost estimates because of early market issues, such as low production scale and novel manufacturing processes. For example, Bloomberg New Energy Finance's estimate of the market price of batteries for PEVs in the first half of 2013 was $599/kWh, similar to modeled costs approximately 2 years ago, but prices are generally following a declining trajectory similar to the DOE estimates (Wilshire 2013). Although significant improvements would still be needed to achieve DOE cost and performance goals for batteries ($125/kWh), recent cost improvements improve opportunities for further vehicle drivetrain electrification. Figure 6 shows declining costs and improving performance for batteries. Investment is also scaling up the production of current battery technologies to serve a growing market. The most evident example is the announcement of Tesla's battery manufacturing facility in Nevada, which is expected to produce 35 GWh of lithium-ion (Li-ion) battery cells by 2020—a number that is greater than the global capacity for Li-ion batteries in 2013 (Tesla Motors 2014).

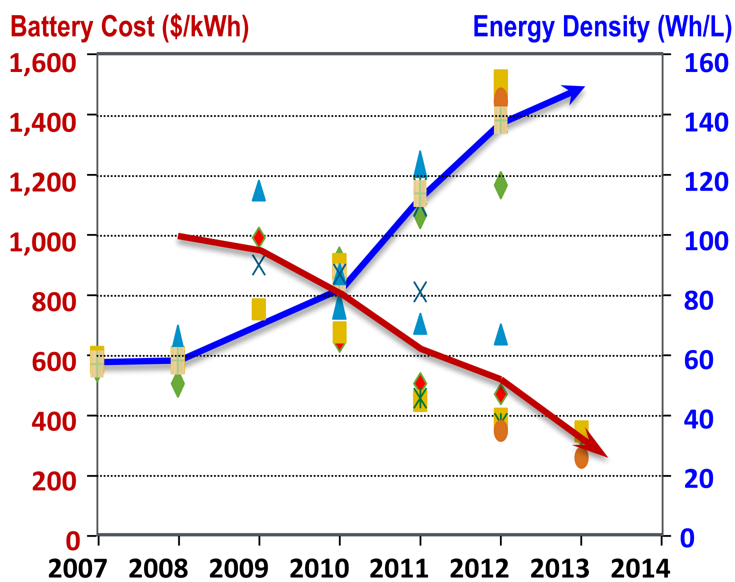

Figure 6. Trends in battery cost reduction and performance improvement (U.S. Department of Energy 2014b)

While Li-ion technology is the prevailing battery chemistry used today, there is significant research and development investment being directed toward alternative battery chemistries, such as lithium sulfur (Li-S) and lithium-air (Li-air). These alternative battery chemistries could enable more transformative changes in both cost and performance that might exceed the current trajectory of Li-ion batteries. In addition to cost and performance, other key battery attributes include durability and fast charging capabilities. Technology improvements in all of these attributes can be incorporated into new generations of vehicles and perhaps into older vehicles when batteries are replaced. The combination of scaling production, improving performance, and decreasing battery component costs will enhance the market competitiveness of PEVs.

Battery Electric Vehicles

Battery electric vehicles (BEVs) have a single drivetrain consisting of an electric motor and on-board battery storage, which is powered by an off-board source. With few exceptions BEV options are typically more range constrained than PHEVs (described below), due to battery costs, energy density, and charge times. Most commercially available models at the time of publication offer below 100 miles on a single charge. The adoption of BEVs, in particular, will be highly dependent on battery costs and energy density. Progress has been made both in vehicles and in charging technologies. Several auto manufacturers have publically announced plans for 200-mile range EVs at less than $40,000 being released in the next few years. Fast charging technologies are also increasing in availability and provide an opportunity to reduce battery-charging times significantly. Tesla has deployed a network of 135 kWh chargers that are capable of providing 170 miles of range in approximately 30 minutes. However, there are currently variations in the standards being used for fast charging technologies, which may limit adoption unless resolved.

Considering operating characteristics beyond battery technology development, light-duty BEVs compare favorably to internal combustion engines on fuel and maintenance costs. The fuel costs of BEVs are lower than conventional vehicle costs at most U.S. electricity and gasoline prices. At the current U.S. average price, the effective cost of electricity (accounting for the efficiency of use) is $1.29/gallon ("Maps | Department of Energy" 2014). The maintenance costs of BEVs, other than the potential need to replace batteries, are typically less than conventional vehicles because fewer scheduled maintenance events are needed due to fewer fluids, regenerative braking that prolongs brake life, and fewer mechanical maintenance issues (M. Davis et al. 2013). If battery costs are reduced and reliability meets expectations, both overall maintenance costs and first costs could fall below conventional vehicles (National Research Council 2013).

Plug-In Hybrid Electric Vehicles ★

As the name implies, PHEVs rely on conventional (typically gasoline) combustion engines that are coupled with battery electric-driven motors to leverage the strengths of the individual technologies and provide for extended range operations after the battery has depleted. Advantages of a hybrid drivetrain are greatest for stop-and-go duty cycles, whether in LDVs or beyond (e.g., garbage trucks are available as hybrids), but non-LDV markets offer few plug-in hybrid developments. The actual energy use profile and emissions impacts for LDV PHEVs depend on the electric mode share of operation, which has proven to be larger than anticipated. This fraction of miles traveled utilizing electricity, called the utility factor, is expected to depend on the electric range of the vehicle and the users' driving patterns and can be estimated using typical trip distances and simplifying assumptions ("J2841: Utility Factor Definitions for Plug-In Hybrid Electric Vehicles Using 2001 U.S. DOT National Household Travel Survey Data - SAE International" 2014). For example, a PHEV with an all-electric range of 38 miles is expected to drive approximately 60% of its miles on electricity. However, both real-world data and studies show that this methodology may need to be re-evaluated. A study by the University of California, Davis's PHEV center (Davies 2014) has identified four key assumptions in determining utility factor that may be inaccurate: (1) charging of PHEVs occurs once daily; (2)

public charging infrastructure does not increase charge-depleting mileage; (3) consumers' selection among different PHEVs is independent of their patterns of travel behavior; (4) the travel patterns of PHEVs are similar to those of the internal combustion engine (ICE) vehicles.

These assumptions are all embedded in the Society of Automotive Engineers methodology that is referenced above. Early real-world results from vehicles confirm that the estimation methodology could be improved and hint that drivers may be able to adapt their behavior to avoid refueling with gasoline by chaining trips together, charging multiple times per day, or changing the timing and length of travel. Data from DOE's EV Project, a sample of early PEV adopters in personal vehicle applications, found that Volt drivers traveled 74.6% of miles on electric drive, significantly more than the 60% expected from the current Society of Automotive Engineers methods (*The EV Project* 2014). The EV Project also found that Volt drivers charged an average of 1.4 times per day and drove 40.5 miles per day as opposed to 1.1 charging events and 29.2 miles for Leaf owners.

These results suggest the need for a reevaluation of scenario utility factors that were used in TEF. Applying the difference between expected and observed utility factors could justify using a significantly higher GHG reduction potential for PEVs in the CTSI scenario. The TEF scenario included a utility factor for LDV PHEVs of 32%, which was based on the Society of Automotive Engineers standard applied to a pre-determined mix of PHEVs of various electric ranges. For the CTSI scenario, a utility factor of 45% is used based on the ratio of observed electric miles to expected electric miles in early PHEV trials. This results in a greater potential for additional electric travel in both short- and longer-range PHEV vehicles models. Although this method of determining utility factor is based on historical experience, PHEVs could potentially transition to using electricity almost exclusively (~100% utility factor) with adequate range and charging infrastructure.[2] Any remaining PHEV liquid-fuel need could also become increasingly biomass-based in scenarios of growing biofuel use (see "Biofuel Pathways" section). These two potential fueling changes illustrate the flexibility of PHEVs to reach deeper emissions reductions in the long run.

Roadway Electrification ★

One potential strategy to increase the percentage of electric drive while also reducing vehicle energy storage (and associated cost) is to electrify the roadways that vehicles travel on. Electrified roadways transfer power from infrastructure to vehicles, supplementing on-board battery power and expanding design and performance options. Electrified roadways also provide an opportunity to procure electric generation that would provide reduced greenhouse gas emissions over the rest of the grid, which can help to ensure that electric vehicles are utilizing low GHG sources of power.

Specifically, electrified roadways could improve PEV cost-effectiveness, increase market uptake by reducing range anxiety, increase the share of electric miles for PHEVs, expand vehicle electrification among medium- and heavy-duty vehicles, and increase use of electric drive in more traditional hybrid electric vehicles, all of which could enhance opportunities for GHG mitigation. These potential benefits are possible because charging could occur dynamically while

[2] It should be noted that there is also the possibility of a decreased utility factor as PEV driver profiles transition from early adopters to mainstream consumers.

the vehicle is in service. Dynamic access to power removes some of the current cost and performance hurdles for plug-in vehicles by reducing their on-board storage requirements. Roadway electrification also could enable hybrid electric vehicles, which ordinarily do not run for significant distances on electricity alone, to draw power from the infrastructure and run partially or completely in electric drive without adding any more on-board energy storage.

Analytic advances have improved the understanding of patterns of vehicle and roadway use, allowing for estimation of different roadway electrification deployment scenarios. The most straightforward application of roadway electrification involves a limited vehicle population that continuously operates along a dedicated route (e.g., on campuses, ports, or fixed transportation links). Applications at ports and for mass transit in urban settings may be particularly compelling as these could eliminate affected vehicles' tailpipe emissions where air quality concerns are substantial. However, the spectrum of possible applications also extends to a larger number of public roadways. An estimate of this potential in Atlanta shows that 17% of travel mileage occurs over just 1% of roadways and about 80% of travel over 25% of roadways (Gonder 2013). Looking at a broader range of five major metropolitan areas, it is estimated that electrifying 1% of roadways could serve 15%–20% of all travel (Gonder 2014), which suggests that initial investments could target a small fraction of roadways yet leverage a significant GHG reduction potential. Figure 7 summarizes these estimates of the distribution of travel over roadways. Because the technology is embedded into roadways, roadway electrification would likely require substantial federal, state, and local transportation engagement. A more detailed description of roadway electrification technologies is provided in Appendix A.

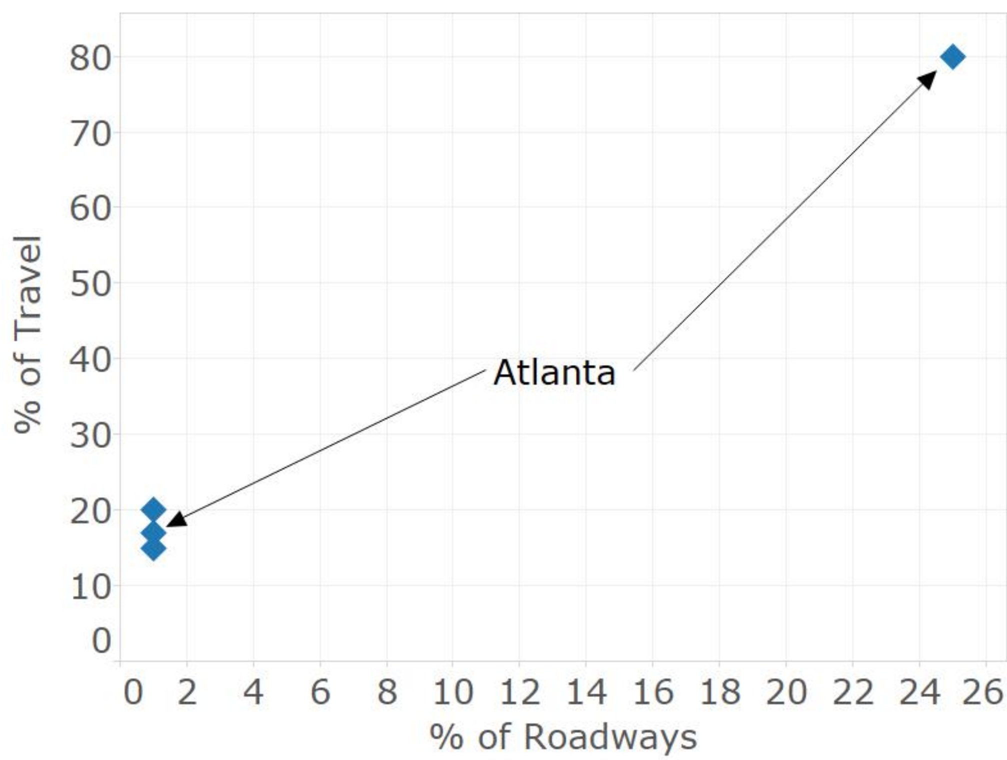

Figure 7. Estimates of roadway electrification opportunities showing how travel shares are distributed over roadways (Gonder 2013; Gonder 2014)

Fuel Cell Electric Vehicles ★

While batteries present one possible path forward in vehicle electrification, significant strides have also been made in decreasing costs and increasing the durability of fuel cells that can be used in mobile applications. FCEVs rely on hydrogen—typically produced off-board and stored in a pressurized vessel on the vehicle—to generate electricity through a fuel cell, which drives an electric motor. FCEVs offer significant range and performance potential, providing driving distances, power delivery, and fueling times that are similar to traditionally fueled vehicles. Like PEVs, FCEVs leverage the efficiency of electric drive to increase a vehicle's overall fuel efficiency while producing no tailpipe GHG emissions. Similar to electricity, the hydrogen used to power these vehicles is an energy carrier that can be made from multiple sources, including renewable energy, some of which could eventually provide a pathway to zero or negative GHG emissions (described in the "Emissions" section of this report). FCEVs can offer performance benefits over PEVs, particularly in non-LDV applications that may be unable to use PEVs at all, but could use FCEVs due to their range, power, and re-fueling characteristics.

Costs for automotive fuel cells have decreased from $106/kW in 2006 to $55/kW in 2013 (Spendelow and Marcinkoski 2013) while durability has increased from 950 to 2,500 hours with a 10% level of degradation in fuel cell performance (Spendelow and Papageorgopoulos 2012). A key challenge in fuel cell development has been removing expensive materials from the fuel cell stacks, while maintaining durability and performance. Figure 8 shows cost reductions and performance improvements for fuel cells. It is projected that these prices will continue to decline as manufacturers incorporate better technologies and reduce the use of costly materials in fuels cells. Platinum, in particular, is an extremely effective catalyst, but also one of the more costly metals. Catalyst power is currently around 5.8kW/g of platinum, which is an 80% reduction over the amount of material required in fuel cells in 2005 for a similar power output. Additional research is looking for alternatives to replace platinum altogether with lower-cost materials. DOE's goal is to achieve a $30/kW fuel cell with 5,000-hour durability (Energy Efficiency and Renewable Energy 2014a).

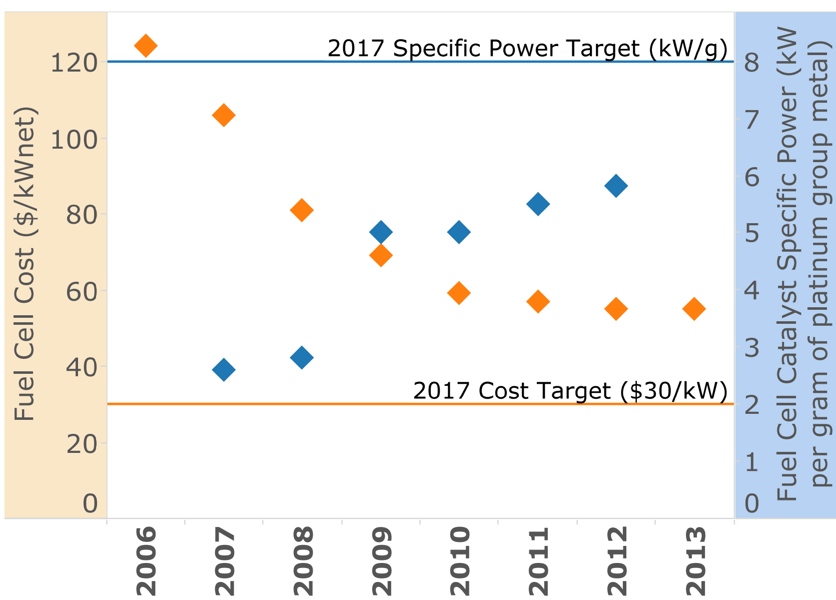

Figure 8. Historical and target costs and catalyst specific power of fuel cells (Spendelow and Marcinkoski 2013; Energy Efficiency and Renewable Energy 2014a)

With these improvements, numerous LDV manufacturers have recently announced models of hydrogen FCEVs. Hyundai began leasing its fuel cell Tucson in 2014, and Toyota announced the availability of the Mirai in 2015. Fuel cells are also used in a number of niche transportation applications, including forklifts and transit buses. Further cost and performance improvements, or targeted markets with suitable operational or environmental needs, would be needed to extend FCEV markets into core medium- and heavy-duty vehicle sectors.

Policy and Market Forces Supporting Vehicle Electrification

Vehicle electrification policies to date have supported PEV (including both BEV and PHEV), FCEV, and roadway electrification research and development, provided consumers with tax credits or other incentives for PEV purchases, credited automakers under CAFE for PEV sales, encouraged construction of charging stations, and provided PEV operational incentives such as high-occupancy vehicle lane access, free charging, and preferred parking. Experience to date suggests that overcoming the first cost is crucial and that the charging and refueling infrastructure challenge may not be solved by policy alone.

Recent policy developments directly support the deployment of both PEVs and FCEVs, most notably that California and seven other states mandated the sale of zero-emission vehicles (ZEVs) (California Air Resources Board 2013). Figure 9 shows projected ZEV-mandated numbers of vehicles in California. While the specific number and characteristics of vehicles sold will depend on how automakers comply, the California Air Resources Board estimates the policy will lead to 3.3 million total ZEV sales by 2025, including 15.4% of annual LDV sales in those markets by 2025 ("The Zero Emission Vehicle (ZEV) Regulation" 2014). Because the states involved represent approximately one-quarter of the U.S. LDV market, these policies, if implemented, will be a significant driving factor in the next decade and could encourage a technological transition nationwide (Greene et al. 2014). ZEV compliance also enables the automakers to meet CAFE targets. CAFE encourages high efficiency technologies such as ZEVs and provides incentives for certain zero emissions technologies in addition to its efficiency incentives.

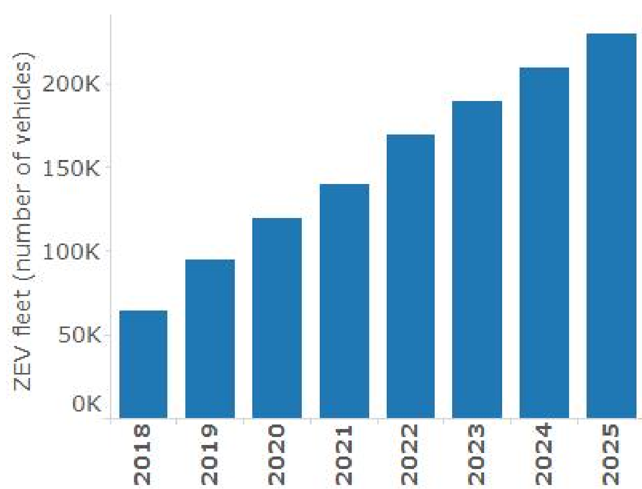

Figure 9. Projected ZEVs in California (California Air Resources Board 2014)

In 2014, 15 models of PEVs from 12 manufacturers were available, up from essentially 0 that were publicly available prior to 2010. Although PEVs were a modest 0.5% of all new LDV sales in 2013, sales growth has generally been robust, such that four available models have sales growth higher than the Prius when it was introduced (Argonne National Laboratory 2014)*,* and overall PEV sales in the United States grew by over 70% between 2013 and 2014. A visualization of monthly sales of PEVs from 2010–2014 illustrates these trends (see Figure 10) ("Alternative Fuels Data Center: Maps and Data" 2014).

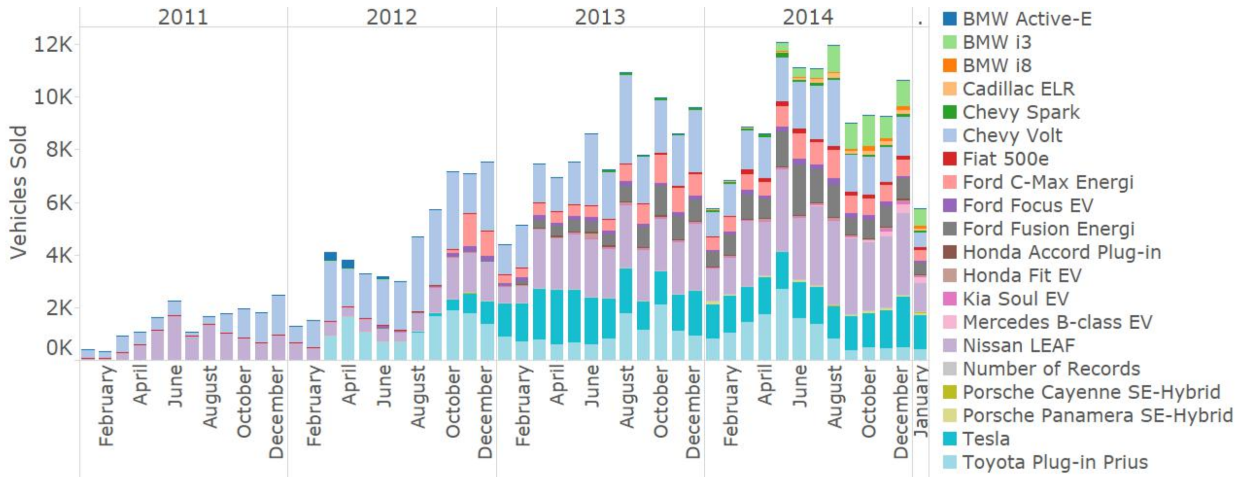

Figure 10. Monthly sales of PEVs, 2010–2014 (Energy Efficiency and Renewable Energy 2014b; Argonne National Laboratory 2014)

Barriers to the Adoption of Electric Vehicles

Although PEVs are fully commercial and FCEVs have been demonstrated and are being introduced, barriers remain to these technologies. Despite rapid battery cost reductions, significant vehicle cost reductions are still needed for PEVs to be competitive for many consumers and in most non-LDV applications, as shown in Figure 11. The figure illustrates current vehicle and fueling costs over 5 years of vehicle ownership. The figure also shows anticipated cost reductions for various PEV models due to DOE's EV Everywhere Grand Challenge, which would result in greater parity between BEVs and conventional vehicles.

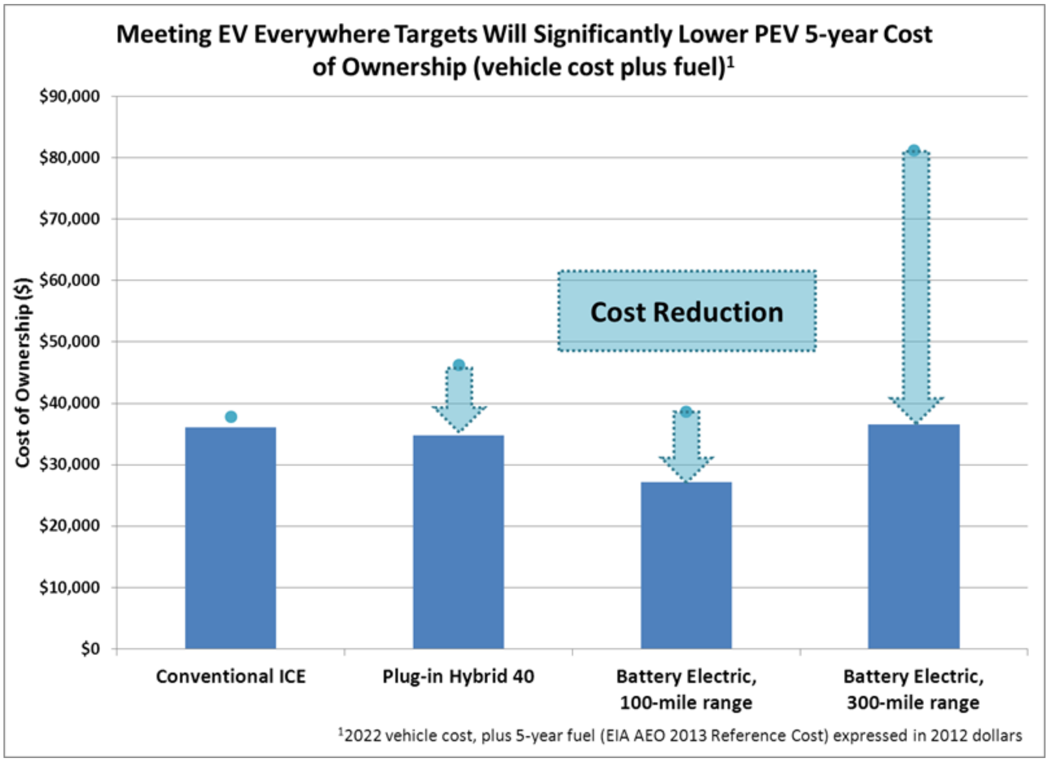

Figure 11. Projected cost of vehicle ownership for 5 years (U.S. Department of Energy 2014b)

Note: Dots indicate estimated cost of vehicle ownership for 5 years at today's vehicle costs. Bars show estimated cost of vehicle ownership for 5 years at estimated costs of vehicles in 2022. Fuel costs are based on EIA AEO 2013 Reference Case. All costs are expressed in real 2012 dollars.

