Title
Strategies for Transitioning to Low-Carbon Emission Trucks in the United States

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STRATEGIES FOR TRANSITIONING TO LOW-CARBON EMISSION TRUCKS IN THE UNITED STATES

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STEPS White Paper Process

The Sustainable Transportation Energy Pathways (STEPS) Program prepares white papers that synthesize research insights from various projects to help address complex sustainable transportation transition issues and inform the discussion for decision makers in industry, government, and civil society. This white paper has already undergone significant review by the entities listed in the Acknowledgements section below. Following a public release, the research team seeks to publish this paper in a peer-reviewed journal.

U.S. Department of Transportation (USDOT) Disclaimer

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EXECUTIVE SUMMARY

The United States and California have both made commitments to an 80% reduction in energy-related greenhouse gases (GHGs) from 1990 levels by 2050 in order to help stabilize atmospheric concentrations of greenhouse gases. These commitments do not specifically target transportation or an individual transport mode.

This white paper reviews previous studies and provides a new investigation into the feasibility of achieving an 80% reduction in CO2-equivalent (CO_2e) GHG emissions in the United States and California from trucks in the 2050 time frame ("80-in-50"). We assess the technological and economic potential of achieving deep market penetrations of low-carbon vehicles and fuels, including vehicles operating on electricity, hydrogen, and biofuels.

This paper provides a side-by-side comparison of potential truck technologies and fuels, and analyzes the technical, economic, and other challenges associated with the various options. Finally, it presents several scenarios for achieving an 80-in-50 target for trucks.

Overall, we find that achieving such a target for trucks will be very challenging and, if focused on hydrogen and electric zero emission vehicle (ZEV) technologies, will require strong sales growth beginning no later than 2025 and nearly a complete transition to sales of these vehicles by 2040 to achieve needed stock shares by 2050. We find that introducing sizable quantities of low-GHG biofuels compatible with today's diesel engines can ease the transition time to ZEVs or even cut needed ZEV shares significantly, but this involves other very challenging aspects. This paper does not consider local pollutant emissions such as NOx, which in some places (notably California) could require an even faster transition to ZEVs than called for by climate-related goals. We do not

Key Findings

This paper reviews estimates of truck CO_2e reduction potential and costs, and develops new scenarios to achieve an "80-in-50" target. These scenarios indicate that a combination of strong uptake of zero-emission trucks and advanced biofuels will likely be needed to hit such a target, but even with this combination, meeting the target will be very challenging.

The costs of deploying ZEVs and advanced biofuels to reduce truck GHG emissions may be substantial in the near term but should decline over time, relative to a baseline scenario.

The number of ZEV trucks (and the sales trajectory) that could be needed by 2030 suggests that policies targeting the sales of ZEVs may be needed as a complement to fuel economy standards. Similarly, policies may be needed to ensure that sustainable, low-carbon hydrogen and diesel-replacement biofuels become available in large volumes in the coming decades.

attempt to determine which strategy (ZEVs or biofuels) is superior and conclude that a combination is the most likely way to achieve large reductions in GHG emissions going forward. The tradeoffs involved—notably the ease of biofuels' fleet penetration versus the reduction of criteria pollutants offered by ZEVs—may ultimately determine which path is chosen in different markets.

Presently, trucks dominate goods movement in the U.S., carrying 72% of the tonnage, 42% of ton-miles, and 70% of the goods value. The truck scenarios developed for this paper include eight different truck types, with a high share of truck miles and fuel use accounted for by long haul Class 8 trucks, although short haul heavy-duty trucks and commercial pickup trucks are also important.

In reviewing three prominent studies of low-carbon truck futures, we note the lack of a clear consensus of an optimal pathway or even the feasibility of achieving 80-in-50. Two studies focused primarily on the potential for significant utilization of biofuels for heavy-duty vehicles, with both studies projecting emissions reductions far short of an 80% reduction target. A broader third study in 2012, by the California Air Resources Board (ARB), achieved an 80-in-50 target with massive uptake of ZEV trucks, but even this approach did not meet ARB's 2032 NOx targets. These three studies, along with the new scenarios presented in this paper, suggest that without strong adoption of very low-carbon biofuels, it will take a very rapid ramp-up of ZEV trucks (i.e. fuel cell and/or electric trucks) beginning shortly after 2020, with a full penetration of these vehicles by 2040, to have a chance for an 80% reduction in CO_2e emissions by 2050. The urgency of this transition to ZEV trucks could be eased considerably by concurrently introducing large quantities of low-carbon biofuels.

The new truck technologies and propulsion systems discussed here include diesel hybrids, liquefied natural gas (LNG),fuel cell, plug-in hybrid, and battery electric vehicles (with only fuel cells and pure battery electric vehicles considered as ZEVs). Given what is known today, the cost of owning and operating these alternative technologies and fuels would exceed that of diesel trucks, at least in the near term. In the case of biofuels, the vehicle capital cost is the same, but near-term fuel costs are significantly higher. If costs of technologies (like hydrogen fuel cells and batteries) and of fuels (like biofuels) decline as we assume in our 2030 cost projections, the costs of a very low-carbon scenario over the next two to three decades appear moderate in the context of overall trucking costs. In the case of our projections for heavy-duty long haul trucks, the costs between 2030 and 2050 actually are below those in the base case due to rising fuel savings. But transition costs over the next decade or two may be high.

As with light-duty vehicles, the challenges for large ZEV trucks include deploying a refueling infrastructure that supports widespread adoption of vehicles, and reducing cost barriers through scale and learning. Strong policies are likely to be needed to overcome these challenges and set ZEV truck sales on a rapid growth trajectory. Ongoing research, development and demonstration (RD&D) programs coupled with fiscal incentives for low-carbon fuel adoption by trucks appear critical; a ZEV requirement in the truck sector, like the California requirement for light-duty vehicles, may also be useful but could be more difficult to manage than for cars given the wide range of truck types and purposes. Fiscal incentives for ZEVs may be an alternative or complementary policy to consider.

Scenario Results

In the scenarios created for this paper (described and documented in the report and Appendix), separate estimates of vehicle market shares and fuel requirements in 80-in-50 scenarios were made for California and the United States. The underlying growth in truck vehicle miles traveled (VMT) is projected somewhat differently by ARB and the U.S. Energy Information Administration (EIA). ARB projects about a 50% increase in California truck miles between 2010 and 2050, and EIA projects an 80% increase nationally. Given either of these projections, this substantial VMT growth increases the challenge of achieving 80-in-50. However, the scenarios here include enough efficiency improvement in diesel trucks to completely offset VMT growth in California and mostly offset growth nationwide (due to the US Phase 2 efficiency standards and assumed continued tightening of this program over time). Additional efficiency improvement comes from shifts to battery electric and fuel cell trucks, further lowering demand for diesel fuel to 2050 (though requiring orders of magnitude increases in electricity and hydrogen use by trucks compared to today). The final contributions to GHG reductions come from deeply decarbonized energy sources, including for hydrogen, electricity and biofuels.

The tradeoff between ZEV sales and the use of biofuels is depicted in Figure ES-1, where a “High ZEV” scenario focused mainly on ZEVs along with very low GHG hydrogen or electricity, is compared with a “Mixed” scenario of 60% blends of very low-carbon GHG biodiesel blended into fossil diesel fuel by 2050. The difference is striking, particularly in the 2030-2040 timeframe, when in the High ZEV scenario very high sales shares of ZEVs must be achieved to be on a path to 80% GHG reduction, whereas these sales shares can be much lower in the Mixed scenario. In the High ZEV scenario, with a flat rise in ZEV market share over time, ZEVs must account for close to 40% of new truck sales by 2030 and account for nearly all new trucks by 2040 in order to hit an 80-in-50 target. If ZEVs are not close to achieving this type of market share growth by 2030, it probably means they will not be able to achieve an 80-in-50 goal without the help of very large volumes of biofuels.