In addition to vehicle technology challenges, PEVs have faced recharging challenges due to the combined effects of (1) lower range, (2) substantially longer charging time compared to liquid fuel refueling, and (3) relatively low access to charging infrastructure beyond the 110-V circuits that are most common in buildings. The first two issues are beginning to be addressed by technology improvements to increase range and reduce charging time; changes in consumer attitudes and behavior; better alignment between vehicle range, vehicle drive cycles, and charging infrastructure; and innovative business models to deliver substitute vehicles when needed or to encourage vehicle selection based total cost of ownership (e.g., from novel business models that provide transportation as a service, can access diverse vehicles, provide alternatives to traditional vehicle ownership and leasing, and therefore can use the least costly option—subject to performance constraints—for each trip). Although electricity service is widespread, reliable, and sourced from diverse energy resources, addressing greater charging access relies upon strategically siting and installing improved charging technologies or developing other charging solutions such as roadway electrification charging. Apart from home charging, public access is likely to improve in urban areas but is expected to remain an ongoing challenge in more remote areas where vehicle range concerns are further exacerbated by long driving distances (Melaina et al. 2013).

FCEVs also face challenges, notably those surrounding the development of refueling infrastructure, which is currently limited to a handful of locations (Energy Efficiency and Renewable Energy 2014c). FCEVs do not have the same level of existing infrastructure that

PEVs have in the widespread availability of electricity. Significant efforts in California, Europe, and Japan seek to catalyze hydrogen infrastructure development through direct government support.

New applications of electric drive technologies in non-LDV markets are rare at this time and face similar challenges, with appropriateness of the technology to the duty cycle, cost, and operational effects of recharging/refueling among the major concerns.

CTSI Vehicle Electrification Scenario

The TEF LDV scenario rapidly reduces the ICE vehicle stock to 13% by 2050 and is based on assumptions that reflected significant improvements in batteries and fuels cells, as well as rapid consumer acceptance and systematic reduction in any non-cost barriers to adoption. The CTSI scenario continues to reflect TEF's growth of PEVs and FCEVs, and the same vehicle technology mix is used in both scenarios. A comparison of the advanced vehicle sales growth in the past 4 years to those in the TEF scenario shows the TEF scenario with 2014 market shares for car PEVs of 1.7% compared to actual market share of 0.6% as of December 2014. TEF projected a market share of 3.1% for hybrid electric vehicles, which compared to actual market share of 2.2% as of December 2014 (Polk 2015).[3] Policy and market developments could significantly influence vehicle model availability and consumer uptake trends. The improvements to technology and vehicle performance attributes explored here would increase the appeal of low-emissions LDVs.

Connected and Automated Vehicles ★

One of the more significant technology opportunities in transportation is the possibility of increased automation and connectivity between vehicles, transportation infrastructure, and even buildings. The primary motivations behind the advancement of this technology are related to issues such as safety and congestion reduction, but connectivity and automation could also significantly affect transportation energy use, emissions, and overall system efficiency. Although effects are uncertain, connected and automated vehicles could be an important part of a strategy for 80% or greater reductions in GHG emissions in the long term. Few publications address energy impacts, though early analysis points to large efficiency and energy-saving potential and also to a significant potential for unintended consequences, such as increased travel, which could increase energy use.

Connected and automated vehicles link closely to DOT's core safety mission. DOT is developing new policy to address these vehicles. Four levels of automation for passenger vehicles have been defined, ranging from Function-Specific Automation (Level 1) to Full Self-Driving Automation (Level 4) (National Highway Traffic Safety Administration 2013). The estimates included here focus on the long-term impact of high levels of automation. The timeline for deployment of different levels is uncertain and the subject of intense discussion. A recent survey of experts in the field found that although the range of predicted availability dates varies, the median response was for many automation features to be available by 2020 and full automation to be available by

[3] It is noteworthy that while PEV sales increased between 2013 and 2014, growth was dramatically slowed over the previous pace. HEV sales decreased by nearly 20% year over year. One possible explanation is the dramatic decrease in oil prices in the second half of 2014.

2030 (Underwood 2014).The possible effects of automation on energy use are large but highly uncertain. Two recent studies independently estimated possible impacts of automation technologies and systems, both individually and in combinations, and found that they could dramatically affect energy use (Brown et al. 2014; MacKenzie et al. 2014), ranging from a savings of more than 80% of energy use to a significant increase. These and other potential effects of connected and automated vehicles are summarized in Table 2. These possible impacts include:

- Platooning, with vehicles following closely at high speed to reduce aerodynamic drag and manage vehicle spacing and congestion; this applies to both LDVs and heavy-duty vehicles and has been demonstrated in the U.S. in long-haul trucks
- Efficient driving enabled by better connection and automated controls, ranging from smooth starts and stops and some stop elimination up to full stop elimination and complete trip smoothing
- Efficient routing, including congestion avoidance from better communication connectivity and most efficient route selection
- Additional traveling by underserved populations, such as youth, the disabled, and the elderly
- Faster traveling, made possible due to safe highway operation and leading to higher aerodynamic losses
- More traveling, due to faster travel, reduced traffic, and reduced cost of time because of productive in-vehicle use (i.e., people may live further from destinations or take more trips)
- Lightweighting of vehicles, smaller powertrains, and vehicle size optimization made possible by dramatically reduced crashes, smoothed driving (reducing peak power requirements), and matching of vehicle needs to trip requirements
- Reducing energy spent parking from fewer total vehicles and self-parking; alternatively, parking may be located further from destinations, increasing VMT
- Automated carpooling and ridesharing, creating higher occupancy
- Deploying vehicles matched to user trip needs, enabling short-, medium-, or long-range vehicles to be dispatched as appropriate and increasing the portion of trips that can be met with PEVs in shared vehicle markets.

With such a wide range of possible vehicle, behavior, and system impacts, additional analysis is required to explore the factors influencing likelihood and magnitude of each effect, as well as interactions among impacts.

The freight system also could be significantly impacted by connectivity and automation, especially through platooning. Several demonstrations are exploring technological issues and fuel economy improvement potential. Initial measurements of road trains for trucks have found energy savings of 5% for the lead vehicle and almost 10% for the trailing vehicles (Chan 2012; Lammert et al. 2014). Previous field data had measured approximately 10%–15% energy savings for trucks, with higher potential savings estimated from wind tunnel studies (Brown et al. 2014).

The CTSI scenario includes quantitative values for three factors that represent potential long-term impacts (see Table 3):

1. The "ecodriving" factor represents improved vehicle operation due to best-possible drive cycles, traffic smoothing, and efficient routing and is assigned a value of 40% improved miles per gallon (mpg) based on the best-possible simulated efficiency of transportation over a range of drive cycles, assuming widespread automation and complete drive cycle smoothing (Gonder et al. 2012).
2. A vehicle efficiency factor represents effects of rightsizing, lightweighting, and LDV platooning made possible through vehicle connectivity and automation and is valued at a 50% mpg increase relative to business-as-usual mpg in 2050.
3. A freight platooning factor is valued as a 6.4% mpg increase for heavy trucks. This is applied to the average, reflecting the potential for improving long-haul travel, where most heavy-duty fuel is used. This is in addition to the TEF-identified improvement in efficiency from improved truck technology and brings the total heavy-duty freight efficiency factor to 60% for the CTSI scenario.

Negative effects of connection and automation that increase fuel use are not represented in the CTSI scenario, in the interest of exploring its potential positive role, but this does not diminish these potential unintended consequences.

Table 2. Summary of Estimates of Effects of Connection and Automated Vehicles

Effect	Estimate
Connected and automated vehicle fuel savings (high)	80%
Connected and automated vehicle fuel savings (low)	Negative savings (increased fuel use)
Platooning fuel savings (lead vehicle)	5%
Platooning fuel savings (trailing vehicles)	10%

Table 3. TEF and CTSI Scenario Factors in 2050 From Connection and Automated Vehicles

Factor (in 2050)	TEF Scenario	CTSI Scenario
"Eco Driving"	5% improved mpg	40% improved mpg
Efficiency Factors	Vary by vehicle type	50% reduced fuel use
Heavy-Duty Freight Efficiency	50% improved efficiency	60% improved efficiency

In addition to the factors listed above that are considered in the CTSI scenario, self-driving vehicle technology could enable greater market potential for vehicle sharing business models due to lower-cost logistics. Shared vehicle businesses would use fleet-level purchase and operation practices that could demand highly efficient vehicle technologies and incur rapid vehicle turnover, while reducing the total number of vehicles in the system at any given time (though not necessarily reducing the numbers of vehicles sold because each vehicle would likely be driven many more miles per year). Such a scenario could shift the VMT mix toward newer, more efficient vehicles. Due to uncertainty of the effects of these new business models, they are not explicitly represented here.

Connected and automated vehicles face technological, standardization, regulatory, and market implementation challenges that include safety, reliability, interoperability, insurance, and behavioral elements. There is no guarantee that successful deployment of connected and automated vehicles will lead to energy savings, as significant induced demand, desire for faster travel, or other factors may compete with potential system efficiencies.

Overall options for connected and automated vehicle policy may be characterized by the strength of implementation support and the nature of policy actions to shape how it is used. Connected and automated vehicles require development of the regulatory environment to move beyond the simplest measures (such as detection of obstacles and lane keeping). Whether, and when, a favorable regulatory environment is established will largely determine the direction and timing of growth of these technologies. Policies will also determine whether potential unintended consequences occur or are mitigated and therefore whether connected and automated vehicles become an element of a strategy for greater than 80% GHG emissions reduction, or instead increase emissions. For example, considering the potential for connected and automated vehicles to increase LDV VMT and energy use, policies could provide disincentives for VMT that counter the incentives from connection and automation or determine how connected and automated vehicles are treated by fuel economy standards and testing. Similarly, connection and automation could increase the competitiveness of long-haul trucking relative to freight rail, and the relative policy environment will shape how their relative fuel efficiency is valued.

Transportation Demand Reduction and Demographic Shifts

Transportation demand reduction is an element of a strategy to reach transportation GHG emissions reductions of greater than 80%, and demographic shifts contribute to the context in which these demand changes could occur. Transportation demand can be influenced by a variety of individual and societal decisions that encompass system design, land use, and housing choices. Transportation demand, measured in metrics such as personal VMT, freight ton-miles, or air passenger-miles, is a key variable—along with vehicle fuel economy and fuel carbon intensity—contributing to overall transportation-sector energy use and GHG emissions. Changes in total transportation demand and the distribution of travel across different parts of the roadway network affect core DOT interests, such as safety, congestion, cost-effectiveness of investments in roadways and alternative modes, and fuel tax revenues paid into the U.S. Highway Trust Fund.

For LDV modes, trends reducing personal VMT started before TEF and have continued, which is why we considered lower personal VMT for the CTSI scenario (see Table 4). There are other opportunities for VMT reduction that are not evaluated in detail here, such as transit. Transit in the US is approximately 2% of all trips (U.S. Department of Transportation 2014), but transit miles have grown even over the same period that vehicle VMT has declined (American Public Transportation Association 2014). The future of mass transit funding, development, management, and use is complex and the energy implications merit additional study. Scenarios of increasing VMT are also possible. VMT trends are the focus of this section. For non-LDV modes, TEF identified substantial potential for growth in transportation demand that could neutralize the potential gains in energy efficiency (see Table 5), and the CTSI scenario did not explore non-LDV demand reduction beyond TEF. The TEF project reviewed measures that might reduce future travel demand, examining built environment characteristics, trip reduction, efficient driving, and non-LDV mode switching and estimated a cumulative 7%–15% future demand reduction relative to a business-as-usual scenario, in the long term (e.g., perhaps possible by 2050) ("Energy Analysis: Transportation Energy Futures Study" 2014). Improved effectiveness of alternatives to personal automotive travel, such as information technology and non-motorized mobility, could enable motorized mobility to be used only when it is the highest-value alternative. Thus, a lower-VMT future need not deprive people of valuable services but instead could offer alternative means, such as improved information technology and non-motorized mobility, to accomplish goals. Since TEF, several relevant VMT and demographic trends have become more apparent and their bases better understood, so the higher CTSI number has some basis in recent research and events.

Table 4. TEF and CTSI Scenario Factors in 2050 From Travel Demand Reduction

Factor (in 2050)	TEF Scenario	CTSI Scenario
VMT Per Vehicle	18% below business as usual	25% below business as usual

Table 5.TEF Non-LDV Energy Intensity Improvement Potential in TEF (2050)

	Trucks	Aviation	Inland Marine	Ocean Marine	Rail	Pipeline	Off-road
Energy intensity improvement (%)	50	65	30	75	35	20	18
Activity growth (%)	87[a]	217[b]	32[a]	450[c]	47[a]	16[a]	20[d]
Net change (%)	-7	+11	+1		-4	-7	-2

[a] *EIA projections extrapolated.*
[b] *FAA projections extrapolated.*
[c] *Growth in dollar value of trade (EIA).*
[d] *Projected at half the population growth.*

Source: Copied from (Vyas, Patel, and Bertram 2013)

Historically, travel demand metrics have correlated with economic growth (U.S. Energy Information Administration 2014); after 2007, VMT is not as correlated with economic growth. This apparent shift highlights the question of how to forecast VMT. The U.S. Energy Information Administration's Annual Energy Outlook (AEO) forecasts total VMT based on VMT per licensed driver and the number of licensed drivers. The AEO projects VMT per driver to remain approximately constant through 2040 (see Figure 12).

Recent literature analyzes factors that contribute to VMT trends, including the trends in vehicle registrations, drivers, employment, and household size, as shown in Figure 12. Scenarios that could be constructed based on these more complex relationships could have a range of VMT per capita and net VMT trends, but increases are likely to occur at more modest rates than in the past because some of the underlying trends (increase in employment of women, reduction in household size) may be approaching limits.

The overall trend of declining use of personal vehicles encompasses lower rates of vehicle ownership (Polzin 2006): in 2012, 9.2% of households in the 30-city sample did not own a vehicle, up from 8.7% in 2007 (Sivak 2013). Non-ownership of vehicles may correlate with public transportation, car sharing, urban form, and the quality of the pedestrian experience, parking, income, fuel price, and weather (Sivak 2014). It remains to be seen how the ongoing economic recovery and continued oil market volatility will affect these trends.

Publications summarize demographic, socioeconomic, transportation performance, and land-use trends that are moderating VMT growth rates relative to historical levels. Demographic metrics that are stabilizing or reversing direction after decades of contributing to VMT growth include household size; women's participation in the labor force and share of licensed drivers; vehicle ownership; and baby boomers reaching ages at which travel tends to decline (Polzin 2006; Litman 2014). Transportation system trends that are stabilizing or reversing direction after years of contribution to VMT growth include changes in travel speed, travel cost, public transit and non-motorized mode share, and vehicle occupancy (Polzin 2006; Litman 2014). Changing land-use patterns, policies, and taxes associated with company cars, attitudes and policy regarding young drivers, and public attitudes toward driving and its health and environmental effects may also be contributing to lower VMT (Litman 2014).

Local decisions account for variation in VMT by 25% or more, as demonstrated by studies showing this amount of difference in predicted VMT among different metro areas. Salon et al. (2012) reviewed empirical evidence about effects of major categories of policy action that are under local control, including land-use planning (residential density, land-use mix, regional accessibility, network connectivity, and jobs-housing balance), pricing (road pricing and parking pricing), public transport (public transport access and public transport service), non-motorized transport (pedestrian strategies and bicycle strategies), and incentives and information (telecommuting, employer-based trip reduction, and voluntary travel behavior change programs). The opportunity for land-use planning to affect VMT by 2050 is substantial because approximately 50% of residential housing needed then has yet to be built (Pitkin and Myers 2008). Further research and innovation in pricing of travel, possibly enabled by information technology, may be an important area of future work (Salon et al. 2012; van der Waard et al. 2013). While fuel price alone is not a strong leverage point, targeted pricing policies are reportedly more effective, such as tolls for specific links, cordon pricing that applies a fee for driving within a boundary, distance charging, and time charging. For example, Salon et al. review studies that found 12%–22% reductions in traffic from cordon pricing and 2%–3% traffic volume reduction per 10% increase in cordon charge (Sivak 2014). In addition, a transition from gasoline tax and vehicle ownership tax models to VMT-based tax structures could influence a move to lower VMT.

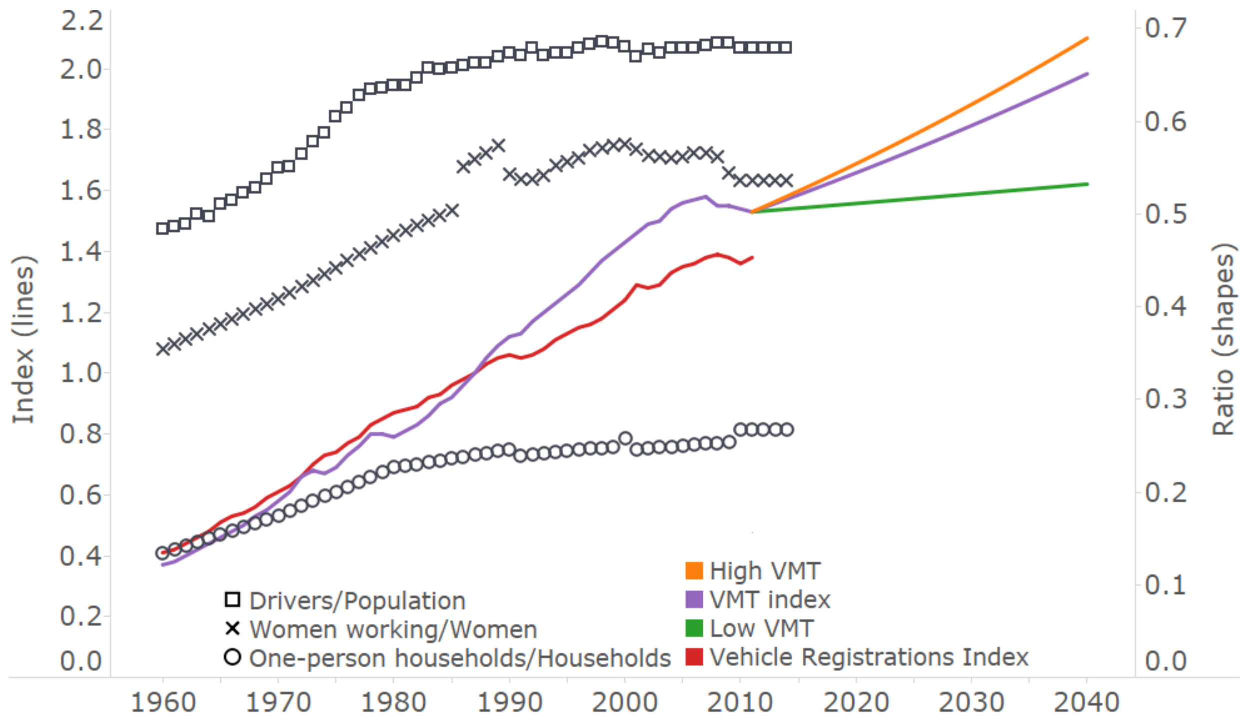

Figure 12. Historical and projected VMT, with related historical trends (Hobbs and Stoops 2002; Lofquist et al. 2012; Smith and Bachu 1999; U.S. Energy Information Administration 2014; Office of Highway Policy Information 2011; Office of Highway Policy Information 2012)

Note: The compound annual growth rate in VMT per driver is 0.1%. In its low and high VMT growth scenarios, the AEO shows total growth in number of licensed drivers is the same at 0.80%. The low-growth scenario shows a compound annual growth rate of -0.70% for VMT per driver. Together, these result in overall national VMT growth rates of 1.1% (high growth case), 0.90% (reference case), and 0.20% (low growth case) (U.S. Energy Information Administration 2014).

Demographic changes among both younger and older adults will affect VMT. Reduced driving and substitution of information technology for driving among people in their 20s and 30s are contributing to VMT trends (van der Waard et al. 2013; Davis et al. 2012; Rypinski and Homan 2011). Analysis of the National Household Travel Survey shows that in 2009 adults in their late 20s to early 30s traveled as much as 2,000 miles per driver per year less than their age group in 1995 and 2001. This observation does not control for income or changes in household formation and parenting. Baby boomers are in the post-50 age range, during which VMT per driver per year declines from its peak around 15,000 miles for 30- to 50-year olds to less than 5,000 miles for the over-85 age group (Rypinski and Homan 2011). Some reports assert that Generation Y has a fundamentally different perspective on mobility, seeking out greater transit and non-motorized mode use and greater information technology use while reducing resources expended on personal automobiles (Davis et al. 2012). Similarly, a recent analysis of mobility trends in the Netherlands found that reduced VMT among young people was the strongest factor explaining the overall stabilization of VMT since 2005 (van der Waard et al. 2013). Divergent trends are likely to shape future VMT for the post-50 age group, with employment increasing for older workers (increased VMT), health and vehicle safety improving (increased VMT), and residence in smaller-lot or attached housing increasing (decreased VMT). If a trend toward lower VMT continues at both ends of the age spectrum, it could continue to reduce the overall VMT growth rate.

Recent literature further explores how information technology and other transportation modes substitute for personal motorized mobility. Because increased VMT is likely to cause greater congestion (Polzin 2006) and expansion of the roadway network may not pay off (Litman 2014), information technology and other modes may be more effective than if VMT and roadways could increase at low cost. Information and communication technology could significantly reduce energy use and GHG emissions but also have energy costs and trade-offs (Ong et al. 2014). Fuhr and Pociask (2011) estimate that an additional 10% of the workforce could regularly work from home, bringing the total to 25%, and reaching a 10-year GHG emissions reduction of 588.2 million tons or about 1% of U.S. GHG emissions. Contrino and McGuckin (2006) find that people use information technology to plan travel and substitute commercial delivery mileage for personal mileage. Using information technology to plan personal travel could reduce fuel usage if vehicle travel is targeted to more effective trips, but improved information and resource savings from Internet use could also increase travel for additional personal trips or additional Internet-initiated commercial delivery. A recent activity-based survey found that people with cell phones generated 30% more GHGs and people with home Internet generated 19% less GHGs due to travel relative to control groups, perhaps because of these other effects (Miranda-Moreno et al. 2012).

The outlines of non-LDV scenarios with significantly reduced demand, such as for air travel and freight, are less apparent than LDV scenarios based on documented VMT-reducing trends. Transportation demand among non-LDVs is project to increase, particularly in aviation and freight (see Table 5). Information technology effects may improve the efficiency of the freight delivery system, and the same demographic trends that reduce VMT may also reduce household demand—or the rate of increase in demand—for goods, but these trends are not as clearly favorable to reduced non-LDV transportation demand as trends toward reduced LDV VMT demand. Other novel technologies, such as personal rapid transit and high-speed rail as a substitute for air travel, are not explored here.

The growing understanding of the causes behind recent slower-than-historical VMT growth suggests features of scenarios with even lower future demand: substituting information and communication technology connectivity for personal vehicle mobility to accomplish many service-delivery and work goals and expanding and improving alternatives so that more people walk, ride bicycles, use public transit, and call upon on-demand transport services. Based on these features, the CTSI scenario has a VMT reduction relative to business as usual of 25% versus 18% in the TEF scenario. We propose that the effects of such a scenario are worth exploring, but do not assert that such a scenario is likely, and consider barriers to reaching that level of reduction in the following paragraphs.

VMT reduction that is a straightforward byproduct of demographic shifts does not require overcoming barriers, although related social changes, such as delayed household formation and the aging of the baby boomer generation may pose broader challenges. VMT reduction through substitution of information technology for physical movement involves challenges of implementing online systems, such as those for internet commerce and public services, as well as workplace challenges for remote work.

The built environment, including the roadway network, has a long lifetime, and its footprint may persist well beyond the duration of the physical materials. Urban areas that were developed with cars as the primary personal transportation mode tend to be designed in ways that discourage walking, biking, and mass transit use. This can be addressed through policy actions such as pricing measures, land-use changes, and alternative mode improvements, but these may face substantial social and political barriers. Barriers could also include many of the factors discussed above: scenarios challenging to VMT reduction would include countervailing conditions, such as low fuel prices, low costs of driving, low investment in public transit, or commuting and connectivity practices unfavorable to information technology displacing a share of commute trips. Overcoming these barriers could enable transportation demand reduction to contribute to reducing GHG emissions from the transportation sector by 80% or more.

Biofuel Pathways

Transportation systems make up the foundation of strategies for the distribution of biofuels across the United States. Increased use of certain biofuels pathways could play a pivotal role in reducing GHG emissions and reaching the CTSI goal of an 80%–100% reduction by 2050. In the TEF scenario, biofuels were a key component to reducing petroleum use and GHGs. For example, in TEF's 80% carbon-reduction scenario by approximately 2050, advanced biofuels contributed around 70 billion gallons to the fuel mix in 2050. With lifecycle emissions approximately 70 to 80% lower than gasoline (dependent on the specific feedstock and pathways), this could displace approximately 510 to 620 MMT of GHG emissions per year by 2050.[4] We used the same advanced biofuel contribution for the CTSI scenario, because it is already an aggressive exploration of what could be possible. TEF found that it would be extremely difficult to reach aggressive emissions-reduction goals without the inclusion of biofuels. Since the study's release, key milestones have been reached by the biofuel industry: new advanced biorefineries have been completed at pilot, demonstration, and pioneer scales (U.S. Department of Energy 2014a) and new conversion technologies have been developed (Bioenergy Technologies Office 2014).

In the short term there are modifications to existing facilities that could aid in reducing emissions and serve as a bridge to advanced biofuel development. For example, modifications can be made to cornstarch-to-ethanol facilities for increased efficiency or for processing cellulosic materials. Existing ethanol facilities can decrease energy use and lower cost, which Fulton et al. assert could result in an approximately 30 million–52 million metric ton GHG emissions reduction in 2030, or 3% of 2012 GHG emissions in the transportation sector (Fulton et al. 2014). In addition, cellulosic ethanol production from "bolt-on" equipment in existing ethanol refineries could result in a 13-million-metric-ton/year decrease in GHG emissions in 2030 (Fulton et al. 2014).

In the long term, advanced biofuels can play an important role in transportation sector GHG emissions reductions, especially because the feedstock is sustainably harvested, non-food biomass. Widespread adoption of advanced biofuels requires further development of feedstock supply, refinement conversion technologies, and increased market competitiveness. Feedstock for conversion to biofuels will need to be planted and harvested, and the logistics of feedstock transportation and preparation will need to be streamlined. This feedstock also has the potential to be utilized for other applications, such as biopower (perhaps for PEVs) or biomass-based

[4] Assumes WTW gasoline emissions of 10.7 kg CO_2 eq./ gge, and WTW pyrolysis gasoline emissions between 1.8 and 3.4 kg CO_2 eq./ gge, depending on the conversion pathway and feedstock used (from GREET 2013).

products, and the dynamics of the competitive allocation among these markets is uncertain. In addition, more testing and refining of conversion technologies will be necessary. The finished fuel will need to be priced competitively with conventional fuels in order to achieve high consumption levels.

Understanding around the potential environmental impacts of biofuels is still evolving and there are still uncertainties regarding land use change and its impact on the carbon cycle. Additional biofuel pathways have been introduced in a tool for emissions estimation, GREET, since TEF was released—jet fuels, algae, renewable diesel, and gasoline from cellulosic feedstocks (Argonne National Laboratory 2008). Recent GHG emissions estimates for the fast pyrolysis gasoline pathway suggest a more than 60% decrease in GHG emissions compared with petroleum-based gasoline[5] (Han et al. 2013), and algal biofuel could have up to a 60% GHG reduction over conventional diesel (Frank et al. 2012). The "Emissions" section includes biofuels in its discussion of the emerging literature on transportation emissions.

The biofuels industry could even further limit its impact on the environment by employing carbon capture and storage (CCS) in biomass conversion to biofuels. CCS captures and stores the CO_2 that originates from carbon in the biomass that is converted to CO_2 using production or industrial processes. The CO_2 is isolated from these processes utilizing the same methods that would be used for fossil fuels CCS (Joint Task Force Bio-CCS 2014), and bioprocesses often produce pure-stream CO_2 that may be amenable to capture. If CCS is employed for processes that use sustainable biomass, it could reduce global CO_2 emissions by 10 billion tonnes per year by 2050. This reduction does not include the decrease in emissions that is accomplished by replacing fossil fuel use (IEAGHG 2011). Because of challenges in the collection and storage of this CO_2, CCS at biorefineries is not included in the CTSI scenario.

Advanced biofuels are easier to deploy in non-LDV sectors of transportation than ethanol. Biodiesel is commercially available and commonly used in 5% or 20% blends with diesel fuel. Renewable jet fuel can be utilized in the aviation industry to reduce emissions, and this has gained more attention in recent years. Many commercial carriers have demonstrated that the regular use of renewable jet fuel is feasible. In addition, The U.S. Department of Defense has made increased use of alternative fuels (including biofuels) a priority and supports renewable jet fuel companies, transferring investment risk from private to public sectors (Davidson et al. 2014). In addition, biogas—produced from wastewater treatment plants, landfills, and digestion of other organic waste streams—is already being used as a transportation fuel in California, primarily in non-LDV applications (Bilek 2013). Milbrandt (2013) estimates that 7.9 million tonnes per year of methane could be available from these sources for use in transportation or power applications. The productive use of this methane could be especially environmentally valuable because methane is a more potent GHG than CO_2. Overall, advanced biofuels could be a critical component of a strategy to reduce GHG emissions from the transportation sector by 80% or more.

[5]This reduction was measured on a well-to-wheel basis, which is defined and discussed further in the "Emissions" section.

Radically More Efficient Vehicles

New vehicle technologies could decrease the relative fuel consumption of vehicles and, barring a compensating increase in VMT, decrease overall GHG emissions from the transportation sector, potentially contributing to a strategy for 80% or greater reductions in the long term. For the dominant LDV sub-sector (Figure 2), estimated shares of energy use within the vehicle are shown in Figure 13, illustrating the significant opportunity to increase efficiency and decrease emissions by reducing the losses that account for 83% of energy used.

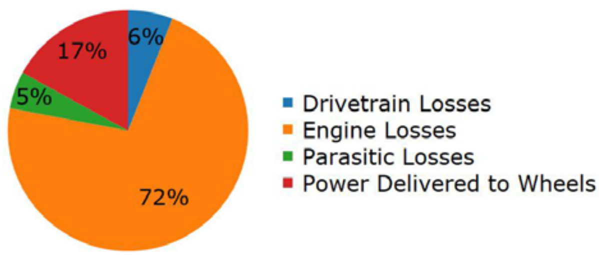

Figure 13. LDV energy use ("Alternative Fuels Data Center: Maps and Data" 2014)

Related transportation interests include safety implications, especially those associated with lighter passenger vehicles, and fuel tax revenue payments to the U.S. Highway Trust Fund. For non-LDV modes, TEF found significant potential for improvement (see Table 6). Other than platooning in heavy trucks, the CTSI scenario does not explore non-LDV vehicle efficiency beyond levels assumed in the TEF scenario. This is due to the CTSI focus on highway vehicles—whereas many types of non-LDVs are not highway vehicles—and because TEF already mapped out an aggressive exploration of known potential.

Table 6. Energy Intensity Improvement Potential for Non-LDV Modes in TEF (2050)

	Trucks	Aviation	Inland Marine	Ocean Marine	Rail	Pipeline	Off-road
Energy intensity improvement (%)	50	65	30	75	35	20	18
Activity growth (%)	87[a]	217[b]	32[a]	450[c]	47[a]	16[a]	20[d]
Net change (%)	-7	+11	+1		-4	-7	-2

[a] EIA projections extrapolated.
[b] FAA projections extrapolated.
[c] Growth in dollar value of trade (EIA).
[d] Projected at half the population growth.

Source: Vyas, Patel, and Bertram 2013

For LDVs, these efficiency gains can be accomplished through a number of strategies, such as mechanical, electrical, or controls improvements; powertrain hybridization; the use of lighter materials; energy density advances in batteries; and a decrease in overall vehicle size. A National Academy of Science study (National Research Council 2013) explains that currently known technologies could offer substantial fuel economy increases through incremental technological improvements, through both load reduction and drivetrain enhancements. For new, average, conventional LDVs sold in 2050, the study estimated a mid-range of 74 mpg for an EPA fuel economy test value, and an optimistic value of 94 mpg. Some of these improvements could also carry over to the other pathways described in this report. For example, a significantly lighter vehicle would likely require less energy for equivalent performance, which would reduce the required battery size for a PEV or tank size for a FCEV and consequently reduce vehicle cost. Perhaps most importantly, many of the strategies for increased vehicle efficiency are complementary and independent of fuel, applying to current internal combustion engine vehicles, PEVs, FCEVs, and other alternative fuel vehicles.

Improvements to ICEs represent substantial opportunities for fuel savings because they are widely used. Jones (2008) outlines technologies and potential fuel consumption reductions in spark-ignition engines, which are commonly used in light-duty gasoline-powered vehicles: fast combustion with high dilution tolerance (3%–5%), cylinder deactivation (3%–8%), direct injection (1%–3%), turbocharging and downsizing (3%–7%), and valve event manipulation (4.5%–16.5%). Optimizing electrical components could decrease consumption by 2%–7%. Efficiency technologies continue to spread in the market; for example, powertrain hybridization is becoming increasingly common.[6]

Financial incentives are limited for automakers to pursue radical increases in vehicle efficiency, as consumer willingness to pay for greater efficiency may be limited and some approaches to making vehicles radically more efficient would require a significant change to vehicle features such as size, acceleration, and trunk space. Some vehicle efficiency strategies, such as lightweighting and fuel reformulation, would benefit from or require change across the sector. For example, safety concerns associated with lightweighting can be mitigated if vehicles have connected and automated technology features for enhanced obstacle detection and crash prevention and through improvement of crash compatibility features. Reformulation of liquid could increase vehicle efficiency, but this would require stakeholder agreement among vehicle manufacturers, fuel providers, and regulators.

CAFE standards are the primary federal policy that regulates vehicle efficiency. These standards increase vehicle efficiency when they are set at levels that require change. Decisions about the pace of such changes balance the interests of auto manufacturers, available technological options, and regulatory goals. In the next 10 years at least, these standards are expected to drive significant adoption of efficiency technology, for LDVs as well as medium- and heavy-duty vehicles. The standards also include favorable treatment of electric drivetrain vehicles, but the engineering analysis that supported the development of the standards does not assume that significant electrification will be necessary to meet the 2025 standard (in contrast to the more aggressive scenarios explored under CTSI). Standards through 2050 are uncertain but would be an important influence on efficiency of on-road vehicles in the longer term influencing how radical energy efficiency improvement could contribute to an 80 – 100% decrease in transportation-sector GHG emissions.

[6] It should be noted that a number of these technologies are currently being incorporated to some extent in current vehicle models by almost all major vehicle manufacturers.

Emissions

A key metric for estimating the value of the preceding technologies and strategies is the effect on GHG emissions. Emissions occur not only during vehicle use, but also during fuel production, vehicle manufacturing, and other life cycle stages. In addition to emissions as a metric, reducing the carbon intensity of the fuel production stage, through low-carbon electricity or hydrogen production, is an important GHG mitigation strategy that is beyond the scope of this report. The actual emissions effects of particular strategies and the CTSI scenario depends on their relative emissions profile over the entire life cycle. Life cycle, not tailpipe, emissions are a critical metric because emissions can occur across all of the stages of production, distribution, operation, and disposal of a product or service. Here, we compare biofuels, electricity, and hydrogen strategies with their conventional vehicle alternative, with respect to GHG emissions, particulate matter emissions, and other radiative forcing effects. Other strategies may also have associated emissions that must be assessed to get an accurate estimate of net emissions, but these are not examined further here. Fine particulate matter emissions are provided as the single emissions metric most closely related to health effects of air pollution, although other air emissions are also important. Life cycle emissions vary depending on specific processes involved. We provide estimated effects based on selected current processes and also based on potential future process improvement.

Life Cycle Greenhouse Gas Emissions of Transportation Fuels

The desire for low or zero GHG emissions road transportation has led to research and development of many alternative fuel options and advanced vehicle technologies. To inform policy as well as research and investment decisions, a solid understanding of the comparative advantages of these alternative pathways to reduce GHG emissions, from a life cycle perspective, is essential.

Life cycle assessments can be divided into two different categories: one is attributional life cycle assessment and the other is consequential life cycle assessment. Attributional life cycle assessment quantifies the emissions and resource flows of a product but does not consider indirect effects (e.g., market-driven effects) arising from changes in the output of the product. Consequential life cycle assessment attempts to assess how relevant environmental flows will change overall in response to system changes, such as decisions about land use, infrastructure investment, or vehicle choice. Scenario analysis is one approach to estimate these more comprehensive effects. Historically, the majority of life cycle assessments applied to transportation fuels have been attributional, and all life cycle assessment studies reviewed here employed attributional methods though some studies included potential land use change in their estimates. Land use change can have indirect effects due to increased competition for land between biofuel feedstock production and food.

When life cycle assessment methods are applied to transportation fuels and their use in vehicles, the analysis is generally referred to as a well-to-wheels (WTW) study (Figure 14). The activities from resource recovery through processing and the delivery of the fuel to the vehicle are referred to as the well-to-tank stage, and the use of the fuel in the vehicle is referred to as the tank-to-wheel stage. To understand the GHG impacts of various advanced fuel and vehicle technologies, the life cycle assessment needs to take into consideration GHG emissions from both the fuel-cycle (i.e., WTW) and vehicle-cycle (see Figure 14). For conventional petroleum fuels and vehicle technologies, emissions associated with vehicle and parts manufacturing are estimated an order of magnitude lower than the fuel-cycle WTW GHG emissions (Dunn et al. 2012; Burnham 2012). However, the relative contribution of GHG emissions associated with vehicle and part manufacture to total life cycle emissions may increase with a transition to alternative fuel and vehicle technologies due to the likely low fuel-cycle GHG emissions of alternative fuels. For example, a study by Aguirre et al. (2012) indicates that battery manufacturing alone accounts for approximately 24% of the total life cycle GHG emissions of BEVs charged with California electricity (see Figure 15).

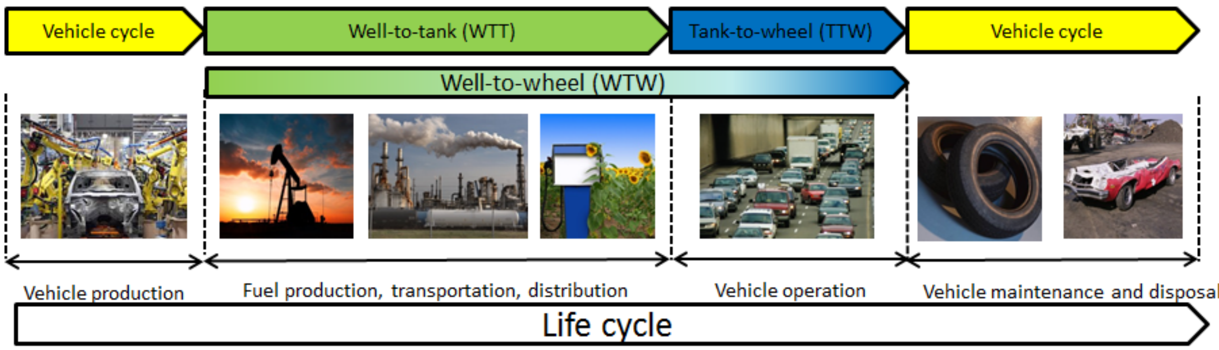

Figure 14. Illustration of the life cycle of transportation fuels and vehicles

A number of recent studies compared LDV GHG emissions for various combinations of alternative fuels and vehicle technologies, including hybrid, PHEVs, BEVs, FCEVs, and vehicles fueled with biofuels. The results from different studies are not directly comparable because the system boundaries (e.g., whether vehicle manufacturing and infrastructure-related emissions are included), fuel production technologies (e.g., current or future), vehicle platform (e.g., performance and efficiency), primary energy sources (e.g., fuel mix for electricity production and type of feedstock used to produce biofuels), and modeling approaches differ among studies, and the assumptions are often not clearly documented. Nevertheless, within limitations, we summarize the general observations derived from a limited review of life cycle studies on the GHG emissions of vehicles powered by electricity, hydrogen, and selected biofuels. Unless noted otherwise, the life cycle GHG emissions presented below are on a basis of per vehicle mile driven.

Under current alternative fuel and technology options and average electricity mix, conventional gasoline ICE vehicles have the highest life cycle GHG emissions among corn ethanol E85-fueled, gasoline hybrid, gasoline plug-in hybrid, hydrogen fuel cell, and BEVs with an on-road driving range of 70 miles charged with U.S. average electricity mix (see Figure 15) (Nigro and Jiang 2013; Joseck and Ward 2014). Table 7 summarizes a life cycle GHG emissions comparison among these vehicles based on Joseck and Ward 2014. Among the alternative fuel and vehicle technology options, corn-ethanol-fueled E85 vehicles appear to have the highest variation in life cycle GHG emissions, reflecting the variability around corn yield, ethanol yield, energy and fertilizer requirements by corn farming, and energy use by ethanol production.

Table 7. Current Estimated Life Cycle GHG Emissions

	Well-to-Tank	Tank-to-Wheel	Vehicle Cycle	Total (g CO_2 eq/mile)
Gasoline LDV (26.3mpg)	100	314	46	460
Alternative fuel LDV				327–382

Source: Joseck and Ward 2014

Note: The current gasoline ICE vehicle with a fuel economy of 26.3 mpg is estimated to have life cycle GHG emissions of 460 g CO_2 eq/mile, among which the well-to-tank and tank-to-wheel stages of the fuel cycle contribute to 100 and 314 g CO_2 eq/mile, respectively, and the vehicle cycle accounts for the remaining 46 g CO_2 eq/mile. Compared to the gasoline ICE vehicles, the alternative fuel and vehicle options can reduce life cycle GHG emissions by 17%–29% based on average current cases (Joseck and Ward 2014).

Life cycle emissions for plug-in electric vehicles depend, in part, on assumptions about emissions from electricity generation. We did not conduct a new life cycle emissions assessment of plug-in electric vehicles, a major analytic project. Instead, we reviewed the literature on life cycle emissions of plug-in electric vehicles. This literature used a wide range of assumptions about types of electricity generation, which influenced the resulting emissions. Figure 15 shows the share of electricity generation by type for each of the studies reviewed here. The electricity generation mix in a long-term, low-emissions scenario could include greater shares of low-emissions sources than those assumed in this literature.

Figure 16 summarizes the range of life cycle GHG reductions reported in the literature for current and future alternative fuels and vehicle operations when compared to the current gasoline vehicles. The electricity generation projections in Figure 15 influence the net GHG benefits of plug-in electric vehicles over traditional vehicles. With continuous development and improvement of vehicle, engine, and transmission technologies due in part to the more stringent requirements in CAFE standards and other regulatory requirements, the life cycle GHG emissions are expected to decline across all fuel and vehicle technologies over time.

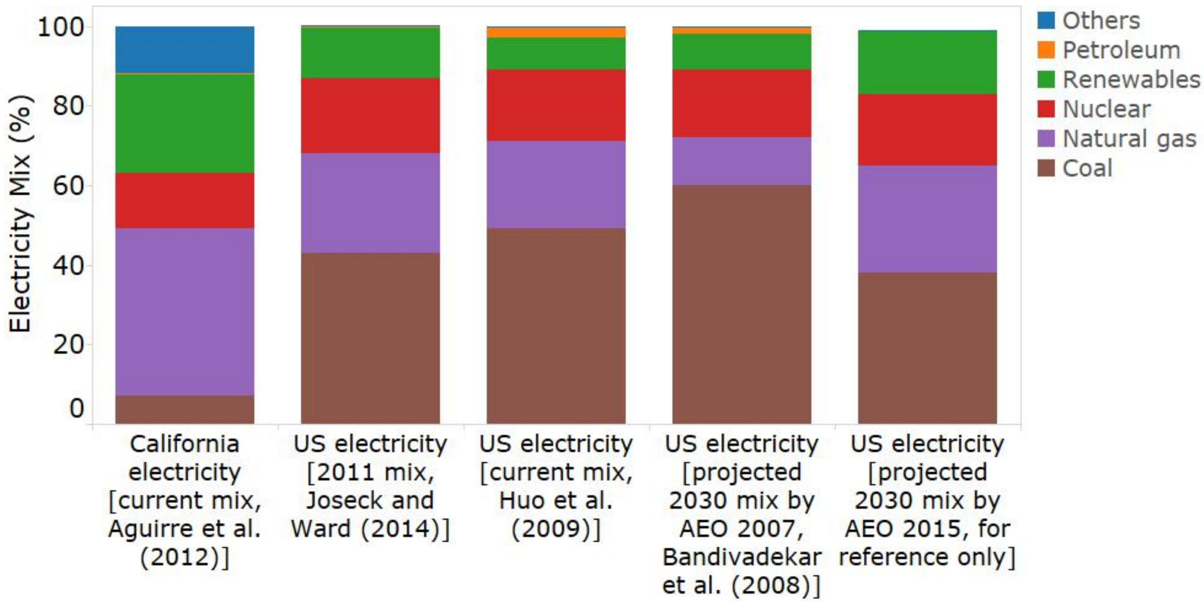

Figure 15. Electricity mix modeled in life cycle studies for advanced fuels and vehicle technologies (Aguirre et al. 2012; Joseck and Ward 2014; Bandivadekar et al. 2008; Huo et al. 2009)

Note: The electricity mix modeled by the LC studies varies significantly, which influences the LC GHG emissions of fuels and vehicles examined. This figure shows the electricity mix used by the studies reviewed in this section. Figure 15 shows the share of electricity generation by type for each of the studies reviewed here, as well as for EIA's AEO 2015. While not specifically included in the LCA for this report, AEO 2015 reflects recent increases in natural gas and renewable electric generation and declining coal generation. This trend supports that the electricity mix, and subsequently electric vehicles, has become cleaner over time.

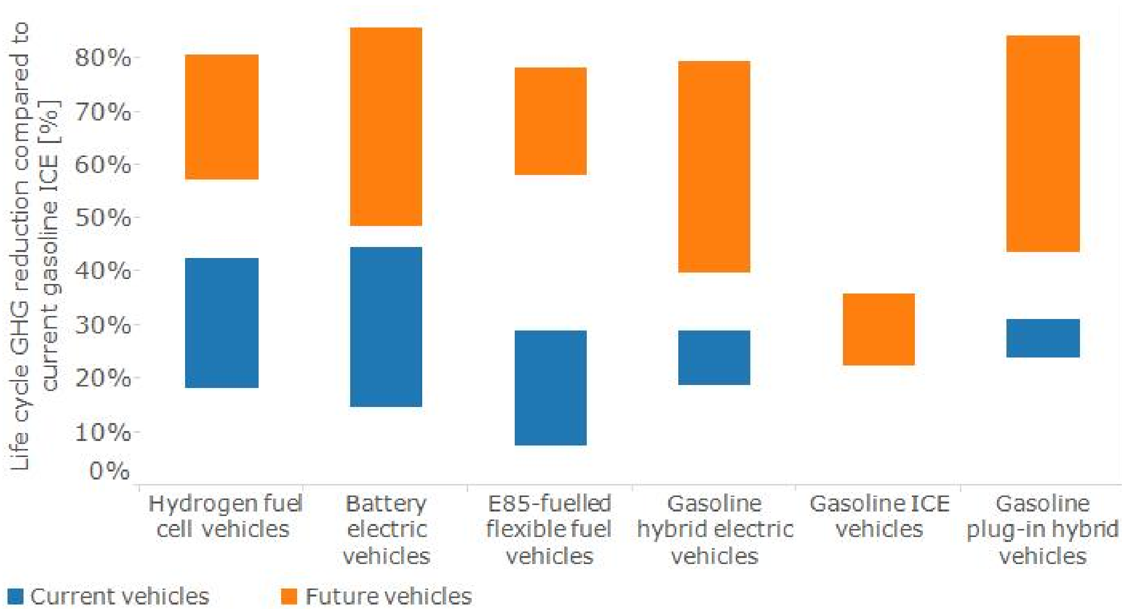

Figure 16. Life cycle GHG reduction of current and future alternative fuel and vehicle options compared to the current gasoline ICE vehicles (Joseck and Ward 2014; Bandivadekar et al. 2008; Nigro and Jiang 2013)

Nigro and Jiang (2013) reported WTW emissions only. Vehicle-cycle emissions are taken from Fred and Joseck (2014) and are added to the WTW emissions to derive life cycle GHG emissions for the comparison.

Note: This figure summarizes the ranges of LC GHG reduction estimated by the literature reviewed when compared to the current gasoline ICE vehicles. Each study reported its own LC GHG emissions for current gasoline ICE vehicles and alternative options. Because the definition on future fuel and vehicle technologies varies by studies, the relative GHG reduction achieved by alternative fuel/vehicle options are calculated and reported using the estimates within each study. For example, the Massachusetts Institute of Technology study (Bandivadekar et al. 2008) estimated the LC GHG emissions of the current gasoline ICE at 446 g CO2 eq/mile. The study examined the potential of life cycle GHG reductions by electricity- and hydrogen-powered vehicles and gasoline hybrid and gasoline PHEVs relative to gasoline ICE vehicles in the next two decades (i.e., around 2035). While gasoline ICE vehicles are estimated to have higher GHG emissions compared to these alternative fuel and vehicle options in 2035, the gasoline ICE vehicle in 2035 is expected to yield a 36% reduction in life cycle GHG emissions compared to the current generation gasoline ICE vehicle because of the efficiency improvement and continued downsizing of gasoline engines enabled by higher power density (Bandivadekar et al. 2008). Gasoline hybrid, gasoline plug-in hybrid (with 30 mile all-electric range), hydrogen (from distributed natural gas) fuel cell, and BEVs based on the 2007 AEO projection for 2030 [see Figure 15]) are estimated to achieve 39%, 39%, 33%, and 20% life cycle GHG emissions reductions, respectively, when compared to gasoline ICE vehicles in 2035. The study indicates that the smaller GHG reductions by BEVs (U.S. average grid) is mainly caused by the weight increase of the battery pack and resulting increased energy use required during vehicle operation, compared to a gasoline plug-in hybrid operating in charge-depleting mode.

Regardless of the type of vehicle technologies, life cycle studies agree that deep GHG reductions cannot be achieved without increased vehicle electrification and/or alternative fuels with very low WTW (fuel-cycle) GHG emissions (Nigro and Jiang 2013; Joseck and Ward 2014). For example, renewable electricity (e.g., from wind and solar) used to charge BEVs, low carbon hydrogen (e.g., from water electrolysis using renewable electricity) used for FCEVs, and cellulosic-biofuel hybrid vehicles offer the lowest GHG-emitting options, which could reduce life cycle GHG emissions by up to 85% compared to the current gasoline-fueled ICE vehicles (Joseck and Ward 2014). For these very low carbon-emitting fuel and vehicle technology options, the vehicle cycle (including vehicle and part manufacturing and assembling, recycling, and disposal) is often the dominant source of the life cycle GHG emissions. Table 8 shows estimated vehicle cycle shares of life cycle GHG emissions once most GHG emissions are removed from the fuel portion of the life cycle.