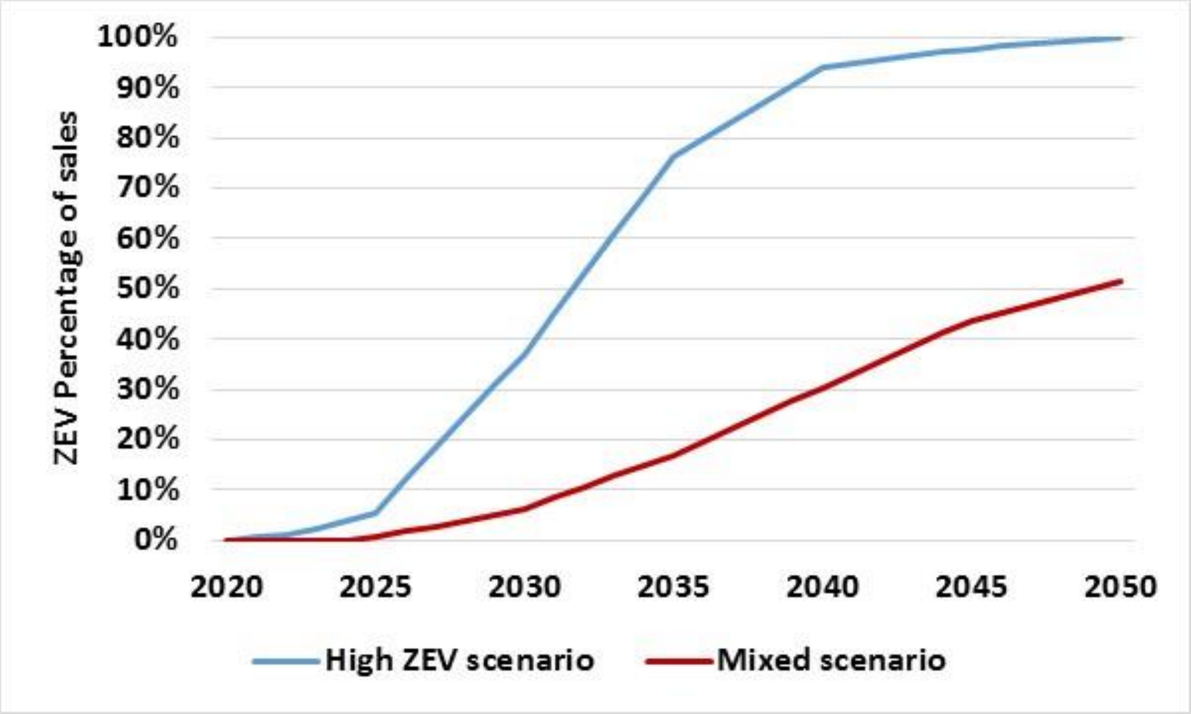

Figure ES-1. Required ZEV sales share to hit 80-in-50 target with no biofuels v. scenario with 60% biofuels blends by2050

The resulting fuel use by fuel type in these scenarios is shown in Figure ES-2, both for High ZEV scenario and a Mixed scenario. Either way, total truck fuel use in 2050 is well below baseline fuel use in 2010, although the use of hydrogen, electricity and (especially in the Mixed scenario), biofuels use is far higher than in 2010, when it is quite low for trucks. Further, these fuels are assumed to be deeply decarbonized by 2050: biofuels have an average 80% lower carbon intensity (CI) than diesel, and hydrogen has an 80% lower CI in California and 85% lower CI in the U.S. context in order to reach the overall 80% reduction in GHG emissions. This reduction in CI is dramatic, so these scenarios also involve moving to new generations of feedstocks and fuel pathways, such as cellulosic drop-in biofuels and hydrogen from renewable sources.

Producing the volumes of low-carbon fuels shown in figure ES-2 will be very challenging, particularly considering that such fuels will also be demanded for use in other modes. The volume of hydrogen needed in the ZEV scenario for the U.S. is nearly equal to total industrial hydrogen production in the country today (and this is a fairly large industry, with demand from refineries and other chemical producers). And since almost no hydrogen is used for transportation, it would require a complete development of a hydrogen production and refueling infrastructure. If hydrogen refueling systems begin to be developed for light-duty vehicles, as is now occurring in California, this could help to plant the seeds for a future system for trucks. Biofuels consumption shown in the Mixed scenario is well above current transportation biofuel use in the U.S. today. It is also a different type: drop-in diesel fuel (or possibly renewable natural gas, or RNG), rather than ethanol, which dominates today.

Achieving this biofuel mix will require entirely new conversion processes and different feedstocks (such as waste products and dedicated cellulosic crops).

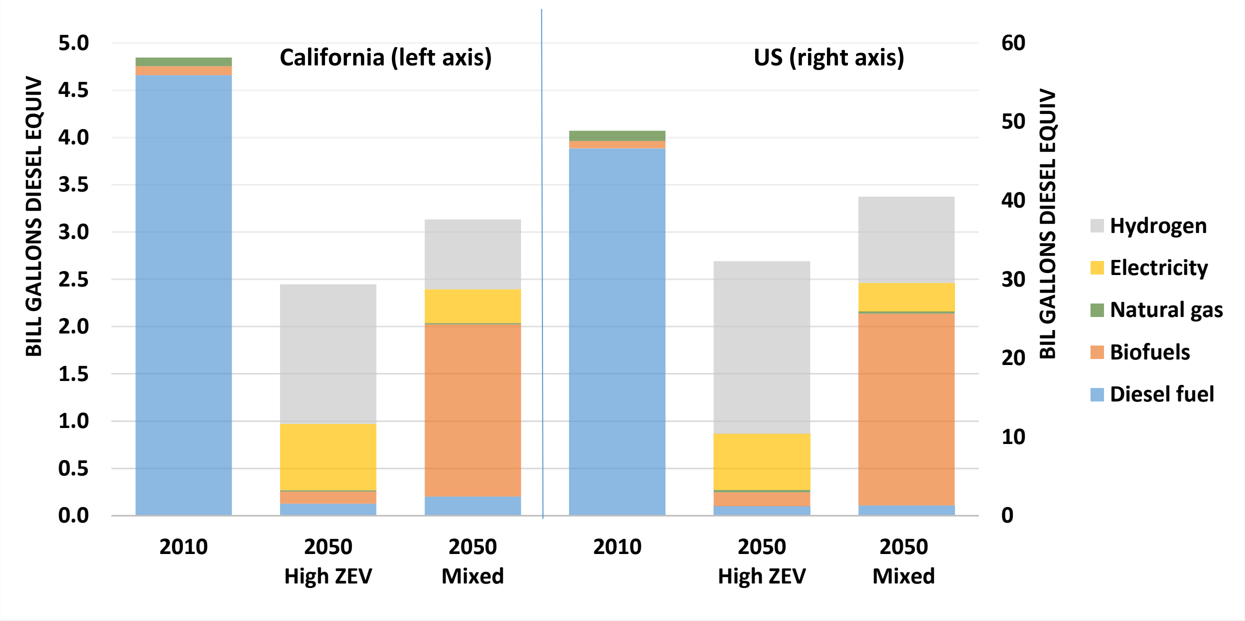

Figure ES-2. Energy use by fuel type, year and scenario, California and U.S. results

Conclusions

This white paper finds that achieving an 80-in-50 target for trucks will be very challenging, and it will likely take a combination of strong efficiency improvements and rapid uptake of new vehicle and fuel types to achieve, with hydrogen fuel cells and biofuels possibly both playing very important roles and electricity playing a smaller role. But since the ultimate role of each energy pathway is unclear, it seems wise to pursue all these technologies and fuels in combination, possibly for another 15 years or more, at least until a dominant pathway emerges. An equilibrium combination may also emerge, which may vary by truck type and use. Even with a combined strategy, the targets for each fuel and vehicle type will be challenging, but likely less so than for a single-pathway approach.