Table 8. Estimated Share of Life Cycle GHG Emissions From Vehicle Cycle With Low Carbon Fuels

Fuel and Vehicle Description	Vehicle Cycle Share Emissions
Fuel cell vehicles using hydrogen from 100% renewable electricity	70%
Battery electric vehicles charged with 100% renewable electricity	91%
E85 vehicles fuelled with cellulosic ethanol (e.g., switchgrass-derived ethanol)	61%

Source: Joseck and Ward 2014

Fuel production (e.g., biofuel conversion, liquefaction, or compression of hydrogen along with necessary transportation) and feedstock production (e.g., growing dedicated energy crops) become minor GHG contributors to the life cycle GHG emissions. Because some GHG emissions from vehicle cycles are likely unavoidable (i.e., always positive), 100% reduction in life cycle GHG emissions (compared to gasoline ICE vehicles) would require use of some fuels with negative WTW GHG emissions.

Applying CCS to renewable fuel (e.g., hydrogen and biofuel) production has the potential to further reduce life cycle GHG emissions. A study by National Research Council (2013) indicates that biofuels produced in facilities employing CCS could have slightly negative WTW GHG emissions. Similarly, the use of biomass in a power plant fitted with CCS could produce electricity with negative WTW emissions. Coupling CCS with dedicated energy crops for either electricity or biofuel production likely offers the highest GHG reduction potential if the energy crops are grown sustainably on marginal land and are capable of significantly increasing soil carbon.

Life Cycle Fine Particulate Matter Emissions

Literature comparing fine particulate matter emissions (those with 2.5 micrometers in diameter and smaller, referred to as $PM_{2.5}$) across vehicles powered by gasoline, biofuels, electricity, and hydrogen fuel cells is very limited. Huo et al. (2009) examined WTW emissions of five air pollutants (volatile organic compounds, oxides of nitrogen , particulate matter less than 10 micrometers, $PM_{2.5}$, and carbon monoxide) for a number of fuel and vehicle options, including corn- and cellulosic-ethanol-fueled E85 vehicles, gasoline hybrid vehicles, BEVs, and hydrogen FCEV (see Figure 17). In addition to estimating the magnitude of WTW $PM_{2.5}$ emissions, the authors also reported locations of emissions in terms of urban versus total emissions. With the exception of gasoline hybrid vehicles, all of these alternatives increase WTW $PM_{2.5}$ emissions compared to gasoline ICE vehicles. Corn ethanol E85-fueled vehicles, BEVs charged with electricity from a grid relying heavily on coal (see U.S. electricity in Figure 15) and hydrogen (from natural gas steam reforming) FCEVs could increase WTW $PM_{2.5}$ emissions by 143%, 170%, and 21%, respectively, compared to gasoline ICE vehicles. The majority of WTW $PM_{2.5}$ results from coal mining and coal combustion for the BEVs charged with the modeled electricity mix. Trends towards cleaner energy sources in the future could reduce these emissions. Farming equipment powered primarily by diesel fuel and fertilizer manufacture account for the majority of WTW $PM_{2.5}$ emissions for the corn-ethanol-fueled E85 vehicles. Despite the much higher WTW $PM_{2.5}$ emissions from corn-ethanol-fueled E85 vehicles and BEVs than those from gasoline ICE vehicles, a large portion of these emissions is generated during fuel (ethanol and electricity) production stage and occurs in rural areas. Huo et al. (2009) estimated that corn-ethanol-fueled E85 vehicles and BEVs could reduce urban $PM_{2.5}$ emissions by 22% and 54%, respectively. Among all vehicle options, only BEVs and hydrogen FCEVs have zero vehicle exhaust $PM_{2.5}$ emissions (though $PM_{2.5}$ emissions are still generated from break and tire wear during vehicle operations). Readers are encouraged to refer to Tessum et al. (2014) for more information on the health effects of $PM_{2.5}$ for electric vehicles (with zero tailpipe emissions) powered by electricity from coal, natural gas, or renewable sources (biomass or wind, water or solar) in comparison to ICE vehicles operated on gasoline and ethanol.

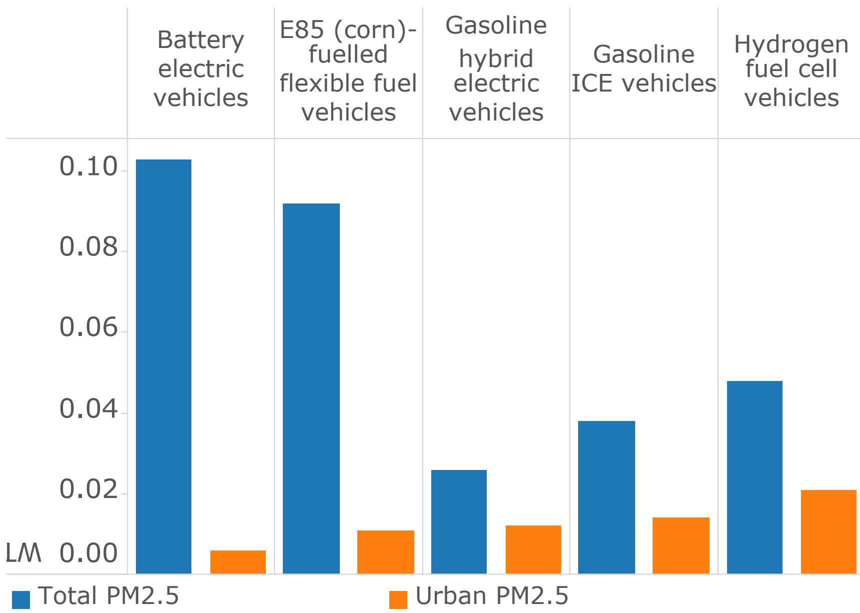

Figure 17. WTW PM2.5 emissions (total vs. urban portion of WTW PM2.5 emissions) (Huo et al. 2009)

Other Radiative Forcing Effects

Life cycle studies on the global warming effects of transportation fuels, in general, have been focusing on long-lived GHGs, including CO_2, methane, and nitrous oxide, while short-lived radiative forcing effects, both positive and negative, are largely ignored (Cai and Wang 2014; Stratton et al. 2011), in part due to the greater uncertainty of their effects. The global warming potentials or cooling effects of short-lived gases and particles depend on the location, timing and source of the emissions, posing significant challenges to their use in life cycle studies. The transport sector is a large emitter of some short-lived climate pollutants, including black carbon, non-absorbing aerosols, and contrails (Intergovernmental Panel on Climate Change 2014). Black carbon and non-absorbing aerosols, emitted primarily from incomplete combustion of fuels and biomass, can have direct and indirect radiative forcing effects whereas contrails from aircrafts have impacts on the troposphere layer and also on aircraft-induced cloudiness, which could indirectly affect radiative forcing. Because of the relatively large share of emissions of short-lived pollutants from the transportation sector (Unger et al. 2010), these pollutants are essential to an improved understanding of the impacts and mitigation opportunities in transportation compared to other sectors.

Cai and Wang (2014) recently assessed the impact of black carbon (with climate warming effect) and primary organic carbon (with climate cooling effect) on the WTW GHG emissions for a variety of fuel and vehicle technology options. Their results indicate that black carbon and primary organic carbon emissions add less than 1% to the comparable WTW GHG baseline for gasoline ICE, gasoline hybrid, gasoline plug-in hybrid, BEVs (charged with U.S. electricity mix) and hydrogen (from natural gas) FCEVs in the near term (2015) using the 100-year global warming potentials. However, vehicles fueled with biofuels could see greater increases in their WTW GHG emissions when the black carbon and primary organic carbon emissions are considered, increasing by about 9% (on average) for vehicles fueled with E85 derived from corn stover (with 100-year global warming potentials). Biomass-fired boilers, which are assumed to be employed to produce steam and electricity in the corn stover ethanol plant, are the dominant source, responsible for about 65% of WTW black carbon and primary organic carbon emissions of corn stover ethanol-fueled E85 vehicles. It is worth noting that uncertainties around these emissions from cellulosic ethanol production could be high given that good quality data (e.g., emissions factor for the unique biomass-fired boilers employed in the cellulosic ethanol biorefinery) are often scarce. In addition, uncertainties about the global warming potentials of these emissions can also influence the estimates.

The CTSI scenario addresses potential reductions in transportation energy use but does not translate these into GHG emissions reduction because of the challenges and uncertainties in developing life cycle emissions estimates. Future work could further develop and apply emissions metrics for analysis of transportation-sector GHG mitigation options.

CTSI Scenario

We developed a high-level scenario for future transportation energy use, nominally in 2050, based on the TEF scenario. As discussed in the preceding sections, certain assumptions were changed toward greater energy use reduction. These scenarios do not represent a prediction of transportation energy use reduction. Instead, they provide a framework in which to explore what might be necessary for deep reductions in energy use and what the consequences of such reductions might be. It is acknowledged that individually these scenarios are aggressive and that collectively even more so.

The options discussed in this report interact with each other and with other transportation system trends. For example, reductions in demand for personal mobility could reduce the demand for vehicles and fuels. Increased use of electricity, hydrogen, and biofuels reduces demand for other fuels, which could impact global and local prices. If automation allowed fewer vehicles to serve more needs, it could reduce the number of vehicles and demand for fuel. In developing a CTSI scenario, only some of these interactions could be considered. Full evaluation of the interactions between subsectors will require energy-economic modeling, but no such model of the transportation sector is currently able to evaluate the novel options considered here.

All of these interactions occur within a broader energy economic context that is shaped by fundamentals such as global oil and gas prices and economic growth. High global oil price scenarios imply potentially more favorable relative costs for vehicles that reduce use of fossil fuels and conversely low global oil price scenarios entail less favorable relative costs. High economic growth scenarios tend to provide greater opportunity for technological change, which can favor efficiency, but these scenarios also increase utilization of energy, often overwhelming the efficiency gains. These and other background conditions in the TEF and CTSI scenarios are based on reference cases from the AEO. This scenario does not include potential feedbacks, such as the possible impacts on the global price of oil if oil demand declines due to decarbonization of the sector.

The TEF study included nine technical reports, each focused on different aspects of the transportation system. The TEF summary included a simple scenario that combined the impacts of the opportunities identified in the papers. This scenario was not a forecast, but it did find that the technical options exist to reduce U.S. GHG emissions from the transportation sector by more than 80% in the long term, by approximately 2050. The scenario involved the simultaneous development of numerous challenging transportation system changes, each of which faces significant technological and business risk. This report summarizes in a single publication the potential of emerging technologies and strategies that could contribute to a transformative transportation sector emissions goal.

The TEF and CTSI scenarios both use a version of the Buildings Industry Transportation Electricity Scenarios tool. For the CTSI scenario, we updated this tool with the AEO 2013 reference case (Energy Information Administration 2013), which has forecasts with reduced VMT, improved vehicle efficiency, increased electric drive vehicles, and reduced biofuels relative to the version used in TEF, which relied on AEO 2011 (National Renewable Energy Laboratory). TEF included impacts from several effects that are not updated here and are left unchanged in the CTSI scenario (Table 9). Additionally, the LDV fleet mix was left unchanged, as shown in Table ES-1, reflecting the need for additional choice and policy impacts modeling and the observation that progress in the marketplace so far is consistent with, but does not exceed, the trajectory consistent with development of this rapidly evolving LDV fleet. A trajectory towards robust contribution of advanced LDVs to deep emissions reductions would continue and accelerate trends to date. Actions to accelerate these trends might include strongly coordinate research, development, demonstration, deployment, and a favorable economic environment for these vehicles. Additional methodological information appears in Appendix B.

Table 9. Transportation Energy Scenario Assumptions and Results

Factor (in 2050)	Business as Usual	TEF Scenario	CTSI Scenario	Notes
VMT Per Vehicle	13,500	18% below business as usual	25% below business as usual	See "VMT Reduction and Demographic Shifts"
"Eco Driving"	No improvement	5% improved mpg	40% improved mpg	See "Automation"
Efficiency Factors	Varies by vehicle type	Varies by vehicle type	50% reduced fuel use	See "Automation"
Percent of PHEV Drive on Electric		33%	45%	See "Electric Vehicle Pathways"
Heavy-Duty Freight Efficiency	8.2 MPG	50% improved efficiency	60% improved efficiency	See "Automation"
Percentage of the LDV fleet composed of advanced drivetrains	14%	92%	92%	
Output Metrics (2050)				
Transportation CO_2 Emissions (includes transportation electricity use) (million metric tons CO_2)[a]	1,584	112 (93% reduction)	-88 (106% reduction)	
Net Transportation Petroleum Use[a] (quadrillion Btu)	21.3	-2.0	-4.4	

[a] CO_2 = carbon dioxide; Btu = British thermal unit. Advanced drivetrains refers to HEVs, PEVs and FCEVs.

[b] Negative values for petroleum use indicate more liquids production (from biofuels) than consumption in the sector. Negative values for CO_2 emissions include CO_2 reductions from net liquids production, essentially assuming they are used in other sectors or exported and displace the relevant fuel (such as diesel) in other sectors. Alternatively, this can be viewed as additional technical potential beyond that required to reach zero emissions in the transportation sector directly.

Although we present only a single CTSI scenario, the new and updated options explored in CTSI could be used to generate multiple scenarios for different pathways to reduce transportation petroleum use and GHG emissions by more than 80%.

Discussion

Deep reduction or near-elimination of GHG emissions in the transportation sector represents a challenging, long-term goal that no single strategy can address alone. The portfolio of strategies that meets this goal will include reducing GHG intensity of transportation energy sources, improving energy efficiency of transportation technologies, and reducing overall transportation use. Candidate strategies for consideration today may encompass a broader range of strategies than will ultimately be pursued and at the same time may miss some key elements that could ultimately make significant contributions. This is to be expected given imperfect foresight, rapid technological change, and the ambitiousness of the stated goal. Persistent evaluation of possible strategies based on new data and technologies can help to steer investment in future transportation systems toward options that are the most feasible and impactful.

The strategies that are emphasized in this report—vehicle electrification pathways, connected and automated vehicles, reduction in demand, biofuel pathways, and radically more efficient vehicles—could transform both technological and behavioral aspects of the transportation system. Full implementation of all strategies is estimated to yield the potential for negative GHG emissions. There may be value in pursuing some level of redundancy if policies seek to ensure that a goal is met, especially because each strategy included here would require very significant change to the transportation system. Electric drive and biofuels technology strategies may complement each other due to different advantages and disadvantages for different vehicle types and duty cycles. Efficiency improvements arise from a similarly complementary suite of options (lightweighting—enabled by increases in safety with vehicle connectivity— mechanical, thermodynamic, and electrical efficiency measures), and the odds of delivering significant efficiency improvement may be increased by pursuing a portfolio of promising options. While electric drive, biofuels, and efficiency improvements are primarily technological changes, behavioral aspects of transportation are also critical to deep reductions. Behavior will determine the effects of connected and automated vehicles as well as transportation demand reduction strategies. The emerging landscape of transportation demands, and services to meet those demands, may feed back to technological change in vehicle efficiency, vehicle size, and fueling systems if they enable new market models that can accelerate market adoption of advanced technologies or shift vehicle and fuel needs of future systems, as could be the case if automation and urbanization facilitate high-utilization vehicle sharing, smaller vehicles, or both. The technologies and strategies discussed in this report are primarily illustrated with examples from light-duty passenger vehicles, the largest sub-sector, and also apply to medium- and heavy-duty on-road vehicles. In addition, there may be opportunities to leverage some of these technologies off-road, in military, marine, rail, transit, and aviation operations.   It should also be noted that technologies that can enhance mobility, sich as connected and automated vehicles also have a potential to significantly increase transportation sectoer energy use.

Pursuing deep reductions in transportation GHGs may increasingly integrate efforts that today are distinct. Today, transportation goals emphasize safety and congestion mitigation, with energy use as a lesser priority. The U.S. Highway Trust Fund, as well as many state transportation funding mechanisms, depend on fuel usage, putting roadway infrastructure funding at odds with energy use reduction because fuel tax revenues are reduced when efficient and non-petroleum vehicles reduce petroleum fuel usage. In response, states have levied fees on electric drive vehicles, a disincentive for their market adoption. Aligning incentives between transportation, energy, and community-level quality-of-life goals with respect to low-emissions and high-efficiency transportation technologies, as well as connected and automated vehicles and VMT behaviors, could help meet both types of objectives.

The broad range of strategies for deep transportation-sector emissions reductions merits periodic assessment, and these assessments could be improved. Selection of metrics of interest could guide improvement of assessment of options, as could a clear definition of the risks that the portfolio is intended to mitigate, scenarios for timing and magnitude of investment, and further development of insights into the interactions among strategies. With improving resolution of these overall analytic framing issues, future work could develop further detail on pathways to deep reductions including:

- Chronicling the emerging understanding of effects of information technology, including vehicle connectivity and automation and VMT reduction such as the role of internet commerce and possible trade-offs between personal and freight transportation.
- Deepening the exploration of medium- and heavy-duty vehicle GHG emissions reduction opportunities in applications such as transit and class 8 truck operations along the lines of the previous issue as well as an acknowledgement of projections of significant growth in freight VMT.
- Deepening the analysis of issues around multiple fuel pathways and market adoption effects of access to enabling infrastructure for electric, hydrogen, and biofuel refueling.
- Developing pathway characteristics for alternative timing, vehicle, and infrastructure visions of a transportation system transformation to inform national, state, and local planning for future vehicle needs.
- Identifying various business models for providing mobility services and the impact that these shifts could have an impact on reducing greenhouse gas reductions.
- Exploring how transportation demand is influenced by changes in policy surrounding the built environment at the local, municipal, and planning area levels.
- Quantifying critical material resource levels needed to achieve and sustain a clean transportation sector.
- Extending life cycle emissions estimates in two ways: (1) exploring life cycle emissions changes in response to transportation system changes through scenario analysis; (2) exploring the opportunities for research and development to improve overall emissions from various fuels.
- Demonstrating and validating the potential of the transportation technologies described in this report to reduce GHG emissions. These demonstrations also could increase the understanding of opportunities and barriers to deploying these technologies.
- Identifying related opportunities for DOT, such as utilizing right-of-ways for renewable energy generation or biomass feedstocks. Research on biomass harvesting from right-of-ways could be cocrdinated through the existing Sun Grant Initiative between DOT, DOE, and the U.S. Department of Agriculture.

- Identifying and quantifying the impact of individual behavioral choices that can lead to a more energy efficient use of the various modes of our transportation infrastructure.
- Examining the impact of demographic shifts on technology adoption scenarios and associated energy impacts.

Such analysis could present and periodically update a detailed, quantitative vision of pathways to deep transportation-sector reductions in GHG emissions. This vision could inform national, state, and local strategies to transition to a cleaner and more effective future transportation system.

Conclusions

A low-emitting, low-petroleum U.S. transportation sector would likely need to use diverse strategies, systems, and technologies to reduce energy intensity, carbon intensity, and demand for transportation while preserving or improving transportation service. There is no single technology that can lead to dramatic reductions in emissions and petroleum use, but combinations of technologies and strategies have the potential to do so. DOT's CTSI has identified emerging and disruptive technologies and strategies with technical potential to reduce emissions and petroleum use by close to 100% by mid-century. This report is a step toward the CTSI goal of identifying and characterizing a wide range of transformative options to help reduce technological and economic risk to reaching emissions targets. These options—electric drive pathways, connectivity and automation, reduction in transportation demand, biofuel pathways, and vehicle efficiency improvements— and others may warrant further investigation. The CTSI scenario estimates an additional 15% CO_2 emissions reduction over TEF could be possible given recent developments in these areas. This report does not predict development of these options but estimates of their effects could be useful to envision and identify concrete steps to explore transformative change in transportation-sector GHG emissions. These developments are each likely to be disruptive, changing existing business models and creating economic opportunities and new business models.

Based on publications and industry experts, PEV battery cost reductions and diversification of makes and models have contributed to the increase in PEV availability during recent years. If these trends continue, then longer-term scenarios with higher PEV uptake (such as the scenario considered here) may be more likely.

Transportation connectivity and automation shows initial potential to transform transportation energy use. Connected and automated vehicle systems can directly improve efficiency and also may open certain markets to lower-emitting technologies and systems. These systems can also induce greater demand—by reducing costs of personal travel and freight transport, improving the driving experience, and facilitating travel by non-driving populations—so net effects are uncertain.

Demand for personal LDV travel is moderating after decades of growth; scenarios for declining VMT are more plausible, although pathways to lower demand for non-LDV transportation are less clear. Trends in lower-carbon fuels could also change the range of plausible future scenarios. Advanced biofuels are progressing and show promise in decreasing GHG emissions. Finally, vehicle efficiency could be radically improved through mechanical, electrical, and controls enhancements along with the use of lighter materials. The CTSI scenario estimates energy reductions but does not estimate corresponding life cycle GHG emissions reductions, and future work could complete this analysis.

These emerging trends are examples of the many options that could reduce GHG emissions. Each of these options faces significant challenges to deployment into the complex transportation system, and this report does not address all of these challenges, nor does it predict that they will be overcome. However, by focusing on emissions reductions beyond 80% by 2050, expanding the set of technological and social possibilities with a strong focus on the transportation sector, exploring recent developments in these options, and identifying potential next steps for periodic reassessment of options, this report offers a distinctive overview of transportation-sector options to mitigate climate change.

Appendix A. Electrified Roadways Overview and Case Study Methods and Results

Technologies for roadway electrification include charging options that are in-motion or stationary and that are conductive or inductive, with advantages and disadvantages for each in any given application. Conductive charging occurs through an electrical connection, while inductive charging occurs through a magnetic field that induces an electrical current. In-motion charging has the advantage of being possible during vehicle use and the disadvantage of requiring charging infrastructure over a larger length of roadway. Conductive, in-motion charging may be accomplished through a catenary or conductor rail system. Recent electrification and wireless power transfer projects include efforts by the Korea Advanced Institute of Science and Technology/Online Electric Vehicle (Rim 2014), Wireless Advanced Vehicle Electrification (Utah State), Bombardier/Primove ("World's First High Power Inductive Charging Station Launched" 2013), Qualcomm ("Qualcomm Halo Wireless Electric Vehicle Charging Trialled in London" 2014), Momentum Dynamics ("Momentum Dynamics" 2014), Volvo/Siemens, and DOE projects (Paulus 2014). Vehicle and service types include trams, transit buses, campus feeder buses, trolleys, corporate fleets, paratransit, and trucks. Road types include both limited-access and public urban streets in addition to parking locations.

Table A-1. Roadway Electrification Projects by Vehicle Service, Road, and Technology Type

Project Name	Vehicle/Service	Road	Technology
Korea Advanced Institute of Science and Technology/ Online Electric Vehicle	• Tram • Transit buses	• Controlled • Urban streets	Inductive Stationary and In-Motion
Wireless Advanced Vehicle Electrification/Utah State	• Campus feeder bus • Monterey, California, trolley • Long Beach transit bus	• Urban streets to campus • Urban streets • Urban streets	Inductive Stationary
Bombardier/Primove	• Transit bus	• Urban streets	Inductive Stationary
Qualcomm	• Corporate fleet demo • Drayson racing team	• Urban streets	Inductive Stationary
Momentum Dynamics	• BARTA paratransit	• Urban streets	Inductive Stationary
Volvo/Siemens	• Trucks	• Port-to-distribution center dedicated road	Conductive
DOE	• Oak Ridge National Laboratory /Toyota/GM • Hyundai/Mojo Mobility	• Limited access national laboratory roads	Inductive

An analysis of the electrical energy demand of electrified roadways highlights that the demand time period may coincide with renewable generation and thus lead to expanded capability to accommodate renewables in the electrical grid and reduction of the GHG impacts of transportation.

As an illustration of the roadway electrification opportunity and the potential interaction with renewable electricity, NREL performed a case study on roadway electrification in Colorado with scenarios for electrified roadway and renewable electricity development through 2050. Assumptions described a set of electrified roadways, vehicle trips, and drive cycles that were used to calculate electrified roadway and PEV plug-in charging loads in terms of an electricity demand to the electrical grid. The Regional Energy Deployment System model was used to develop a scenario of the types of electricity generating facilities available on the electrical grid. The PLEXOS model was used to determine how those electricity generation facilities would be used to meet electrical load, with various assumptions about the timing of plug-in charging and electrified roadway demand.

Total transportation energy demand of a light-duty vehicle fleet was reduced in electrified vehicle scenarios due to increased use of PEVs, which are highly efficient because of the inherent efficiency advantages of electric motors. Transportation energy demand was transferred to the electric sector from liquid fuels, such that at most there was a 10% increase in annual electric generation in roadway electrification scenarios relative to baseline.

Impacts of this increased generation on the electrical grid included cost, emissions, and renewable electricity integration.

Summarizing findings from the case study, electrification of roadways could increase the total amount of electric demand and would change the dispatch of electricity when compared to stationary charging at residential, work, or public locations. Overall, the results show that in Colorado, there could be greater potential for renewable energy use with roadway electrification because of the increased load and shift in the timing for electricity demand to coincide more with renewable energy generation.