Regardless of the specific scenario or strategy adopted, strong policies would be needed in order to achieve a low-carbon truck future. This White Paper has reviewed a range of existing and potential policies. We find that the main policy in place at this time is the national fuel economy standard for trucks. This policy, assuming considerable tightening over time, will likely play a critical role in cutting fuel use and CO_2e emissions, but to reach very low CO_2e levels it may also be necessary to encourage (or require) trucking firms to adopt new types of vehicles and fuels; for this change to happen, other policies will likely be needed, such as new alternative fuel-related incentive programs or truck ZEV requirements. To achieve the large volumes of advanced, low-GHG biofuels in the Mixed scenario, new policies that complement or go beyond the Renewable Fuel Standard and California's Low Carbon Fuel Standard may be needed to encourage a rapid migration to and ramp-up of such biofuels, which are typically derived from waste materials and cellulosic feedstocks, and to drop-in biofuels such as “renewable diesel” fuel that can be used in any proportion in diesel engine trucks. Policies would also need to address and help overcome sustainability-related obstacles such as indirect land-use change.

Additional research is needed in a number of areas, including a more detailed analysis of the driving cycles of different types of trucks, how suitable electricity and/or hydrogen is for these various truck types, and how refueling infrastructure transitions can be optimized. An assessment of the maximum realistic rates of market uptake of ZEVs is also needed. Better understanding of some fuel pathways is also needed. For example, RNG (derived from feedstocks such as municipal solid waste, wastewater treatment plants, dairy farm bio-digesters, etc.) could provide a clear transition pathway—starting with the introduction of trucks running on fossil natural gas and leading to RNG—to achieving a low-carbon future. The potential availability of feedstocks and the cost of RNG are critical uncertainties at this time. Technologies that would extend the driving range of long haul ZEV trucks (e.g. catenary and dynamic wireless charging systems) also deserve research attention.

In addition, a better understanding of how trucking companies make purchase decisions is needed, including the effect of expected truck holding times and turnover rates, the importance of truck resale value and demand for (or aversion to) new technologies in secondary markets, and how purchase decisions vary by company size and type and by truck type.

Finally, this paper has not looked at the potential to cut fuel use and GHG emissions via changes in freight movement. The baseline truck VMT projections are unchanged in our two low-GHG scenarios. A broad understanding is needed of the potential to cut truck VMT and energy use via urban logistics, dispatching, information/communication technologies, automation, modal shift to rail, and truck in-use fuel-economy improvements (e.g. from ecodriving), among other things.

1. Introduction

In order to limit climate change effects to manageable levels, greenhouse gases (GHGs) must be dramatically reduced. To stabilize atmospheric concentrations of GHGs, many researchers have suggested a goal in developed countries of 80% reduction from 1990 levels by 2050 (International Energy Agency, 2014) and President Obama has set similar goals (White House, 2009). The Intergovernmental Panel on Climate Change (IPCC) 2-degree projection requires a complete elimination of energy-related GHG emissions by late century (IPCC, 2014). Given the significant expected increases in energy use by the trucking sector, reducing overall GHGs to these levels will require major changes in both the way goods are moved and how vehicle technologies are used. Increasing energy efficiency will be important, but transitioning a significant percentage of the sector to zero emission vehicles (ZEVs) and fuels will be necessary to achieve the targets.

This paper focuses on new truck technologies and fuels that may be required to achieve deep GHG emission reductions from trucks in the United States and, more locally, in California in the 2050 time frame. It covers the trends, available technologies for efficiency and for deploying new fuels, the potential for adopting these technologies and fuels in the medium and longer term, resulting impacts on GHG emissions, and potential policies to achieve specific targets. Given the scope of the paper and resources available, it does not consider potential changes in freight movement or methods of reducing truck vehicle miles traveled (VMT), or achieving energy savings from logistics, information and communications technologies (ICT), automation, changes in spatial structure, or other strategies related to goods movement.

The two main strategies discussed in this paper include adoption of zero emission technologies, such as fuel cell and plug-in electric vehicles (together called ZEVs), and increases in the use of biofuels. Both strategies have advantages and problems. ZEVs reduce both GHG and criteria pollutant emissions. While this paper focuses on GHG emissions, criteria pollutant standards are becoming very strict, and biodiesel may have difficulty meeting those standards. A significant issue with new ZEV vehicle technologies is fleet penetration. Technologies such as fuel cells and batteries may not be capable of ramping up quickly enough to meet the desired GHG reductions. Biofuels, especially drop-in renewable diesel fuel, can bypass this issue because they do not require new vehicle technologies. This paper discusses both strategies but does not attempt to determine which is ultimately superior.