Table A-2. Summary of Roadway Electrification Scenarios Considered in Case Study

Vehicle Population	On-road Charging	Opportunity Charging	Delayed TOU Charging	Comments
#1 2050 Baseline – no EVs	n/a	n/a	n/a	Provides baseline grid conditions
#2 2050 50% EVs w/ opportunity charging	n/a	Yes	No	Provides baseline grid impacts of 50% evs with no e-roadway
#3 2050 50% EVs w/ time of use charging	n/a	No	Yes	Provides baseline grid impacts of 50% EVs with no e-roadway and only evening charging
#4 – 30% eRW HEVs at ~30% (ADOPT Forecast)	Yes	n/a	n/a	E-roadway Scenario based on ADOPT market modeling
#5 - 50% eRW EVs w/ opportunity charging	Yes	Yes	No	Adds e-roadway and is comparable to #2
#6 50% eRW EVs w/ TOU charging	Yes	No	Yes	Adds e-roadway and is comparable to #3
#7 - 50% eRW HEVs	Yes	n/a	n/a	Similar to #3 with higher adoption rate and comparable to #5 and #6 for EV vs HEV
#8 - 100% 50% eRW HEVs 50% eRW EVs w/ opportunity charging	Yes	Yes	No	100% of light duty vehicles using system; combines #5 and #7
#9 - 100% 50% eRW HEVs 50% eRW EVs w/ TOU charging	Yes	No	Yes	100% of light duty vehicles using system; combines #6 and #7

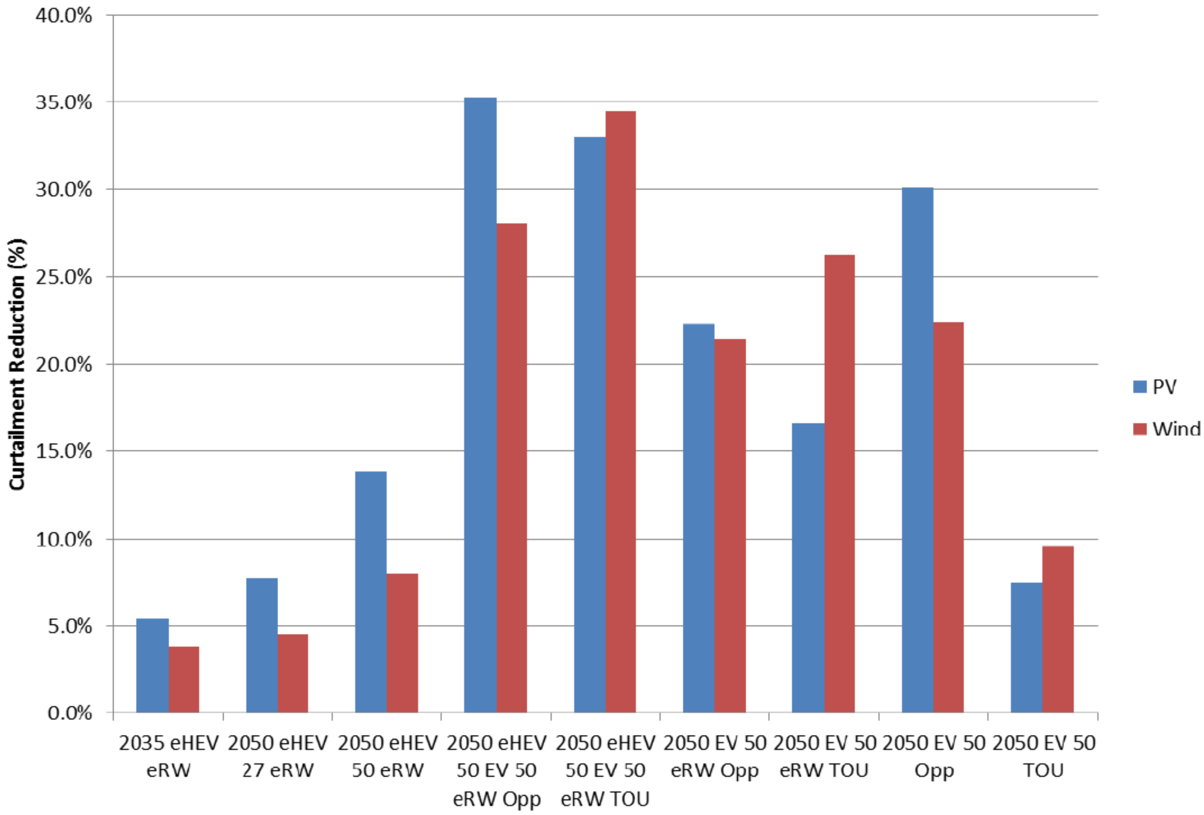

Figure A-1. Reduction in curtailment of renewable electricity in case study scenarios

In high renewable penetration scenarios, curtailment of renewable generation occurs seasonally when load is low and renewable generation is high. Electrified roadway scenarios move some of the load that would have occurred in the evening to the daytime periods and thus offers new load that can utilize the excess renewable generation. Figure A-1 summarizes the amounts of curtailed renewables that are reduced on an annual basis. The labels Opp for opportunity charging and TOU for time-of-use managed charging represent different scenario assumptions about the other ways besides electrified roadway (eRW) for charging vehicles. The two middle cases include 50% HEVs and 50% EVs, which can use the electrified roadway infrastructure and provide the most benefit in reducing renewable curtailment.

Electrified roadways offer an opportunity to power more mobility miles with electricity, without the need for large batteries and long recharge times. The costs and integration of infrastructure to support such a long-term system require significant engineering analysis and optimization. The electrified roadway technology is a potential contributor to the long-term DOT vision of a clean transportation sector that can enhance the utilization of renewables for transportation energy demands.

Appendix B. Clean Transportation Sector Initiative Scenario Methods

The CTSI Scenario uses a simple, spreadsheet-based tool called BITES (Buildings, Industrial, Transportation, and Electricity Scenarios) tool to estimate the combined effect of multiple changes in the energy system. The BITES tool uses a calculator framework to collect approximately 500 inputs, more than 100 of which are in the transportation sector. BITES produces outputs such as the energy use by type and emissions, for each sector. This methodology offers transparency, speed, and flexibility to the analysis of technology impacts.

BITES has been developed and updated over 5 years for use in rapid analysis, or to combine the results of sector-specific analyses.

BITES is not:

- A 'whole economy modeling tool,' which would require longer run times and additional uncertainty in assumptions, would be less transparent and would involve additional complexity associated with economic externalities.
- A simple compilation of individual technology impacts, which would lead to double counting of benefits.

BITES is:

- A method to combine diverse, specific impact estimates from different DOE or DOT programs into a coherent strategy across all program areas.
- A nuanced calculator tool that captures interactions between sectors/inputs and models projected outcomes by taking these relationships into account.
- *For example: Efficiency measures that reduce electric demand also reduce electricity generation required and BITES automatically adjusts the generation totals to match.*

A version of BITES based on the AEO 2011 baseline is available for public and educational use at: bites.nrel.gov.

Table B-1 includes the full set inputs to the CTSI scenario. Note that the outputs in the online version may not match those reported here due to the difference in baselines. A version of the spreadsheet tool with the TEF and CTSI scenarios will be made available with this publication. Inputs outside the transportation sector were not evaluated in this project but left unchanged from the TEF scenario. Green cells were updated from TEF.

Table B-1. Complete Inputs to CTSI Scenario in BITES

	CTSI			
Generation Mix	2030	2050	Legacy	Min CF
Existing Pulverized Coal	39.50%	22.72%	63	40%
Other Fossil Steam	0.22%	0.02%	30	2%
Nuclear Gen II	22.08%	1.94%	80	80%
Existing Pulverized Coal CCS retrofit	0.00%	0.00%	60	40%
New Coal	0.00%	0.00%	60	40%
New Coal w/ CCS	0.00%	0.00%	60	40%
NGCC	14.70%	9.31%	30	28%
NGCC w/ CCS	0.00%	0.00%	60	20%
NGCT	1.08%	0.67%	28	2%
Nuclear Gen III	0.00%	0.00%	60	80%
Small Modular Reactors	0.00%	0.00%	60	80%
High Temperature Gas Reactors	0.00%	0.00%	60	80%
Conventional Hydropower	6.73%	5.44%	80	20%
Small Hydropower	0.56%	4.26%	60	20%
Municipal Solid Waste	0.31%	0.25%	60	40%
Biopower	0.89%	1.18%	60	40%
Conventional Geothermal	1.62%	5.03%	60	40%
Unconventional Geothermal	0.00%	0.20%	60	40%
Onshore wind	4.58%	5.55%	20	10%
Offshore wind	6.27%	8.87%	20	10%
Solar Thermal without Storage	0.00%	0.00%	60	10%
Solar Thermal with Storage	0.14%	1.16%	60	10%
Utility Photovoltaic	3.40%	8.55%	30	10%
Water Power	0.00%	0.00%	20	10%
Total	102.10%	75.15%		
Distributed PV	4.80%	6.60%		
Coal Retirement Schedule		1	"0 = AEO 1 = ReEDS 2 = Lifetime	
AEO Demand	1		"0 = Low Growth, 1 = Reference Growth"	

Industry		
% Reduction from BAU Total Energy Use	2030	2050
Refining	22%	6%
Food	10%	3%
Paper	19%	6%
Bulk Chemical	21%	7%
Glass	24%	7%
Cement	24%	8%
Iron and Steel	16%	6%
Aluminum	22%	9%
Metal Based Durables	10%	3%
Other Manufacturing	10%	3%
Nonmanufacturing	10%	4%

Fuel Mix

Refining	2030	2050
Ethanol Plants		
Natural Gas	NA	NA
Steam Coal	NA	NA
Purchased Electricity	NA	NA
Biofuels Heat and Coproducts	NA	NA
Total Ethanol	0%	0%
Oil and Gas Plants		
Residual Fuel Oil	0%	0%
Distillate Fuel Oil	0%	0%
Liquefied Petroleum Gases	1%	1%
Petroleum Coke	15%	15%
Still Gas	44%	44%
Other Petroleum	1%	1%
Petroleum Subtotal	61%	61%
Natural Gas	25%	25%
Steam Coal	11%	11%
Renewables	0%	0%
Purchased Electricity	3%	3%
Total Oil and Gas	100%	100%

Food	2030	2050
Residual Fuel Oil	0%	0%
Distillate Fuel Oil	1%	1%
Liquefied Petroleum Gases	0%	0%
Other Petroleum	0%	0%
Petroleum Subtotal	1%	1%

Natural Gas	50%	54%
Steam Coal	11%	10%
Renewables	11%	8%
Purchased Electricity	27%	26%
Total	100%	100%
Paper	2030	2050
Residual Fuel Oil	1%	3%
Distillate Fuel Oil	0%	0%
Liquefied Petroleum Gases	0%	0%
Petroleum Coke	0%	0%
Other Petroleum	0%	0%
Petroleum Subtotal	2%	4%
Natural Gas	20%	19%
Steam Coal	11%	10%
Renewables	53%	57%
Purchased Electricity	15%	10%
Total	100%	100%
Bulk Chemical	2030	2050
Heat and Power		
Residual Fuel Oil	1%	2%
Distillate Fuel Oil	0%	0%
Liquefied Petroleum Gases	1%	2%
Petroleum Coke	0%	0%
Other Petroleum	6%	6%
Petroleum Subtotal	7%	10%
Natural Gas	52%	66%
Steam Coal	5%	5%
Renewables	0%	0%
Purchased Electricity	35%	19%
Total Heat and Power	100%	100%
Feedstock		
Liquefied Petroleum Gas Feedstocks	40%	57%
Petrochemical Feedstocks	24%	22%
Natural Gas Feedstocks	18%	15%
Biofuel Feedstock	18%	6%
Total Feedstocks	100%	100%
Glass	2030	2050
Residual Fuel Oil	0%	1%

Distillate Fuel Oil	3%	7%
Liquefied Petroleum Gases	0%	0%
Petroleum Subtotal	4%	8%
Natural Gas	65%	68%
Steam Coal	0%	0%
Renewables	0%	0%
Purchased Electricity	32%	24%
Total	100%	100%

Cement	2030	2050
Residual Fuel Oil	0%	0%
Distillate Fuel Oil	1%	2%
Petroleum Coke	11%	12%
Other Petroleum	3%	7%
Petroleum Subtotal	16%	22%
Natural Gas	8%	7%
Steam Coal	56%	56%
Metallurgical Coal	1%	2%
Coal Subtotal	56%	58%
Renewables	0%	0%
Purchased Electricity	20%	14%
Total	100%	100%

Iron and Steel	2030	2050
Distillate Fuel Oil	0%	0%
Residual Fuel Oil	0%	0%
Other Petroleum	1%	1%
Petroleum Subtotal	1%	2%
Natural Gas	24%	29%
Metallurgical Coal	42%	42%
Net Coke Imports	0%	0%
Steam Coal	5%	5%
Coal Subtotal	48%	48%
Renewables	2%	2%
Purchased Electricity	25%	19%
Total	100%	100%

Aluminum	2030	2050
Residual Fuel Oil	0%	0%
Distillate Fuel Oil	0%	0%
Liquefied Petroleum Gases	0%	0%
Petroleum Coke	7%	7%
Other Petroleum	0%	0%

	2030	2050
Petroleum Subtotal	7%	7%
Natural Gas	31%	31%
Steam Coal	7%	16%
Renewables	8%	6%
Purchased Electricity	46%	39%
Total	100%	100%

Metal Based Durables	2030	2050
Liquefied Petroleum Gases	0%	0%
Distillate Fuel Oil	0%	0%
Residual Fuel Oil	0%	0%
Petroleum Coke	2%	4%
Petroleum Subtotal	2%	5%
Natural Gas	40%	39%
Metallurgical Coal	0%	0%
Steam Coal	1%	1%
Renewables	0%	0%
Purchased Electricity	57%	54%
Total	100%	100%

Other Manufacturing	2030	2050
Liquefied Petroleum Gases	0%	1%
Distillate Fuel Oil	1%	1%
Residual Fuel Oil	0%	0%
Petroleum Coke	0%	0%
Other Petroleum	0%	0%
Petroleum Subtotal	1%	2%
Natural Gas	34%	33%
Steam Coal	5%	5%
Metallurgical Coal	0%	0%
Renewables	17%	14%
Purchased Electricity	43%	47%
Total	100%	100%

Nonmanufacturing	2030	2050
Residual Fuel Oil	0%	0%
Distillate Fuel Oil	17%	20%
Liquefied Petroleum Gases	1%	2%
Motor Gasoline	3%	6%
Other Petroleum	0%	0%
Asphalt and Road Oil	20%	20%
Petroleum Subtotal	41%	47%

Natural Gas	15%	14%
Lease and Plant Fuel (NG)	25%	24%
Steam Coal	0%	0%
Renewables	9%	4%
Purchased Electricity	10%	11%
Total	100%	100%
Build-ings		
Residential		
Building Codes	Low Building Code	High Building Code
Start Date	2019	2022
% Energy Use Reduction	30%	65%
Compliance	81%	81%
Cooling % of Heating Retrofit	80%	80%
Retrofits	Low Shell Retrofits	High Shell Retrofits
% Retrofits in 2030	19%	6%
% Retrofits in 2050	66%	18%
Efficiency Improvement of Retrofits	33%	45%
Cooling % of Heating Retrofit	80%	80%
Fuel Switching - % Electric	2030	2050
Space Heating	0%	0%
Water Heating	0%	0%
Cooking	0%	0%
Fuel Switching Efficiency (Gas Used/Site Electric Used)		
Space Heating	2.50	
Water Heating	1.10	
Cooking	1.10	

Efficiency Improvement	2030 % Penetration	2030 % Energy Use Reduction	2050 % Penetration	2050 % Energy Use Reduction
Heating and Cooling Equipment				
Space Heating Equipment	100%	9%	100%	16%
Space Cooling Equipment	100%	14%	100%	58%
Appliances				
Water Heating	100%	25%	100%	46%
Refrigeration	100%	10%	100%	67%
Cooking	100%	3%	100%	7%
Clothes Dryers	100%	24%	100%	77%
Freezers	100%	3%	100%	7%
Lighting	100%	77%	100%	90%
Clothes Washers	100%	24%	100%	77%
Dishwashers	100%	24%	100%	77%
Color Televisions and Set-Top Boxes	100%	19%	100%	27%
Personal Computers and Related Equipment	100%	19%	100%	27%
Furnace Fans and Boiler Circulation Pumps	100%	46%	100%	67%
Other Uses	100%	19%	100%	27%

Commercial

Building Codes	Low Building Code	High Building Code
Start Date	2019	2023
% Energy Use Reduction	30%	65%
Compliance	81%	81%
Cooling % of Heating Retrofit	80%	80%

Retrofits	Low Shell Retrofits	High Shell Retrofits
% Retrofits in 2030	74%	26%
% Retrofits in 2050	0%	100%

Efficiency Improvement of Retrofits	20%	42%
Cooling % of Heating Retrofit	80%	80%

Fuel Switching - % Electric	2030	2050
Space Heating	0%	0%
Water Heating	0%	0%
Cooking	0%	0%

Fuel Switching Efficiency (Gas Used/Site Electric Used)	
Space Heating	2.50
Water Heating	1.10
Cooking	1.10

Efficiency Improvement

	2030 % Penetration	2030 % Energy Use Reduction	2050 % Penetration	2050 % Energy Use Reduction
Heating and Cooling Equipment				
Space Heating Equipment	100%	6%	100%	9%
Space Cooling Equipment	100%	29%	100%	90%
Appliances				
Water Heating	100%	21%	100%	52%
Ventilation	100%	23%	100%	33%
Cooking	100%	0%	100%	0%
Lighting	100%	54%	100%	90%
Refrigeration	100%	4%	100%	5%
Office Equipment (PC)	100%	13%	100%	15%
Office Equipment (non-PC)	100%	13%	100%	15%
Other Uses	100%	13%	100%	15%

Transportation

LDV Stock (%)	2030	2050	Intro. Year
ICE Cars	33%	6%	
ICE Light Trucks	20%	2%	
HEV Cars	6%	2%	
HEV Light Trucks	5%	5%	
PHEV Cars	16%	21%	2015
PHEV Light Trucks	8%	14%	2016
EV Cars	3%	18%	2020
EV Trucks	1%	5%	2021
Fuel Cell Cars	6%	20%	2020
Fuel Cell Light Trucks	2%	7%	2020
Diesel Cars	0%	0%	
Diesel Light Trucks	0%	0%	
Total	100%	100%	
Fraction of Car	64%	67%	
Fraction of Light Trucks	36%	33%	
Total Light Duty Vehicles	262,431,641	304,904,738	

Efficiency Factor (over 2010 ICE MPG efficiency)	2030	2050
ICE Cars	2.00	4.20
ICE Light Trucks	1.50	3.20
HEV Cars	3.00	7.00
HEV Light Trucks	2.20	4.80
PHEV Cars	4.10	6.80
PHEV Light Trucks	2.40	4.60
Fuel Cell Cars	5.30	7.00
Fuel Cell Light Trucks	4.00	4.40
Diesel Cars	1.80	3.80
Diesel Light Trucks	1.50	3.20

	2030	2050	
LDV VMT fraction	0.99	0.89	12% in 2030, 18% in 2050

	2030	2050	
Eco-driving	5%	40%	5% is top of range

PHEV	2010	2030	2050
Percent of PHEV Drive on Electric	45%	45%	45%
Miles per kWh for PHEV & EV	2.8	3.2	3.5

Biofuels (billion gallons)	2030	2050	Intro. Year
Corn Ethanol	12.3	18.3	
Cellulosic Ethanol	3.3	8.6	2010
3rd Generation Biofuels	26.5	72.4	2010
Algae (Doesn't Consume Biomass)	0	17.6	2015
Coal and Biomass to Liquids	0	0	2013
Biomass CCS (1=Yes; 0=No)	0		
Mode Switching			
Rail	2030	2050	
% HT Switched to Rail-Freight	8%	10%	
% Air Switched to Rail-Pass	0%	0%	
Efficiency Improvements			
Commercial Light Trucks	2030	2050	
Fraction Advanced	25%	100%	
Efficiency Improvement	30%	50%	
Heavy Trucks	2030	2050	
Fraction Advanced	25%	80%	
Efficiency Improvement	30%	60%	
Aircraft	2030	2050	
Efficiency Improvement	20%	55%	
Fraction Biofueled	25%	50%	
Ships	2030	2050	
Efficiency Improvement	8%	23%	
Rail	2030	2050	
Freight-Efficiency Improvement	10%	28%	
Passenger-Efficiency Improvement	0%	0%	
Military Use	2030	2050	

	Efficiency Improvement	0%	0%	
	Pipeline Use	2030	2050	
	Efficiency Improvement	8%	15%	
Hydrogen Fuel Sources (%)		2030	2050	Intro. Year
	SMR	97%	59%	
	Coal (CCS)	0%	0%	2028
	Biomass (CCS)	2%	22%	2033
	Electrolysis	1%	19%	2033
	Total	100%	100%	
		2010	2030	2050
	Electricity for H2 Production (kWh/gge)	52	49	42.3
CHP				
On/Off Switch	CHP On/Off (1=On; 0=Off)	0		
Total CHP		2030	2050	
	Total CHP Capacity (MW)	#REF!	#REF!	
Generation Mix	**Industry**	2030	2050	
	Natural Gas	55%	60%	
	Coal	10%	5%	
	Petroleum	10%	5%	
	Biomass (Bl. Liq, Wood, Biogas & Biomass)	15%	15%	
	Other	0%	0%	
	Fuel Cell	10%	15%	
	Total	100%	100%	
	Commercial	2030	2050	
	Natural Gas	65%	55%	
	Coal	0%	0%	
	Petroleum	0%	0%	
	Biomass (Bl. Liq, Wood, Biogas & Biomass)	25%	30%	
	Other	0%	0%	

	2030	2050
Fuel Cell	10%	15%
Total	100%	100%
Electric Utility	2030	2050
Natural Gas	100%	100%
Coal	0%	0%
Petroleum	0%	0%
Biomass (Bl. Liq, Wood, Biogas & Biomass)	0%	0%
Other	0%	0%
Fuel Cell	0%	0%
Total	100%	100%
Displaced Boiler Efficiency	2030	2050
Displaced Boiler Efficiency	85%	90%

Appendix C. Clean Transportation Sector Initiative Workshop and Teleconference Summary

Clean Transportation Sector Initiative Workshop
February 5–6, 2014

A Review

Please note: The executive summary and subsequent review in this document are intended to provide an accurate account of the comments made by workshop presenters, panelists, and audience members. The comments contained in this document do not necessarily represent the views of OST-R, DOT, NREL, or DOE. *Comments made during panel and audience discussions are italicized.*

Please see http://www.rita.dot.gov/rdt/ for CTSI workshop presentations.

Introduction

On February 5 and 6, 2014, the U.S. Department of Transportation (DOT) Office of the Assistant Secretary for Research and Technology (OST-R) and the National Renewable Energy Laboratory (NREL) hosted the Clean Transportation Sector Initiative (CTSI) workshop at DOT headquarters in Washington, D.C. The purpose of the workshop was to have stakeholder feedback in assisting the CTSI team in identifying the scope of effective research, development, and deployment strategies that can help the nation achieve a reduction between 80% and 100% greenhouse gas (GHG) emissions in the surface transportation sector by mid-century. Input from the workshop participants has been compiled in this document in an executive summary and thorough review of presentations and comments organized by the chronology of the workshop agenda. Presentations from the workshop will be made available online at http://www.rita.dot.gov/rdt/.

Workshop participants represented a variety of organizations within the federal government, industry, academia, and clean technology media. Additionally, The Energy Gang Podcast with Stephen Lacey (Greentech Media), Katherine Hamilton (38 North Solutions), and Jigar Shah (Inerjys) was hosted by DOT after the conclusion of the workshop with special guests Greg Winfree (OST-T) and Austin Brown (NREL). A summary of the podcast is listed after the workshop review, as is the workshop agenda.

While the executive summary and review provided in this document are intended as a thorough account for workshop participants, they do not necessarily represent the views of OST-R, DOT, NREL, or DOE.

Executive Summary

In the endeavor to create a blueprint for how we can achieve a zero to near-zero GHG emissions transportation sector by mid-century, we need to challenge ourselves as to whether we are going far enough with our research to find the answers. The potential transformative benefits of succeeding as well as the potential disastrous consequences of failing are justification for doing so. In meeting this challenge we should keep in mind the potential wealth generation in leading clean technology research and deployment, in a society being unburdened by an overbearing fuel market, and in a healthier and safer public. Whether we are optimistic or pessimistic on the odds of success does not matter—occurring and projected climate impacts are forcing the issue, so we must find a way to respond effectively to ensure successful achievement of the goal.

Along the way, we will need to consider whether we have fully explored key data that can affect a range of projections, whether we are finding new ways to account for a fast changing industry and society in our models, and whether we are really providing the full picture of what could be. The Secretary and the President are committed to moving forward with efforts like CTSI in order to enhance the lives of all Americans for generations to come.

The U.S. portion of global transportation emissions is relatively small, so a sharp reduction of transportation and upstream emissions would result in 0.1° Celsius by 2100. Although this sounds like a small amount, it is actually 87% of the impact of all current U.S. carbon dioxide (CO_2) emissions during that time period. This would be a major step forward in avoiding greater than 2° Celsius warming, above which more catastrophic climate impacts are projected to occur. The impact of global zero-emissions transportation has been estimated to be a reduction of 1° Celsius, indicating the importance of the aggregate of such measures from all regions of the world. A co-benefit to reducing transportation emissions is a substantial improvement in air quality, which would help avoid 5,000 deaths per year by 2030.

One of the aspects that should be considered in transitioning to a clean transportation sector is the need to thoroughly investigate the demand characteristics of transportation users. For example, do they live in an apartment without access to garage-style charging? Furthermore, we should make sure that we are considering the demand characteristics of groups like millennials who have been found to be 16 times less likely to buy a car than baby boomers. Because of the diversity of demand characteristics of transportation users, we should make sure that any endeavor to achieve a clean transportation sector not be at odds with people who are already reducing emissions through walking, riding bicycles, and taking transit.

Recent improvements in battery cost, improvements in electric vehicle (EV) driving behaviors, and increasing clean transportation options, as well as other factors, indicate a more reasonable likelihood of attaining significant emissions reduction than were accounted for in past studies. Additionally, while vehicle miles traveled (VMT) projections typically show ever-increasing growth, actual VMT has been on the decline. Also, remarkable statistics for solar, wind, and EV technologies underlie a rapidly changing environment for clean energy and mobility. These factors may be further cause for revised or additional scenarios.

Roadway electrification has the potential to increase the operable range and overall utility of any vehicle with a battery that can be charged from the road. Such systems can be integrated with renewable energy resources and smart-grid operations for even lower emissions potential. This type of mobile charging can allow for smaller batteries in EVs or can provide larger-capacity batteries an extra boost to travel longer distances seamlessly as normally associated with quicker fueling internal combustion engine (ICE) vehicles. Also, roadway electrification has the ability for relatively small portions of roadway to service large numbers of vehicles as follows:

- Electrifying 1% of U.S. interstate highways would cover 17% of traveling road vehicles.
- Electrifying 5% of U.S. interstate highways would cover 40% of traveling road vehicles.
- Electrifying 25% of U.S. interstate highways would cover 80% of traveling road vehicles.

The costs of not addressing climate change justify an effort to achieve zero GHG emissions transportation by mid-century. Strategies used should not be limited to what current model confidence and marketing tells us—we should act now with the long-term outcome in mind. It is not likely that petroleum or biofuels pathways will get us to a near-zero emissions transportation sector by mid-century. Additionally, there are major non-climate concerns with the use of these fuels, such as the large amount of water required to make biofuels.

Due to end-use attributes, the large-scale deployment of wind, water, and solar (WWS) energy can power the world with less than 12 terawatts (compared to the 17 terawatts that power the world with the current energy mix). Developing and long-term economics also point to a transportation sector powered by WWS energy as being a prudent pathway. Already, solar and wind are reaching a point where they will soon be less costly than fossil fuels, with the latter being $0.08/kWh more in 2030 than the cost of renewable energy. Placing an emphasis on urban traffic designs that optimize buses, smaller EVs, bicyclists, and pedestrians can make even more efficient use out of clean energy used for transportation.

The costs of oil and legacy electricity services have risen substantially the past decade. This situation will only be exacerbated as their associated natural resources become more difficult to cost-effectively obtain. Nationally, we pay $600 billion more per year for oil and $200 billion more per year for electricity than we did in 1999. The average cost for automobile travel per month is roughly $800, while the same metric is just $300 for car sharing and $200 for transit. Even when driving an automobile, you cannot beat the price of electricity. As an example, the lowest priced fossil fuel (natural gas) is $1.90/gge while the average price for electricity is $1.20/gge. Furthermore, EVs powered by conventional energy (e.g., electricity from coal and natural gas) have less impact on the climate when compared to the impact of efficient ICE vehicles. As we transition to a cleaner power sector, the gap between EVs and ICEs will widen in terms of cost and climate impact.

By embracing a new approach to power and transportation energy usage, we can unlock a new $10 trillion economy over the next decade. However, transportation has the toughest pathway ahead for implementing better GHG emissions reduction strategies. Thankfully, the business context for a transition to a clean transportation sector is promising. Continuous technology innovation means that the business case for reducing GHG emissions is only held up by a lack of effective business models and financial innovation. This is all even more important considering that if we continue to operate the sector in a "business-as-usual" manner, we will need $0.40 tax on the gas dollar to maintain it. By shifting to clean technologies on a large scale, we can largely avoid this additional cost to society.

Social, economic, and technological disruptions will have key impacts on the timeline for achieving a clean transportation sector. One effort to both introduce and measure such disruptions is DOT's Applications for the Environment: Real-Time Information Synthesis (AERIS) program, which is modeling the environmental potential of connected vehicles, infrastructure, and people. By introducing a system with integrated eco-signals, eco-lanes, cooperative adaptive cruise control, and other features, emissions reduction can be an endemic facet of a transportation system that multiplies the impact of new technologies, business model innovation, and societal changes. Agencies representing other economic sectors (e.g., power, industry) can take an approach to disruptive technologies similar to that of AERIS for the integration of a unified energy asset across sectors.

Looking at current disruptions in transportation, there are some that need to be undertaken wisely. New smartphone applications used in the traditional realm of taxi and limousine services are providing a necessary wake-up call to what is perhaps an inflexible industry, as well as raising concerns over the need to regulate such services to protect the public from potential excess cost and safety problems. If regulated properly for a good balance between innovation and protection of the public, these types of technologies could drive unrealized efficiencies in the transportation system and also provide researchers with larger and more refined data sets for robust analyses.

We are faced with answering the question of what strategies can help us move beyond current scenario projections that still have us falling short of achieving near-zero GHG emissions by mid-century. There is the potential of conventional ICE vehicles to undergo transformative change enough that they could even outcompete EVs in reducing emissions and operating costs. However, these approaches will require radical engineering of ICE design to be marketable. Additionally, because CAFE standards do not get us beyond 80% GHG emissions reduction, we will need more energy options for vehicles.

In addition to vehicle improvements, vehicle automation can help us achieve deeper emissions reduction. While there is great promise in this area, research on overall benefits is nascent with the need to be wary of potential impacts, such as induced demand. We also need to explore the changing understanding of VMT. While it was initially assumed that the recent years of declining VMT was due to the economy, VMT continues to decline even after economic recovery. We need to revise our scenarios to account for a broader range of VMT scenarios—particularly because our current scenarios only show growth in contrast to recent data.

The optimal management of critical materials will play a key role in achieving and sustaining a clean transportation sector. The U.S. Department of Energy (DOE) has stressed three management strategies in particular—diversifying the supply chain, developing substitutes, and reusing and recycling. Already, we have seen market disruptions caused by critical materials with dysprosium oxide having a recent 25-fold increase in price and then declining over a 2-year period. Some materials like lithium are less of a concern, though the large-scale transition of the transportation fleet necessary for a clean transportation sector could change this. While some strategies such as magnet-free wind turbines and reduced use of rare earth metals in vehicle motors are a good step forward, issues such as geopolitical control of materials, lag times associated with new mining efforts, and the difficulty with recycling certain critical materials are factors transportation planners and decision makers will need to consider.

Review of Presentations and Comments During the CTSI 2-Day Workshop

Day 1, February 5

Greeting and Challenge From the Department of Transportation

Deputy Assistant for Transportation Policy Beth Osborne spoke of the need for the workshop participants to consider demand characteristics of residents in urban settings. Beth posed the following questions:

- How do you sell an EV to people who do not have a garage or live in an apartment?
- How do we deploy charging technology in hard to reach places like back alleys?
- How do I make sure my neighbor does not use my charger?
- Are we addressing boomers moving back to the city? Are we considering enough millennials who increasingly have a different perspective on vehicle ownership with a proclivity toward wireless devices, virtual travel, and automated travel rather than driving a car?

For context, Ms. Osborne noted research that indicates that boomers are 16 times more likely to buy a car than millennials are. She also pointed to the need to take on this endeavor without being at odds with people walking, riding bicycles, and taking transit.

Potential Considerations for CTSI Report, Research Areas/Questions, and Comments

Report Consideration/Research Question: How and to what degree can matching charging infrastructure with more walkable and diverse-living areas increase deployment rates of cleaner vehicles and infrastructure?

Comment: Conductive and inductive charging could be integrated into street parking. Building codes could be revised to include consideration of vehicle charging access in apartment buildings, condominiums, and other living areas that do not always offer areas for private charging of an EV.

Transportation Emissions Reduction and Climate and Air Quality Response

Dr. Drew Shindell of NASA provided a presentation on the impact of a zero-emissions (i.e., GHGs and warming aerosols) transportation sector by mid-century on climate model projections and air quality indicators. The U.S. portion of global transportation emissions is relatively small, so a reduction of 0.1° Celsius by 2100 was projected as the impact of such a change. Although this sounds like a small amount, it is actually 87% of the impact of all current U.S. CO_2 emissions and would be a major step forward in avoiding greater than 2° Celsius warming, above which more catastrophic climate impacts are projected to occur. Furthermore, the impact of global zero-emissions transportation was estimated to be a reduction of 1° Celsius, indicating the importance of the aggregate of such measures from all regions of the world. While these figures are not published, these analyses were used for a reasonable discussion on the climate impacts of a clean transportation sector.

Dr. Shindell stressed the importance that the major impacts of significant transportation emissions reduction depend on whether we are considering the short term or long term. In the short term—within a decade or two—the most significant impacts are those of improved air quality, with 5,000 deaths avoided per year in 2030. In the long term—mid-century and beyond—the most significant impacts are those related to climate change with the realization of global cooling and associated other impact improvements being realized in that timeframe. The main takeaway from this portion of the presentation was that achieving a clean transportation sector by mid-century is a win-win scenario in terms of localized air quality and climate change impacts. Additionally, the speaker suggested that these impacts need to be better accounted for when weighing the costs and benefits of moving to a clean transportation sector by mid-century.

Potential Considerations for CTSI Report, Research Areas/Questions, and Comments

Question: What cost-savings in terms of air quality and climate change impacts can a clean transportation sector by mid-century generate for the United States? How and to what degree would this incentivize an increased deployment rate of cleaner vehicles and infrastructure?

Comment: A vehicle powered by fossil-fuel-based electricity (e.g., coal, natural gas) is less damaging to the climate than a vehicle powered directly by liquid fossil fuels (i.e., an ICE-propelled vehicle). With the power sector becoming cleaner each year, this difference between non-ICE and ICE vehicles will become even more apparent.

Comment: By 2100, the power sector (if unchanged) will be the number-one source of warming in climate models. However, transportation (if unchanged) will also have a large impact on climate models at more than one-third of the impact of the power sector.

Comment: Significant worldwide reductions of transportation GHGs and warming aerosols are unlikely to occur without significant U.S. reductions, so the seemingly low percentage of climate impacts are actually key to much larger reductions globally.

Fuel Pathways Overview

Austin Brown of the National Renewable Energy Laboratory (NREL) gave an overview of the Transportation Energy Futures (TEF) study, which was a large part of what brought the DOT/DOE CTSI into being. Brown noted that while the initial scenario of reducing energy usage by 80% in 2050 was considered somewhat of a reach at the start of TEF, it has become a more reasonable scenario with the new CTSI "reach" goal of achieving 80%–100% emissions reduction.

Brown compared several previous analyses (including TEF) that looked at what were considered optimal projections for emissions reduction in the on-road transportation fleet. He noted that since these studies were published, *in situ* improvements in battery cost, EV driving behaviors, increasing clean options, and other factors appear to be indicators of more reasonable attainment of significant emissions reduction than were accounted for in the past studies.

In addition to the *in situ* improvements in non-ICE vehicles in the past couple of years, Brown suggested that continued improvements in non-ICE *and* ICE vehicles will lead to even more optimistic scenarios for the sector's long term. Additionally, it was noted that while VMT projections show ever-increasing growth, actual VMT has been on the decline. This decline in

VMT was initially thought to have been due to an economic downturn, but VMT has not been on the upturn with the rebound of the economy. These factors could be further cause for scenario revisions.

Brown discussed the potential impact of regional policy/regulation regimes (e.g., California 20-15-2025 zero-emissions vehicle [ZEV] and plug-in hybrid electric vehicle [PHEV] requirements, or conversely, taxes on ZEVs and PHEVs in other states). He also discussed media reports of poor EV sales and argued that they have actually been rather good from a historical perspective of new automotive technology introductions. Brown underscored the following factors that can affect the rate of deployment of cleaner vehicles:

- Technology turnover rate
- Policy uncertainty
- Infrastructure business models
- Different vehicle characteristic requirements.

Brown concluded his presentation with the encouraging results of the DOE white paper "Revolution Now." Remarkable statistics in solar, wind, and EV technologies underlined a rapidly changing environment in clean energy and mobility. Of note in this report, battery costs for EVs have dropped 70% since 2008 and continue to decline.

Potential Considerations for CTSI Report, Research Areas/Questions, and Comments

Question: What would a matrix of the best EV policies across the country look like in the form of a unified strategy for deployment? What would be the impact on scenario projections for a clean transportation sector by mid-century?

Comment/Question: The reference for optimal EV battery costs by 2020 is now $300/kWh. Anecdotal evidence suggests that some manufacturers may have already achieved below $200/kWh. What are the potential impacts of in situ variables exceeding optimal projection of variables in models?

Comment: While automotive technologies have historically taken a long time to deploy at the sector level, much of this record occurred before the widespread use of micro-processors, making rapid change difficult prior to the 1980s. This led to further discussion that while it is a false analogy to compare advances in automotive technology to Moore's Law, there are some similarities as we enter new design and manufacturing parameters thanks to enhanced engineering relative to decades past.

Fuel Pathways Breakout

Following Brown's presentation on fuel pathways, a breakout session was held on the same topic with the following questions to begin the discussion:

- Which fuel pathways or combinations of pathways would be most transformative to transportation sector emissions reduction over the next 40 years?

- What federal and other actions are most important to these transformations? For example, what strategies are most important for optimal synchronization or chronology of deployment of fuels infrastructure and associated vehicles?
- How should technological risk be considered in management of the portfolio of public and private investments in different fuel-vehicle pathways (cost vs. benefit of multiple pathways)?

Below are some of the points raised by participants during the session:

- *There are vested interests in the transportation sector that are still leaning toward hydrogen as replacement fuel and toward more efficient use of gasoline. Utility companies as well as consumers are supportive of the use of EVs. A follow-up comment at the session was that some auto manufacturers are in a "wait-and-see" mode, while others are taking the approach of "let's drop legacy vehicles and move forward."*
- *A speaker from a corporation made the following points about electrification being the most transformative pathway to reduce sector emissions:*
    - *EVs make the most efficient use of energy—cars do not care where the electrons come from so we should use the most efficient energy source.*
    - *An electric fleet is as clean as the grid that powers it. The grid is changing rapidly toward cleaner renewable energy.*
    - *The cost of EVs is continuing to improve with battery costs declining 7%–10% each year. The infrastructure to support EVs is established and is all around us. Recently, a Tesla Model S car drove from Los Angeles to New York City in 3 days using $0 in fuel charges thanks to Tesla superchargers that can charge a vehicle for 200 miles in 30 minutes.*
- *The choice of fuel for transformative pathways is modally and timeline dependent. In short- and mid-term, line-haul and heavy-duty vehicles will make better use of natural gas, biofuels, and other liquid alternative fuels. Passenger vehicles will benefit more from electrification. Analysis should also consider multiple-mode travel that may use more than one fuel pathway. Furthermore, remote travel (e.g., Alaska) may alter the fuel choice for transformative emissions reduction or even mix them in a hybrid scenario.*
    - *A post-workshop comment was that while natural gas is indeed an attractive choice for reducing emissions in the heavy vehicle sub-sectors, a recent study in the journal* Science *indicates that methane emissions leakage at the point of extraction could be much larger than previously estimated. This could potentially reduce the GHG emission effectiveness of switching from diesel to natural gas. However, there is still the benefit of reducing other global warming species, such as the aerosol black carbon, when switching to natural gas.*
- *More efficient modes of travel, such as passenger train and transit, can lead to a pathway being more transformative.*
- *Government organizations can assist with the deployment of transformative fuel pathways through tax incentives, regulations, and research and development. Government can also help with education and outreach, which can be particularly*

effective by being presented without a conflict of interest. Government should help businesses and officials to see beyond current market parameters. Government could consider lifting restrictions on biofuels production. A workshop follow-up comment was that the life cycle emissions and resource use (e.g., water) of biofuels are worth the higher levels of production that would occur with the lifting of restrictions.

- *In deploying transformative fuel pathways for emissions reduction, we must be mindful of the life cycle emissions "built in" to the related transportation infrastructure needed for the deployment to succeed in the first place. This should be part of the long-term accounting of emissions reduction for different pathways or combinations.*
- *Input from the U.S. military would help inform the discussion on transformative fuel pathways.*
- *Fuel pathways toward cleaner emissions may be altered by the different environment we are in now in terms of cheaper natural gas and new oil reserves. An in-session comment was that looking back, natural gas was very cheap in recent years, but now it is increasing. For this reason, it would be good to take the "all-of-the-above" approach so long as a focus is placed on approaches that begin to rise to the top in terms of long-term emissions reduction and cost.*
- *The timeline for a clean transportation sector by mid-century will likely be lumpy along the way as both obstacles and beneficial disruptions occur that impact transformative fuel pathway deployments.*
- *While we need to be cognizant with the problems associated with identifying a single fuel pathway, research and policy should still focus on an intended outcome (e.g., near-zero transportation emissions) to allow the cream of the "all-of-the-above" mix of pathways to rise to the top.*
- *There is not a simple linear path to long-term goals. An intelligent mix of fuel, infrastructure, vehicles, and other pathways will be necessary (e.g., incorporating pathways such as multi-sector efficiencies).*
- *The difference between 80% and 100% GHG emissions reduction in the sector is pivotal to the transformation.*
- *GHG reductions greater than 80% by mid-century is a hard goal. For example, we will need to take into account the impact of a collapse in petroleum and natural gas prices and/or a boom in petroleum and natural gas exports.*
- *A post-workshop comment was that getting down to about $1 per gallon to compete with electricity in the future seems like a tall order for fossil fuel options even if there is a collapse.*
- *Electrification is key because biofuels' CO_2 emissions are still not low enough to meet the goal.*
- *Eventual 100% electrification is essential—biofuels do not get us low enough in terms of emissions.*
- *The transportation energy portfolio cannot be entirely electric for the on-road sector.*

- *State DOTs are often disconnected from the technical issues of energy and climate—they are infrastructure focused.*
- *In the transition from early adopter to a mass market for clean vehicles, we need to account for the role of fleets, the incremental cost barriers for fleets, the impact of incentives for fleets (e.g., CALSTART use of CMAQ), and economies of scale.*
- Which fuel pathways or combinations of pathways would be most transformative to transportation sector emissions reduction over the next 40 years?
    - *Why Electrification is essential:*
        - *Multiple power sources are used*
        - *Technology is currently available*
        - *Efficiency improvements are noticeable*
        - *Zero emissions are emitted from the vehicle*
        - *It is utilized with private and commercial vehicles (rail and truck)*
        - *There is a great need for capital investment*
        - *It can be the conduit to transition to other technologies, such vehicle-to-vehicle, vehicle-to-infrastructure, and autonomous vehicle communications.*
- What federal actions are most important?
    - *Establish collaborations and partnerships on every level: federal, state, regional, local, and industry*
        - *State DOTs are disconnected and focus primarily on current infrastructure concerns and budgets—they are infrastructure focused.*
    - *Capitalize on the military investments and use as a driver of change*
    - *Use incentives for fleet turnover (e.g., voucher program)*
    - *Understand market responses to short- and long-term energy pricing*
    - *Research, development, and deployment*
    - *Lead the campaign to educate and promote public awareness*
    - *Complete near-term actions for DOT and DOE*
        - *Raise national awareness*
        - *Use network collaboration*
        - *Establish local infrastructure issues—codes, standards, and regulations.*
- How should technological risk be considered in management of the portfolio of public and private investments in different fuel-vehicle pathways?
    - *Conduct an analysis on the effect of multiple pathways and infrastructure on a national level and compare it to the regional level*

        - *Must understand the balance*
    - *Determine how to get a price signal*
    - *Focus on outcomes that get results.*

Roadway Electrification Overview

Tony Markel of NREL presented the potential benefits of roadway electrification as one part in an overall effort to achieve a clean transportation sector by mid-century. Roadway electrification has the potential to increase the operable range and overall utility of battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and hybrid electric vehicles (HEVs) through inductive or conductive energy transfer using either a static or mobile charge. Such systems can be integrated with renewable energy resources and smart-grid operations. Markel pointed out that dynamic charging in the roadway can allow for smaller batteries in various EVs or can provide larger-capacity batteries an extra boost to travel longer, seamless distances normally associated with quicker fueling ICE vehicles.

Markel provided a list of many of the different companies involved in roadway electrification technologies (see associated presentation) and discussed an example of Korea Advanced Institute of Science and Technology/On Line Electric Vehicle, which has demonstrated an inductive charging system that powers a bus inductively at a theme park in South Korea. Another example of working technology was of Siemens's use of conductive power (catenary) provided to freight trucks while in motion on the "20-mile, zero emissions freight corridor" on which Siemens has partnered with the Southern California Air Quality Management District between the Port of Long Beach and a business district in Los Angeles.

Markel provided analysis of the impact roadway electrification would have on a scenario in which Colorado has a high percentage of renewable energy on its grid by mid-century. The use of roadway electrification could shift the normal perception of the optimal use of solar power during the day and wind power at night by shifting load patterns. One potential benefit is the spreading of loads throughout the day that can then be more easily managed. Additionally, power demand from roadway electrification could also make great use out of oversupplies of renewable energy that are often inefficiently dealt with by using curtailment. This should be accounted for when looking at the perceived resource demand associated with deploying roadway electrification.

Another benefit of roadway electrification that was discussed is the potential for significant reductions in petroleum consumption with only small (but strategic) portions of the U.S. roads incorporating roadway electrification (refer to presentation statistics). By matching heavily traveled roadways (e.g., interstate highways) with roadway electrification, relatively small deployments of electrification can cover larger percentages of vehicles to enable significant electric range extension. Below are examples from NREL analysis:

- Electrifying 1% of U.S. Interstate Highways would cover 17% of traveling road vehicles.
- Electrifying 5% of U.S. Interstate Highways would cover 40% of traveling road vehicles.
- Electrifying 25% of U.S. Interstate Highways would cover 80% of traveling road vehicles.

Potential Considerations for CTSI Report, Research Areas/Questions, and Comments

Question: What effect would large-scale availability of roadway electrification (25% of interstates for 80% of travelers) have on demand for hybrid electric vehicles, PHEVs, and BEVs? Would it be significant enough to expand optimal deployment rates of clean vehicles by mid-century?

Question: Will roadway electrification infrastructure change in its footprint to energy production ratio with long-term improvements in battery technologies (e.g., smaller batteries that can charge quicker)? Would a change in the size of roadway electrification infrastructure in this way be enough to reduce deployment and life cycle costs significantly?

Comment: The AERIS program investigates vehicle communication benefits for roadway electrification (e.g., vehicle alignment and vehicle-to-infrastructure network applications).

Comment: Roadway electrification could also be a beneficial strategy for addressing management of critical materials—smaller batteries or extended life spans of batteries could reduce the demand for materials like lithium, neodymium, and other critical resources for a clean transportation sector.

Roadway Electrification Breakout

Following Markel's presentation on roadway electrification, a breakout session was held on the same topic with the following questions to begin the discussion:

- What elements of EV transportation could roadway electrification help leverage for more significant deployment levels?
- What potential changes to EV technology (e.g., smaller and quicker charging batteries) and infrastructure strategies (e.g., more effective business models) as well as other disruptions could make the degree of roadway electrification deployment and usage significant?
- What is your assessment of how likely and how transformative roadway electrification might be for the transportation sector over the coming decades/long term?

Below are some of the points raised by participants during the session:

- *There are many parallels with renewable energy and roadway electrification—they are beneficial to each other's deployment.*
- *Roadway electrification can help reduce battery costs to consumers even further by reducing size and/or effectively extending battery range capacity.*
- *Roadway electrification helps extend charging options significantly, adding to the marketability of EVs.*
- *Roadway electrification could be layered with other technologies like eco-lanes, other managed lanes, and platooning. Additionally, smartphone technology could help address payment issues by creating an app to pay for the EV's real-time usage (or in packets through a subscription).*

- *Even though Better Place went out of business, they had a good software system that based on communication between the vehicle and power infrastructure. Perhaps this type of software could be used with roadway electrification.*
- *We should make sure to incorporate "big data" so that we can predict demand of roadway electrification before it is needed or in intelligent conjunction with charging and receiving services at the home, road, and destination.*
- *Many potential compatible technology uses with roadway electrification are pointing to the possibility of it being a form of "flexible" or "adaptive" infrastructure, suggesting that the idea of "sunk costs" in roadway electrification could be mitigated through time.*
- *Roadway electrification could be suitable for vehicles like the Tesla Model S in which drivers want to think about charging as little as possible.*
- *There should be test beds installed to demonstrate resilience to weather and other impacts, as well as to test out V2V and V2I communications.*
- *A partnership between utilities and OEMs needs to be established.*
- *What is the answer to the chicken and egg question? How many EVs do you need on the road before you start to have justification for using roadway electrification? Perhaps existing vehicles like hybrid electric vehicles can be modified to provide more immediate demand. As an illustration, the Prius was the number one selling passenger vehicle in the world in 2012.*
- *A business model needs to be argued for the United States or little progress will be made. The same goes for a business model for utilities and OEMs.*
- *This might be something that would benefit a place like London where you have parking problems and a willingness to pay for congestion charging.*
- *Best applications for roadway electrification are routine and repetitive routes (e.g., campus buses). Heavy-duty vehicles may have a better case for return on investments than passenger vehicles.*
- *An environmental impact analysis was conducted by University of California, Davis on roadway electrification that found a net social benefit, but who pays for the deployment and maintenance?*
- *Manufacturers do not have sufficient development of equipment ready.*
- What elements of EV transportation could roadway electrification help leverage for more significant deployment levels?
    - *Dedicate routes/lanes especially for public transit and possibly freight*
    - *Save time and decrease costs on charging*
    - *Apply first to larger vehicles, where both inductive or conductive charging are better than for small vehicles*
    - *Understand charging cost and who is responsible for it*

- *Charge in parking lots (commercial and multifamily) as a first step before charging on highways.*
- *Customize batteries*
- *Increase usage on buses, fleets, trolleys, and rail*
- *Apply on toll roads.*

- What potential changes to EV technology (e.g., smaller and quicker charging batteries) and infrastructure strategies (e.g., more effective business models) as well as other disruptions could make the degree of roadway electrification deployment and usage significant?
    - *Charge station availability (swappable configuration) and decreased charging times*
    - *Battery customization*
    - *Increased battery range will decrease range anxiety*
    - *Parking ease, rental options, car share, and ride share*
    - *Individual vs. social cost options*
    - *Wireless model.*
- What is your assessment of how likely and how transformative roadway electrification might be for the transportation sector over the coming decades/long term?
    - *We need further research and test bed.*
    - *We need to understand weather impacts on this type of infrastructure.*
    - *Consumer education has to be established on the benefits.*
    - *We need to assess what security risks there are and what measures will need to be taken accordingly.*
    - *Incentives need to be used.*

Zero-Emissions Strategies Over the Long Term

Dr. Mark Delucchi of University of California, Davis gave a presentation on the larger-scale deployment strategies for achieving a clean transportation sector by mid-century as well as a related discussion on urban planning. Dr. Delucchi presented the case that the associated costs of not addressing climate change significantly justify an effort to achieve zero GHG emissions transportation by mid-century. Co-benefits of realizing this goal include dramatically reduced air pollution, congestion, and mortality rates attributed to transportation.

Dr. Delucchi stressed that change must be implemented in the transportation sector—fuel economy improvements will not get us there. If we do not make significant changes, all the negative consequences of transportation usage will remain or grow. Additionally, every major energy event in the past four decades was not predicted by modeling. We should not base our strategies on what model confidence and marketing tells us—we should act now with the long-term outcome in mind.

Dr. Delucchi and others' analyses have led them to the conclusion that no petroleum or biofuels pathways will get us to a near-zero emissions transportation sector by mid-century. Additionally, there are major non-climate concerns with the use of these fuels, such as the large amount of water required to make biofuels. This raises the question of how zero-emissions energy like WWS can power the world's economic sectors. The attributes of these renewable forms of energy provide some unexpected answers in that their deployment can power the world with less than 12 terawatts (compared to the 17 terawatts that power the world with the current energy mix). This is in large part due to the end-use technologies associated with renewable energy being different than conventional energy. Additionally, water usage associated with WWS renewable energy is dramatically lower than what is associated with petroleum and biofuels.

Dr. Delucchi suggested that in addition to climate change, the long-term economics point to a transportation sector powered by WWS renewable energy as being a prudent pathway. Already, solar and wind are reaching a point where they will soon be less costly than fossil fuels. We also need to factor in other costs associated with fossil fuels, such as air pollution, increased mortality rates, and the impacts of climate change. Dr. Delucchi presented data that climate change damage by 2030 will add $0.08/kWh to the cost of energy from fossil fuels. The external costs are not trivial. The life cycle impacts of WWS renewable energy are significant but still much lower than fossil fuel energies.

Dr. Delucchi argued that to deploy WWS renewable energy at such large scales, investments need to be made to make these technologies inherently available. Overcapacity, vehicle-to-grid technologies, hydrogen generation in place of WWS renewable energy curtailment, and other strategies are some examples.

To conclude the presentation, Dr. Delucchi provided an overview of urban planning that can support a long-term goal of a near-zero emissions transportation sector by mid-century. The research suggests that we can reduce energy demand without forcing people to give up cars. By designing city roads so that smaller and lighter vehicles can operate at 25 mph or less in mixed lanes with pedestrians and bikes, but not heavier or faster vehicles, significant gains can be made in the form of near-zero mortality rates, much lower congestion, more cost-effective mobility options, and much lower emissions. This means we should begin to focus on kinetic energy per person-mile. Doing so places an emphasis on optimizing buses, smaller EVs, bicyclists, and pedestrians. Dr. Delucchi proposal for implementing a design that achieves these goals is a dual road-system that separates light-weight/low-speed transportation from other traffic.

Potential Considerations for CTSI Report, Research Areas/Questions, and Comments

Question: What measures can be taken to more readily deploy substantial amounts of WWS-based renewable energy in the transportation sector?

Comment: The dual-road concept may be more suitable for developing countries where their infrastructure has not matured yet, allowing for new designs more readily. However, even mature urban areas in the developed world may be amenable as car sharing and other less permanent modes of travel become more popular, as compared to car ownership.

Comment: Perhaps this urban design should be targeted rather than set up in a city's master plan so that its application is more effective.

Zero-Emissions Strategies Breakout

Following Dr. Delucchi's presentation on zero-emissions strategies, a breakout session was held on the same topic with the following questions to begin the discussion:

- How can we begin to tie the transportation sector to the rapidly evolving power sector?
- How can urban-form transportation efficiencies help us reach long-term, low-emissions transportation targets sooner and/or at a lower cost?
- What are the economic benefits of a pathway toward zero-emissions transportation by mid-century?

Below are some of the points raised by participants during the session:

- *We can start to tie the transportation and power sectors by starting at the home. Micro-generation, smart-grid applications, and building codes can help connect renewable energy from a person's house to a person's car. Also, changing attitudes due to the remarkable growth in wind and solar power is making the thought of using renewable energy for both home and vehicle use more acceptable.*
- *Car ownership used to be an aspirational thing for most people, compared to now where it is increasingly being seen as a way to be stuck in traffic rather than being socially connected in virtual or physical form. It is much less so now, which perhaps suggests that urban planning suitable for cleaner forms of transportation deployment will become increasingly attractive. To these points, it was suggested that there are still many places that do not have many non-automotive options available, so this transition of the perceived value of owning a car is not uniform.*
- *Bike sharing options are exploding with Washington, D.C., and New York City leading the way. This trend may begin to impact urban design and associated emissions.*
- *More buildings will begin to generate clean power on their own, reducing overall grid-energy demand and providing additional zero-emissions fuels for vehicles.*
- *There are economic benefits to achieving a zero-emissions transportation sector by mid-century. By avoiding oil import costs, savings can be applied to electricity, which can further drive down the cost of operating EVs. Additionally, there is potential for many more jobs to be created by developing a clean economy at such a large scale.*
- *There are costs associated with transitioning away from fossil fuels. Jobs in fossil-fuel-related industries will suffer. However, with the large-scale deployment of clean fuels and technologies, many more jobs could potentially be created, including transference of previous legacy-fuel-associated jobs into clean energy and tech jobs.*
- *California has had 25 years of policy favoring clean energy. We are beginning to see very positive economic results as their gross domestic product versus energy consumption is far better than most other states. Additionally, a recent report showed that the top seven wind-energy-producing states had a decline in electricity prices the past decade, whereas other states actually had a significant increase in electricity prices.*

- *Washington State has the highest registration of EVs, a very clean energy mix (thanks to hydro resources), and one of nation's lowest electricity prices per kilowatt-hour. Norway has a similar mix with very high EV penetration rates (roughly 10% of all light-duty vehicle sales each of the past 4 months). Places like these might be microcosms for the advantages of an economic structure built around clean power and transportation that are tied to the same clean fuel source.*
- *Urbanization is happening fast globally—how can we capitalize on this opportunity of lower barriers to new transportation system entry due to a lack of entrenched infrastructure and other variables associated with areas undergoing a transition to urbanization?*
- *DOT and DOE need to have an "Impact Statement" for sustainability. Government programs need to be linked to sustainable metrics.*
- *Planning needs to have funding levers to incorporate sustainability.*
- *Incentive programs should be in place when technologies are ready to scale (e.g., finance energy savings).*
- *We need to better understand the shift in our culture so we can better leverage it.*
- *We need to better understand how to develop integrated and holistic solutions.*
- *There should be a term with more positive associations than "disruption" can sometimes imply.*
- *Technologies available to us today that can support near-zero emissions need to be scaled now.*
- How can we begin to tie the transportation sector to the rapidly evolving power sector?
    - *Need for pro-planning culture (an example of this occurred when Kennecott, a mining company, developed a long-term plan for a community in Utah on former mining land)*
    - *Need development to be contingent on markets and infrastructure that are sustainable*
        - *Use planning and integrated energy efficiency models like those of California metropolitan planning organization.*
    - *Need to be able to retrofit market infrastructure in established urban areas.*
- How can urban-form transportation efficiencies help us reach long-term, low-emissions transportation targets sooner and/or at a lower cost?
    - *Utilize education and programs, such as Solar Challenge and Sun Shot grants*
    - *Define the win-win scenario*
    - *Retrofit market infrastructure in established urban areas*
    - *Focus on the changing energy landscape*
    - *Engage all the multiple players*
    - *Develop integrated and holistic solutions.*

Day 2, February 6

OST-R's Role in Advancing Clean Transportation Strategy

DOT Assistant Secretary for Research and Technology Greg Winfree spoke of the need to really challenge ourselves as to whether we are going far enough with our research to find the answers to how we can achieve a clean transportation sector by mid-century. He stressed that the potential transformative benefits from achieving such a goal, and the potential disastrous consequences of not meeting the challenge, are justification for doing so. The Assistant Secretary asked participants to consider the following:

- The potential wealth generated on the road to a clean transportation sector as we strive to lead the world in clean technology research and deployment
- The potential wealth generated from a society not shaped so strongly by the whims of an overbearing fuel market but rather by markedly increasing transportation efficiencies and lower costs across the coming decades
- The potential wealth generated from a healthier and safer public that breathes cleaner air and travels far more safely to its intertwined destinations
- A 21st century transportation system that can be in harmony with our environment and robust in our pocket books at the same time.

Winfree asked workshop participants to think about these outcomes as they explore the possibilities of research and decision making that can point toward a clean transportation sector. He suggested that foresight and perseverance put forth in the early years of this century will leave a legacy. He challenged the attendants to bring this spirit of intellect and commitment to the proceeding discussions by asking each other the following:

- Have we explored all the key data that can impact our range of projections?
- Are we finding new ways to credibly include variables from a fast-changing industry and society into our models?
- Are we really providing the full picture for what could be?

The Assistant Secretary pointed to the recent announcement by the National Highway Transportation Safety Administration (NHTSA) that it will step up its efforts to explore vehicle-to-vehicle communication technologies. Winfree expressed the opinion that there are a multitude of benefits beyond safety that can come from this technology, including reduced emissions and congestion as well as more efficient ways to use the overall transportation system. Assistant Secretary Winfree ensured the workshop attendants that the Secretary and the President are committed to moving forward with efforts like the CTSI to help avoid potentially significant and extreme consequences posed by climate change.

Potential Considerations for CTSI Report, Research Areas/Questions, and Comments

Question: What areas of research could be explored further to address the concern that our projections for optimal emissions reduction in surface transportation by mid-century fall short of what will be needed to more seriously address climate change impacts?

Game Changers Speaker, Managing Disruptions

Matthew Daus of the International Association of Transportation Regulators spoke of the need to find a balance with disruptive technologies like taxi phone apps. Daus made the argument that we should consider whether disruptions can be sustainable solutions or potential emissions multipliers. His particular concern was a lack of ground rules for new software applications that can constitute taking property in the world of taxis and limousine services.

Daus stressed that we need to allow these technologies to exist but regulators need to have the ability to protect the public from being ripped off or potentially having safety problems. Some of these technologies have gone into a grey area where there may be law violations. Customers should not have to pay $70 to drive five blocks. Localities are passing laws to address this by reducing minimum fairs (e.g., from $45.00 to $9.75). The environment for establishing a fair structure is colored by company-related lawsuits. Daus suggested that this is made even more difficult by an environment where lawmakers are immediately lambasted on social media if they attempt to make changes in law. Lawmakers also want to have the appearance that they are attune to the latest technologies.

Daus pointed to safety concerns with the use of phone apps in the taxi and limousine service industry as unlicensed drivers are driving passengers. Additionally, there may be emissions concerns through induced driving caused by the accessibility of the apps. Daus argued that this type of service is not truly ride-sharing but rather hitchhiking.

Daus argued that these new applications are not about transportation so much as they are really about profit expansion for companies trying to expand the sales utility of smartphones and the economic usability of peoples' data. While this type of disruption could destroy an industry (i.e., taxi and limousine service), Daus pointed out that this might indeed be a consequence of said industry not being flexible enough to adapt to a changing consumer base.

Daus discussed some regulated technologies that are more balanced in terms of providing a disruption that can move transportation forward while still protecting the public. One example was the use of software that communicates through vehicles' on-board diagnostic systems in San Francisco. The big data generated from this technology is providing a massive array of safety, environmental, and economic data that can be used to improve the riding public's experience and to provide analysis needed by transportation planners and decision makers. Another technology described by Daus was one that provides limousine services for physically challenged transportation users. This technology provides far more efficient service than traditional services for this population and reduces costs at the same time to the tune of billions of dollars.

Daus concluded his presentation by saying that software application disruptions have helped wake up the taxi and limousine service industry. Once a fair structure is in place, these types of technologies can play a major role in efforts like the CTSI in trying to achieve near-zero GHG emissions by mid-century.

Potential Considerations for CTSI Report, Research Areas/Questions, and Comments

Question: What set of parameters would best define a transportation service app that both injects innovation into the sector to advance (directly or indirectly) clean transportation while protecting other public interests (e.g., safety and cost) at the same time?

Game Changers Speaker, a $10 Trillion Economy

Jigar Shah of Inerjys and founder of Sun Edison and the Carbon War Room gave a presentation on how to stimulate wealth in the transportation sector in a manner that helps to concurrently work toward a clean transportation sector by mid-century.

Shah presented the question of how we get back to 4% growth—the consumer spending power of 1999. With the cost of oil, electricity, and related health care premiums going up while take home pay goes down, we are in a situation where any substantive improvement in the cost of transportation would be greatly beneficial to individuals and the economy as a whole. This situation will only be exacerbated as traditional natural resources used for fuels become more difficult to cost-effectively obtain. By embracing a new approach to power and transportation energy usage, we can unlock a new trillion-dollar economy that will not only remedy this imbalance but also open the door to greater wealth opportunities in these sectors than seen before.

Shah stressed that because the transportation sector has the most inertia compared to other sectors, DOT has to take a leading role and give people hope that we can transform ourselves. This means not only investing in technology but also actually deploying technology at a scale large enough that it helps people and moves us forward to long-term goals. DOT should be writing a plan to do this effectively over the long term.

Shah gave several examples of how this can make sense on an aggregate and on an individual basis. Nationally, we pay $600 billion more per year for oil and $200 billion more per year for electricity than we did in 1999. The average cost for automobile travel per month is roughly $800. In comparison, the same metric is just $300 for car sharing and $200 for transit. Even if one chooses to drive an automobile instead, you really cannot beat the price of electricity. As an example, the lowest price fossil fuel (natural gas) is $1.90/gge while the average price for electricity is $1.20/gge.

Shah estimated that for the decade between 2010 and 2020, there is a $10 trillion market for climate solutions with one-third of the 100,000 businesses needed in that market coming from a clean transportation sector alone and 10% of those businesses needed for the U.S. transportation sector. Car sharing is one such example of a solution with a market share already of $1 billion and a projected market share of $6 billion by 2020.

Transportation represents the greatest opportunity in the overall $10 trillion climate solution potential market, but it has the toughest pathway ahead in terms of implementing better GHG emissions reduction strategies. Thankfully, the business context for a transition to a clean transportation sector is promising. To quote Shah's presentation: "Due to continuous technology innovation, approximately 50% of the GHG emissions will always be profitable to eliminate—held up only by lack of effective business models and financial innovation."

Shah presented this wealth opportunity within the context of cost projections for keeping the transportation sector in a state of good repair. If we continue to operate the sector in a business-as-usual manner, we will need $0.40 tax on the gas dollar to maintain it. By shifting to clean technologies on a large scale, we can largely avoid this additional cost to society.

Potential Considerations for CTSI Report, Research Areas/Questions, and Comments

Question: What areas of research could be explored to figure out how business model innovation that was successful in scaling deployment in the solar industry could be used similarly for scaling deployment clean technology in the transportation sector? How would successful business model innovation in transportation affect projections for clean transportation by mid-century?

Comment: A 2014 report (AWEA) indicates that the states with the most renewable energy have had declining electricity costs the past several years, while states with more conventional energy sources used for power have had rising electricity prices. This could be a proxy for future transportation fueling costs (i.e., EVs will cost less and less to operate as the power sector transitions to more renewable energy).

Social, Economic, and Technological Disruptions

Overview

Marcia Pincus, program director for the DOT AERIS program, gave an overview of AERIS before moderating a panel on social, economic, and technological disruptions. Pincus described how her office is modeling the environmental potential for connected vehicles, infrastructure, people, and miscellaneous devices (vehicle-to-vehicle, vehicle-to-infrastructure, vehicle-to-pedestrian/bicycle, and others). Based on initial review, it appears that the environmental benefits of these types of systems will be quite significant.

Eco-signal operations are most cost effective, with a potential to reduce emissions in the existing fleet. Cooperative Adaptive Cruise Control can reduce emissions using V2V communications. Eco-lanes and low-emission zones can go further in making emissions reduction inherit to the underlying transportation system. These applications represent an infrastructure that is not fixed and is adaptive. All of these applications represent a new opportunity to obtain eco-traveler information.

Pincus highlighted that the AERIS team is now looking at larger implications within the transportation sector by looking at eco-integrated corridor management. This work may generate a blueprint for agencies to work together for the integration of a unified asset. The benefits for transportation at this sector level may be significant enough to play a large role in achieving a clean transportation sector by mid-century.

Panel on Social, Economic, and Technological Disruptions

Following her presentation, Pincus moderated a panel with others from companies and non-governmental organizations. The panel focused on social, economic, and technological disruptions. Below are highlights from this lively discussion:

- *Tesla is an example of a technological disruption in which the company intends not to be the next GM but rather a catalyst in the industry that can make the push toward electrification.*
- *Massive adoption of EVs in Norway is associated with social and economic disruptions.*
- *Going to EVs is a no-brainer and better from a life cycle perspective.*
- *95% of all profits in the transportation sector are made by the oil industry with the auto industry making very little of the overall profit.*
- *Countries like India, Jamaica, and Kenya are being presented with an economic choice between very expensive oil imports and increasingly cheaper local renewable energy. Despite this, the adoption rate of clean transportation technologies has been slow. By using business models like those used in the solar industry, the up-front cost of deploying renewable energy infrastructure can be largely or wholly mitigated for transportation, ushering in a large-scale transformation.*
- *Leasing is a social or economic disruption by helping reduce the access barriers to clean transportation choices.*
- *Technologies like direct electronic booking of personal transportation service have disrupted the taxi and limousine service industry. While there are concerns over how the technology is being deployed, there could be benefits to the competition that has resulted from the challenge to the traditional business model.*
- *The federal government needs to cause disruption by accelerating its adoption of a much cleaner federal vehicle fleet.*
- *There are internal obstacles to disruptive change in that older car companies are bureaucratic and not designed to get anything transformative done. Cities can counteract this inertia. For example, New York City requires frequent new city vehicle purchases—allowing for cleaner vehicles to be deployed.*
- *The valuation and structure of vehicle ownership is changing. Third-party ownership is on the rise and may turn out to be a significant disruption that provides greater access to clean transportation options.*
- *Government has to have a point of view on the value of different disruptions. DOT should be very concerned that it has not commercialized some of the more promising applications that could have placed the sector farther ahead than it is today.*
- *The automotive industry is moving at a very slow pace compared to the home computer revolution 30 years ago. We need to provide incentives or legislation to accelerate this pace. An example of acceleration is the issuance of online vehicle recalls voluntarily by automobile companies like Tesla via software. Government needs to adapt to this new paradigm.*
- *The dealership business model is threatening Tesla's survival. This outdated business model prevents Tesla from selling directly to its customers. A better business model must be established with the help of revised regulations so that innovation and the scaling of cleaner vehicles are not stifled.*

- *While adhering to its mandates to protect the public, government needs to be more adaptive to encompass new technologies like camera replacements for side-view mirrors and other technologies that will encourage the public to choose the vehicles of tomorrow.*
- *Tesla has had a clear plan in place for the pathway toward greater EV penetration in the sector. This includes the following:*
  - *Build an expensive sports car ($135,000 for the Roadster)*
  - *Build a competitive luxury sports sedan ($80,000 to $100,000 for the Model S)*
  - *Build an average priced car ($35,000 for forthcoming Model E).*
- *DOT should not be happy that it has not moved the transportation sector further along toward a more economically and environmentally sustainable state than it is currently in.*
  - *Health impacts from the current energy mix used by vehicles are still very significant, and we could be much further along with in our efforts to address climate change. Instead, we are now paying more than $600 billion per year on oil over what we were paying as a nation in 1999. This is a drain on the economy and is bankrupting individuals who need transportation to get to work.*
  - *Whatever needs to be done—better cars and trucks, better mass transit, better apps, better system technologies—do it now and get it into the marketplace.*
- *Corporate bureaucracy can be just as stifling as government bureaucracy. We need to not have the usual suspects always calling the shots in the automotive industry.*
- *While we need to unleash innovation, and government should be a helping partner in that endeavor, the government is also responsible for protecting the public. This means we need to move forward smartly.*

Potential Considerations for CTSI Report, Research Areas/Questions, and Comments

Question: How do we effectively account for a comprehensive set of social, economic, and technological disruptions in our projections for a clean transportation sector by mid-century?

Comment (post-workshop): Considering the example of New York City's policy for new vehicle purchases, this may represent an opportunity for EVs, in that they can be made "new vehicles" by changing out the battery pack for one with greater capacity or faster charging times. This could be a win-win in terms of the city (lower emissions) and private companies (lower fleet-ownership costs compared to purchasing entirely new vehicles).

Social, Economic, and Technological Disruptions Breakout

Following Marcia Pincus's presentation and panel moderation on social, economic, and technological disruptions, a breakout session was held on the same topic with the following questions to begin the discussion:

- Which disruptions do you think would be most transformative to transportation sector emissions reduction?
- What actions are most important to use these disruptions to reduce GHG emissions?

- What interactions between social, technological, and economic variables are most important?

Below are some of the points raised by participants during the session:

- *A meaningful federal gas tax would be transformative to transportation sector emissions reduction. After that runs dry, we will have to find new sources of revenue, perhaps based on innovative business models for electricity delivery to vehicles and the generation of income from renewable energy within transportation right-of-way.*
    - *Deploying a clean transportation sector can help avoid the needed $0.40 per gallon gas tax of the future and stop us from spending an additional $600 billion per year on oil more than we did in past years. DOT needs to do all it can in to employ all of its research and deployment capacity to move society to a new paradigm where a transformed transportation sector can avoid these costs.*
- *Norway is already undergoing a transformation in large part due to the tax breaks that EVs enjoy.*
- *A consistent message across government will help us move toward transformative changes in transportation. Today, there is a mixed message.*
- *Has America lost the ability to do big things? Laws and regulations are on the books and research and development continues on, but we need to start deploying clean technologies at large scales or we will not move forward at the pace necessary to achieve goals like zero or near-zero GHG emissions transportation by mid-century.*
- *We need more effective use of price signals in the short- and mid-term. As an example, there may be rebound effects associated with vehicle automation, such as induced demand.*
- *We need to identify interim goals, either as government or as entrepreneurs.*
- *Transformation will not necessarily occur in the light-duty sectors first—roadway electrification has many benefits for freight that may encourage fleet adoption of partial- or full-EV freight vehicles. An example of this in action is the zero-emissions freight corridor along the I-710 corridor. With 6 miles in testing operation and 20 miles planned, this electrified roadway is demonstrating electric freight potential using Siemens hybrid-electric diesel trucks and overhead catenary charging.*
- *The California ZEV mandate is helping push the beginnings of transportation sector transformation in California.*
- *We need to communicate clean transportation choices better to the consumer—promote and invest to all walks of life. In doing so we should balance societal and economic needs and hopefully implement and deploy in a way that meets both of these needs. To this point, government can move forward by developing its own information-technology-based applications that protect the public and foster innovation at the same time.*

Presentation and Panel Discussion on Achieving and Sustaining a Clean Transportation Sector

Austin Brown of NREL and Dr. Diana Bauer of DOE's Office of Energy Policy Analysis and Integration both gave presentations prior to a panel discussion on the topic of achieving and sustaining a clean transportation sector. Brown presented on near-zero emissions transportation sector strategies while Dr. Bauer presented on critical materials. Laura Vimmerstedt of NREL moderated a panel on the same issues.

Near-Zero Emissions Transportation Sector Strategies Overview

Austin Brown gave a presentation on what strategies can help us move beyond current scenario projections that still have us falling short of achieving near-zero GHG emissions by mid-century. Brown discussed the potential of conventional ICE vehicles to undergo transformative change enough that they may even outcompete EVs in terms of reducing emissions and operating costs. However, he stressed that these would require radical engineering of ICE design to be brought to market. The Progressive X prize is one endeavor that may help overcome this obstacle. Brown pointed out that we can achieve the 2025 CAFE standards without EVs, but if CAFE does not get us to beyond 80% GHG emissions reduction in the transportation sector, we will need more energy options for vehicles.

Another area that could help us achieve deeper emissions cuts is vehicle automation. While there is great potential for emissions savings as pointed out by Marcia Pincus's overview of the AERIS program, Brown stressed that research on the overall benefit is nascent with the need to be wary of impacts of induced demand that might be caused by automation. Additionally, there is a need to look at a range of impacts from low levels of automation to large-scale deployment impacts. Below are some of the variables that Brown listed as areas that could have negative or positive emissions and energy use impacts:

- Travel by the underserved (e.g., persons with disabilities, the elderly)
- The ability to drive faster, which would change the energy efficiency of vehicles
- Less energy wasted on looking for parking
- EVs could benefit from integration of driving and charging infrastructure for more efficient operational use
- Driving algorithms could reduce emissions use
- Larger vehicles (e.g., grocery shopping, recreational trips) could be "checked out" rather than purchased, making for a more efficient use of the fleet
- Delivery services may become very efficient with automated freight or drone delivery. Potential for induced demand as well with "next hour" delivery.

Brown also discussed the potential of VMT to impact the ability to get past 80% GHG emissions reduction. While it was initially assumed that the recent years of declining VMT (antithetical to past years' trends) was due to the economy, VMT continues to decline even after economic recovery. Our current scenarios for ridership growth in the sector forecast a return to normal trends—this is not a given and may suggest the need for revised scenarios and their emissions implications.

Potential Considerations for CTSI Report, Research Areas/Questions, and Comments

Question: To what degree are we considering the recent improvements in the EV and ICE environment (outlined by Austin Brown and workshop participants) in our projections for a clean transportation sector by mid-century?

Comment: By 2050 automation may bring a convergence of the surface transportation modes. The distinction between personal automobile use and transit may blur or disappear. The emotional reasons for the current modal distinctions of passenger travel (e.g., status symbol, the enjoyment of driving) will begin to fade over time.

Critical Materials Overview

Dr. Diana Bauer gave a presentation on critical materials and the role they will play in achieving and sustaining a clean transportation sector. The key themes that her DOE program stresses in regards to critical materials are diversifying the supply chain, developing substitutes, and reusing and recycling. From this perspective, transportation planners and decision makers need to be aware of how critical materials used in vehicle magnets and batteries can be well managed in the face of exponential growth in demand as the sector transitions to a zero or near-zero GHG emissions sector by mid-century.

Dr. Bauer focused on lithium, dysprosium, neodymium, and other specialty metals as potentially challenging for production in order to scale up to meet potentially transformative demand. In addition, competition from other economic sectors will place strain on the ability to secure resources for the sector. This can make for some sticky situations, including a competition for critical materials like neodymium, which is used in EVs as well as wind turbines—what do you do when you are competing with an economic sector that is providing you with fuel for your vehicles?

When determining the importance of future demand on a critical material, DOE considered the interplay of market penetration and material intensity. In DOE's analysis of the impact of various transportation fleet transition scenarios, lithium supply did not appear to be a limiting factor; however, scenarios with higher EV use may have supply and production impacts of more concern.

In contrast to lithium, the analysis showed that dysprosium oxide is of greater concern and may be a limiting factor that needs to be dealt with in scenarios with greater EV penetration in the transportation sector. To illustrate this point, Dr. Bauer provided statistics of a 25-fold increase and then settling down of the price of dysprosium over a 2-year period. An example of how some of these issues are being addressed includes wind turbine designs that do not use neodymium and EV motor designs that have reduced the usage of rare earth metals.

Dr. Bauer highlighted geopolitical, recycle/reuse, and extraction issues with critical materials. China is producing over 95% of rare earth metals used in production, and some of the materials in question are difficult to recycle or do not yet have a robust business model for reuse. To complicate matters further, even if other countries like the United States invest in mining more critical materials for domestic supply, there is an extraction-associated lag-time built in to the supply chain that will delay a response to rapid scaling of clean transportation technology deployment. These are factors that transportation planners and decision makers need to consider as the fleet transitions to cleaner vehicles and energy supply.

Dr. Bauer noted that they are looking at a next round of research that potentially may expand in scope to include other critical materials considered important for the transitioning transportation sector as well as more aggressive fleet-turnover scenarios with associated increases in critical material demand. Overall, investment in the area of critical materials is accelerating. DOE's Critical Materials Hub Institute at the AMES Laboratory will have a $120 million budget over 5 years if Congress approves appropriations. Also, DOE is continuing to strengthen its interagency ties in this area to see if an early warning system can be developed for material criticality.

Potential Considerations for CTSI Report, Research Areas/Questions, and Comments

Question: How will the degree of critical materials management implemented by the United States over the next 40 years impact our projections for a clean transportation sector by mid-century?

Comment: Reuse of out-of-warranty vehicle batteries for energy storage in other sectors could contribute to the need to reuse critical materials.

Panel Discussion on Achieving and Sustaining a Clean Transportation Sector

Laura Vimmerstedt of NREL and the CTSI Team moderated a panel on achieving and sustaining a clean transportation sector with DOT panelists from the government, companies, and non-governmental organizations. Below are highlights from this lively discussion:

- *California's long-term GHG emissions reduction targets, with the largest being reduction of GHG emissions by 80% by 2050. Such a large reduction goal has caused them to take an integrated approach across sectors. Within transportation this has meant going beyond light-duty vehicles to look for zero- and near-zero emissions strategies in freight. One strategy already in action is the 20-mile zero-emissions freight corridor (6 miles being tested on I-701) that uses diesel hybrid-electric trucks that are charged at speed through an overhead catenary system.*
- *It was recommended that a coalition of federal agencies work with states to develop efforts like a national freight strategy. It should not just be DOT/DOE/EPA; it should also include FERC, commerce, and others. Another panelist stated that regulators need to begin to form a holistic framework for achieving and sustaining a clean transportation sector.*
- *EVs hold the most promise for achieving a clean transportation sector, particularly when one looks at the grid integration possibilities and repurpose value of car batteries as energy storage.*
- *What are all the pieces that we have to stitch together as a whole?*
- *Companies like Umicore are advancing our capacity to recycle critical materials across economic sectors. We need policies in place that can provide a structure for these endeavors to be scaled.*

- *What is the consumer angle to all of these big plans and strategies? Who is going to implement it and who is going to buy it?*
- *We need to focus more on the traveler and provided a 2050 scenario to illustrate the point. In this scenario, a traveler is supported by a myriad of technologies that are integrated to ensure she experiences unhindered access to mobility, zero emissions, and complete ease of use so that the technologies fade into the background and a person is simply going from "A" to "B" without distraction.*
- *Transportation business models are not holding up as they used to. A siloed DOT that only worked together when it had to in the past is now doing so because it is synergistic—the CTSI is a good example of this.*
- *DOT (and other agencies) is not commercializing its research enough to make a transformative difference. We need to show the benefit of our efforts to consumers—if you cannot engage up front, it is hard to sell good ideas downstream.*
- *Even if we have geopolitical access to critical materials, obstacles like the difficulty of opening a new quarry for mining will slow the intended progress of moving to a clean transportation sector. Because of this, it is important to support research that identifies ways to extract needed materials more efficiently. We also need to manage waste and recycling across economic sectors better—transportation is a huge user of materials—engaging with the manufacturing enterprise on this issue can help us transition to large-scale use of new materials more effectively.*
- *It was recommended that as researchers, sometimes we need to step back and have a bit more fun in what we are doing so we can begin to see a vision through the forest of numbers. How can we create a future that delights everyone? In the 1950s it was romantic to drive on the empty highway. Going forward, how can we capture that in the explosion of information technology possibilities by translating this tech capacity into meeting the desires of the traveling public? Defining the broader vision and mission in this context can help us market the "moonshot" in a way that it is the preferred pathway forward.*
    - *Making travel as convenient and pleasant as possible will go a long way to getting public support for these more ambitious strategies.*
- *How can we transition from marketing such as "BMW, the ultimate driving machine" to marketing that focuses on the benefits of vehicle automation and autonomy.*
    - *One recommendation was that this all be thought in the context of intermodal travel. By doing so, we can help provide solutions to the "last-mile" concept through more advanced applications of car sharing, for example.*
- *What is the right mix between "command and control?" How do we push-and-pull our way to the intended targets?*

Achieving and Sustaining a Clean Transportation Sector Breakout

Following Austin Brown's and Diana Bauer's presentations and the panelist discussion on achieving and sustaining a clean transportation sector, a breakout session was held on the same topic with the following questions to begin the discussion:

- How would you like to see projections of transportation-sector changes improved?
- In what ways can projections of transportation-sector changes better contribute to decision making than they are now?
- What actions are most important to achieving a clean transportation sector by mid-century and sustaining it thereafter?

Below are some of the points raised by participants during the session:

- *How do we account for the impact of properly marketing to early adopters through different types of services and a focus on different market segments?*
- *The business model innovation by third parties in the solar photovoltaic industry has revolutionized deployment in the energy sector. This is not accounted for well in energy models used for projections. How do we better account for the growth of renewable energy that can fuel the future transportation sector in our projections, and how do we account for similar business model innovation for transportation vehicles and infrastructure in our projections?*
- *At the workshop, biofuels was not covered enough.*
    - *Follow-up comment: This was a shortcoming on the workshop planning side as the CTSI team's invitations for biofuel subject matter experts fell through. That said, the initial TEF study that was part of the development of CTSI focused heavily on biofuels as part of a strategy to achieve an 80% reduction of emissions by 2050. The CTSI is focused on achieving 80%–100% reductions in which the inclusion of electrification and other zero-emissions technologies need to be boosted to enter this range. Biofuels were already "baked in" from this perspective, but we recognize that we did not take advantage of opportunities to look at more advanced biofuel strategies at the workshop. This is something that we should address in requests for feedback.*
- *A similar comment to the above was made regarding fuel cells.*
- *We need to look at what energy pathways make sense from a rural or urban perspective in terms of life cycle emissions.*
- *Hemp could play a major role in the biofuel arena.*
- *The Sun Grant Initiative could be a useful resource for further developing biofuel potentials in our projections.*
- *We need to be more mindful of infrastructure emissions life cycle challenges and opportunities in our projections. Consideration of these factors may make achieving 80%–100% emissions reduction more challenging.*
- *Projections should try to incorporate new opportunities to reduce emissions in the transportation sector, such as solar roadways and solar-powered lighting for roadways.*
- *We need have better mechanisms and fewer obstacles to put the ecosystem of risk takers (e.g., those that helped wind and solar markets explode) into the market so that transportation solutions are adopted at a far quicker pace.*

- *There needs to be a way to encapsulate the efforts of private venture capitalists and feed them into our scope of projections. The projections should not be based on only the efforts of Ford, GM, Toyota, etc.*
- *It was recommended that we be more involved with "hackathons" and other coordinating efforts that can move software development needed for new technologies further along. To this point, it was recommended that we strive to make our data more accessible.*
- *One area that was said to not have been covered at the workshop well was the need to further define our suburban development scenario inputs by looking at the potential of planning structures like Envision Utah to provide underlying GHG emissions reduction for various technologies and modes of travel.*
- *Another area that was requested to be covered more was the issue of cyber security related to vehicle automation, vehicle autonomy, and transportation sector and power sector integration.*
- *The energy benefits of 3D printing in transportation are things we should have covered at the workshop or should discuss in follow-up activities.*
- *Transportation's resiliency to climate change and extreme events is something that should be covered more in follow-up activities. Potentially, a clean transportation sector will be more inherently resistant to extreme events in the future.*
- *Many of the automation technologies we have discussed as beneficial for a clean transportation sector are seen by some as very dangerous. Efforts to educate the public on the safety benefits of these technologies, as well as efforts to mitigate actual problems, need to be made.*
- *Autonomous vehicle impacts are missing from our modeling and subsequent projections.*
- *We need to facilitate legal regulatory framework for autonomous vehicles.*
- *We need to translate the large field of opportunity for clean transportation solutions into a message of hope for the public. Too often we do a lot of valuable engineering, but it does not translate readily into a commercial product that the public can use. We need to tie these efforts to large targets so that people see the connection between our research and the desire to meet the challenge of societal goals. If something important is taking 8–9 years to deploy, we need to find ways to cut that down to 4 years.*
    - *It was recommended that we find a way to better address the political side of research outcomes to avoid the Solyndras of the future. The "Revolution Now" publication by DOE was seen as a good approach in this regard. DOE's Sunshot program was also seen as a good approach by focusing on soft costs and financing—transportation research could learn from this.*
- *There needs to be a proper forum for financial innovation and a way to capture the potential benefits in scenario projections. Additionally, there needs to be more effort by departments to approve innovation so that the private sector can bring important things to market more quickly.*

- *How do we get research commercialization and the fostering of innovation on Secretary Foxx's radar so that big policy decisions can be made? To that point, how do we get decision makers to go where we see the optimal pathways?*
- *How do we take all the disparate efforts that have been discussed at the workshop and create a viable blueprint and set of products that we can use? How do we break down government and industry silos in order to do so?*
- *There is a concern that DOT will lag all the innovation that is happening in clean transportation. DOT needs to carve out its role to remain relevant in the discussion.*
- *How would you like to see projections of transportation-sector changes improved?*
    - *Interact with new disruptive technology—market segmentation*
    - *Understand the indirect impacts for other sectors*
    - *Integrate regionalization choices*
    - *Utilize biomass/biofuels/solar*
    - *Develop integrated holistic solutions.*
- *What actions are most important to achieving a clean transportation sector by mid-century and sustaining it thereafter?*
    - *Having a portal for consumer analyses*
    - *Understanding consumer behaviors*
    - *Looking at the financial impact on state DOTs*
    - *Clearly identifying cost benefits*
    - *Investing privately*
    - *Involving all players in the planning process*
    - *Creating a DOT impact statement*
    - *Sustaining public policy for continuity*
    - *Finding creative, innovative, and cost-effective ways to utilize research and development funding.*
- *What areas did we not cover at the workshop that need further investigation for their importance in possibly impacting scenario projections?*
    - *The life cycle emissions of transportation infrastructure should be included in total emissions projections. This share of emissions may increase while vehicles' shares decrease.*
    - *We need a list of inter-operability for V2v V2I and an implementation of associated international standards.*
    - *We need research, development, and deployment case studies for potentially disruptive technologies such as solar roadways.*

- *We need to get a handle on the overall impact of a transition to a clean transportation sector on critical materials supply chains.*
- *Modeling scenarios should account for the possibility of battery prices being much lower than optimally projected at present. What impact would $200/kWh EV battery prices or lower, before 2020, have on projections? What would further reductions thereafter have on projections?*
- *Projections need to better account for a private role in early transition to market growth. Lessons can be learned from the solar industry in this regard. What impact would potential similar experiences of rapid deployment in the transportation sector have on projections?*
- *Our roadmapping needs to include the venture capital and startup communities. Perhaps they would provide suggestions on the current outline of our research.*

The Energy Gang Podcast: Can Transportation Reach Zero Emissions By 2050?

After the CTSI workshop concluded, a special The Energy Gang podcast was hosted at DOT with hosts Stephen Lacey (Greentech Media), Katherine Hamilton (38 North Solutions), and Jigar Shah (Inerjys and founder of Sun Edison). The Energy Gang's special guests were Greg Winfree, DOT Assistant Secretary for Research and Technology, and Austin Brown, Senior Policy Analyst at NREL. This episode of The Energy Gang was divided into three segments in order to look at the short-, mid-, and long-term strategies and picture for achieving a near-zero GHG emissions transportation sector.

In the first segment focused on the short term, the hosts and guests discussed immediate pressure points for transitioning to a clean transportation sector, such as needed business models and planning. The second segment focused on looking at where the sector will be toward the end of the decade and what thresholds we may be crossing by then. The third segment explored the long term in terms of what it will look like and what that means for the public.

Assistant Secretary Winfree pointed to recently announced NHTSA support of vehicle communication standards that not only address a pressure point of an expected higher safety capacity in the transportation system but also to the beginnings of this type of technology to address the need for an increased capacity for congestion mitigation, GHG reduction, and other key elements of a transition to a clean transportation sector. This is one of the first steps toward automated vehicles and providing a foundational infrastructure in which these vehicles are connected. The support for vehicle communications also acknowledges the need to not only address distracted driving in terms of vehicle-to-vehicle interaction but also for vehicle-to-pedestrian interaction, bicycle, motorcycle, and other modes of travel.

Austin Brown noted that new technologies such as electronic booking of personal transportation services, novel car rental models, and car-sharing services are making potentially cleaner transportation accessible to a broader group of people.

Winfree made the point that vehicles are becoming smartphones on wheels and companies are looking to integrate their services on these types of platforms. Additionally, vehicles are becoming more and more customizable by driver preferences, which may also be an attribute in the short term of a sector transition.

Jigar Shah highlighted the trend in Washington, D.C., of people using bike shares and of a slowdown in terms of vehicle registrations. This coupled with transit and taxi use becoming more robust may point to Washington, D.C., being indicative of changing behaviors in the short term of a sector transition. Stephen Lacey added that older generations are coming back to cities for the ease of use of these services.

Katherine Hamilton pointed to the short-term indicator of power and transportation sector interactions with vehicles becoming part of smart-grid conversations, as well as strong correlations between EV adopters and photovoltaic adopters. These ideas point to people starting to get the sense that electricity is no longer just for the house. This has significance for improvements in efficiency being seen as multi-sectoral.

Winfree discussed roadway electrification technology and its potential to address battery limitations and associated user issues such as range anxiety.

Shah discussed how the remarkable growth in the solar industry has been linked to a passion to make money through deployment in this segment. There are some examples of promise in transport, such as natural gas in heavy-duty vehicles and Tesla's success with the Model S, but overall, this has not been matched in the transportation industry.

For the second segment of the podcast, Lacey asked the hosts and guests to consider where we will be in 2020 as we start to see the effects of a markedly changed power sector, an EV infrastructure that is more mature, and a convergence of economic sectors through common energy sources.

Jigar put forth that all new marginal power capacity will be filled by renewable energy sources by 2020. Lacey posed the question of whether we could see the same trend happening for transportation. Brown pointed to a trend in the transportation sector that might indicate this—the declining cost of EV batteries to the tune of 75% in the last 5 years with a lot of headroom for reductions going forward. This idea points to a large opportunity to continue to make clean vehicles still cheaper. Additionally, fully electric passenger vehicles in the United States have gone from 0 in 2009 to 150,000 in 2014.

Shah was excited at the prospect that by 2020 all new heavy trucks could be powered by cleaner, non-diesel fuels.

Hamilton expressed concern of whether the system has the potential to change by 2020 so that traveling with four kids and two pets on a long highway trip will no longer have to be done with fossil fuels (in contrast to the ability to do this in an urban setting). Winfree responded that unfortunately, the road system that we travel on today dates back to the late 19th century, making significant change to this in less than one decade difficult. However, the increasingly equivalent or superior attributes of EVs compared to ICE vehicles is changing the public's perception of the ability of EVs to meet a diversity of travel scenarios. Beyond 2020, the next sea-change will then address how we move in terms of underlying behaviors and infrastructure.

Lacey posed a question to Brown about the challenges competing alternative fuels like natural gas pose for EVs. Brown responded that while heavy-duty trucking has a somewhat controllable infrastructure and VMT per vehicle high enough for scale use of particular fuels, the value proposition for light-duty vehicles is more in favor of EVs with much less competition from other energy systems, such as fuel cells and hydrogen.

Shah suggested that the combined management of home appliance systems and vehicle charging services through software applications and related devices is still struggling to find market penetration. He suggested that related successes in the solar industry may provide solutions in the years to come.

Winfree was asked how policy necessary for a cleaner transportation sector going forward can be developed. He responded that the DOT Office of the Secretary is committed to working collaboratively across DOT modes to find solutions that can address this. DOT is a custodian of the taxpayers' dollars; therefore, DOT will work with its federal and other partners to make sure that policy developed reflects the best bang for the buck.

In a related question, Shah asked Winfree if he felt that DOT was going to be able to keep pace with innovation in the marketplace or whether that pace would force DOT to fall back into a regulatory role. The Assistant Secretary responded that while government often does not respond as quickly as industry does, the two entities have a different set of drivers. DOT's responsibility is to respond as best as possible to the American public. As such, we have several roles. There is the regulatory side needed to protect the public, and there is a need for organizations like OST-R to get back to basic exploratory research. We also have an important role in setting goals and standards that are often difficult for industry to meet on their own. There will be instances where DOT is out in front, and there will be instances where it is DOT's responsibility to get their arm around a situation in order to achieve outcomes that are the most advantageous to the public. With this mindset, OST-R is pushing itself and its partners to help create a 21st century transportation system that is world class and not tied to any limiting paradigms of the 20th century.

Hamilton said she was excited to learn that DOT has the capacity to work across its agencies and programs to find the best solutions. You are still going to need rules, safety, and interoperability, but by having this cross-cutting organizational culture it is easier to see what is possible.

Lacey started the third segment of the podcast by asking the hosts and guests to think of the middle of the century and whether transportation's transformation will be fast enough to achieve near-zero emissions and help stave off the consequences of projected climate impacts. Lacey reminded the participants that the preceding CTSI workshop brought out the notion that climate calamities do not have to be our future—we have a choice to make. In that spirit, Lacey asked the podcast participants what the big changes are that need to be made in order to really accelerate a transition to clean transportation sector.

Brown was of the opinion that a mature system for automated vehicles is one pathway for acceleration, with people being drawn more and more to a seamless life experience. Vehicle platooning, rapid speed, ease of trip planning, and other variables should be balanced with potential backfires such as induced demand and associated increases in energy use. Winfree expanded upon this train of thought by pointing to the recent NHTSA vehicle communication decision as an early tipping point that may lead to an exponential reduction in vehicle crashes. This in turn could lead to the ability to safely use much lighter vehicles not based on a heavy steel cage, which can then lead to reduced emissions.

Shah expressed a concern that our current freight systems have inefficiencies strong enough to force U.S. companies to export their merchandise to Canada ports before being sent overseas in order to save the time of not having to go through U.S. ports. Shah suggested that efforts at making multi-modal systems in transportation a focal point be heightened so that the delivery of goods to U.S. ports for shipment is not so burdensome. Winfree responded that this is indeed a focal point for DOT as indicated by the forming of the National Freight Advisory Council to help form a national freight strategy.

Lacey concluded the podcast by asking the participants their outlook on the feasibility of getting to near-zero GHG emissions reduction in the transportation sector by mid-century. Brown wanted to be optimistic but pointed out that if you want to get to those levels of reduction within a 40-year timeframe, you will have to use every tool you have in the toolbox. Although he said we have many tools that are developing, Brown was not confident that we could do it within the given timeframe. Hamilton and Shah were of a similar opinion, citing a lack of political will and systemic issues in the transportation system that must be dealt with. Winfree pointed out that whether you are an optimist or a pessimist, it does not matter—the projected climate impacts (and those already occurring) are forcing the issue, so we must respond in a way that ensures successful achievement of the goal.

Workshop Agenda

Clean Transportation Sector Initiative Workshop

Reducing greenhouse gas emissions beyond 80% by mid-century

February 5-6, 2014

February 5, 2014 *Fuel Pathways and Roadway Electrification*

9:00 AM *Opening Remarks*
Beth Osborne, Deputy Assistant Secretary for Policy
U.S. Department of Transportation

9:20 AM *Introductions and CTSI Overview*
Kevin Womack, Associate Administrator for Research and Technology, U.S. Department of Transportation

9:45AM **Presentation:** *Transportation GHG Reductions and Climate Response*
Drew Shindell, National Aeronautics and Space Administration

10:15 AM **Presentation**: *Fuel Pathways Overview*
Austin Brown, National Renewable Laboratory

10:45 AM Break

11:00 AM **Breakout Session** – *Fuel Pathways*

12:00 PM Lunch

1:15 PM **Presentation:** *Roadway Electrification*
Tony Markel, National Renewable Laboratory

1:45 PM **Breakout Session**: Roadway Electrification

2:45 PM Break

3:00 PM **Presentation**: *Zero Emissions*
Mark Delucchi, University of California, Davis

3:30 PM **Breakout Session**: *Zero-Emission Strategies*

4:15 PM Brief Review and Prelude

Clean Transportation Sector Initiative Workshop

Reducing greenhouse gas emissions beyond 80% by mid-century

February 5-6, 2014

February 6, 2014 *Disruptive Technologies - Clean Sector Strategy*

8:50 AM *Disruptive Technologies and Their Role Toward a Clean Transportation*
Kevin Womack, Associate Administrator for Research and Technology, U.S. Department of Transportation

9:00 AM *The Office of the Assistant Secretary for Research and Technology Role in Advancing Clean Transportation Strategy*
Gregory Winfree, Assistant Secretary for Research and Technology, U.S. Department of Transportation

9:20 AM **Presentation**: *Game Changers –Climate Wealth & Business Model Innovations*
Jigar Shah, Inerjys Venture, Inc.

9:50AM Break

10:00 AM **Presentation**: *Game Changers – Transportation Network Solutions*
Matthew Daus, International Association of Transportation Research

10:30 AM **Panel Discussion**: *Disruptive Social, Technological, and Economic Change*
Moderator: Marcia Pincus, U.S. Department of Transportation

James Chen- Tesla Motors
Jigar Shah- Inerjys Venture, Inc.
Matthew Daus – International Association of Transportation Research
Nikki Gordon-Bloomfield – Transport Evolved

11:15 AM **Breakout Session**: *Disruptive Social, Technological, and Economic Change*

12:00 PM Lunch

1:05 PM **Presentation:** *Next Steps for a Clean Transportation Sector*
Kevin Womack, Associate Administrator for Research and Technology, U.S. Department of Transportation

1:20 PM **Presentation:** *Near-Zero Emission Economic Strategies*
Austin Brown, National Renewable Energy Laboratory

1:40 PM **Presentation**: *Critical Materials*
Diana Bauer, U.S. Department of Energy

2:00 PM **Panel Discussion:** *Achieving and Sustaining a Clean Transportation Sector*
Moderator: Austin Brown, National Renewable Energy Laboratory

Vincent Valdes - U.S. Department of Transportation
Eric Weaver – U.S. Department of Transportation
Diana Bauer – U.S. Department of Energy
Katherine Hamilton – 38 North Solutions
Henry Hogo – South Coast Air Quality Management District

2:30 PM Break

2:45 PM **Breakout Session**: *Clean Sector Strategies*

3:45 PM Concluding Remarks
Kevin Womack, Associate Administrator for Research and Technology, U.S. Department of Transportation

4:30 PM The Energy Gang Podcast: *Clean Transportation Sector Beyond* 80% *Reduction*
Moderator: Stephen Lacey and Co-hosts Jigar Shah and Katherine Hamilton

Special Guest:
Gregory Winfree - Assistant Secretary for Research and Technology, U.S. Department of Transportation
Austin Brown - National Renewable Energy Laboratory

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