The paper is organized as follows: Section 2 gives background data and projections for freight vehicles in the United States. Section 3 describes the technologies and fuels that can effect or assist in the transition to ZEVs. The section discusses costs, energy efficiencies, timelines for introduction, potential barriers to commercialization for each technology, and fuel. Section 4 discusses the cost of vehicles and fuels in more detail, and includes information about emissions in the near- and mid-term. It compares costs, emissions, and cost effectiveness across technology/fuel types for heavy-duty trucks. Section 5 compares transition scenarios to reduce GHGs in the trucking sector, while Section 6 presents new “80-in-50” multi-technology and fuel penetration scenarios for trucks to reach hypothetical 80% GHG emissions reduction targets by 2050. Section 7 describes various policies that can assist in transitioning to technologies and fuels that will emit lower GHGs and ultimately to ZEVs. Finally, section 8 provides conclusions and recommendations.

2. Background Data, Trends and Projections for the U.S. Freight Sector

The U.S. freight sector moves goods from the nation's ports, airports, and manufacturing facilities to locations all over the country. The Federal Highway Administration's Freight Analysis Framework (FAF) estimated that in 2012 roughly 19.7 billion tons of goods were moved, or about 60 tons per person. The value of these goods was estimated at $17.4 trillion, or over $50,000 per person. The FAF estimates that these values will increase to 28.5 billion tons and $39.3 trillion by 2040 (USDOT FHWA). Analysis of the Commodity Flow Survey 2012 (Table 1) indicates that trucks moved roughly 70% of freight tons, 38% of freight ton-miles, and 74% of freight value. The next-closest sector was rail accounting for 16% of tonnage, 48% of ton-miles, and 3% of freight value.

Table 1. Freight tonnage, ton-miles, and value by percentage in 2012 as a function of mode (data from Commodity Flow Survey as presented in ORNL, 2014)

Mode	Tonnage (%)	Ton-miles (%)	Value (%)
Truck	70	38	74
Rail	16	45	3
Multimode	3	9	14
Air	<1	<1	3
Water-borne	4	6	2
Other	7	2	4
Total	100	100	100

The trucking share of tons and ton-miles is projected to grow slightly at the expense of other sectors (Grenzeback 2013). From a value and tonnage point of view, trucking is the dominant domestic freight mode in the country. It is also the dominant freight mode in terms of energy use and CO_2e emissions. For these reasons, this paper focuses mainly on ZEV options for trucking, however, it also briefly covers other modes (i.e., rail, shipping, air).

The U.S. Energy Information Administration's Annual Energy Outlook (AEO) projects "Reference Case" transportation sector key indicators by mode to 2040. The AEO expects VMT to increase significantly for trucks, air travel, rail, and shipping. While each mode is projected to see substantial energy efficiency gains, the total energy used by freight transportation is still projected to increase. Table 2 shows the projections for yearly percentage increase in VMT, energy efficiency, and energy use by mode out to 2040. Figure 1 shows the projected energy use by year through 2040 for the four modes—freight trucking, rail, aircraft, and domestic shipping (EIA AEO2015). The trucking sector is the fastest growing and by far the largest energy using mode. Its share of energy use grows from 63% in 2013 to 69% in 2040.

Table 2. U.S. EIA AEO 2015 projections by mode for various indicators through 2040

	VMT[1]			**Energy Efficiency[2]**			**Energy Use (Quads)**		
Mode	2013	2040	annual % increase	2013	2040	annual % increase	2013	2040	annual % increase
Trucks	256	411	1.9	6.7	7.8	0.5	5.23	7.23	1.3
Air	997	1199	0.7	62.6	71.5	0.5	2.48	2.7	0.3
Rail	1521	1736	0.01	3.5	4.2	0.7	0.44	0.42	-0.5
Domestic Shipping	377	371	-0.1	4.8	5.8	0.8	0.1	0.08	-0.8

1. VMT is billion miles for trucks, billion seat-miles for air, billion ton-miles for rail and shipping
2. Energy efficiency is the average for the stock of vehicles/equipment. Units are miles/gallon for trucks, seat-miles/gallon for air, ton-miles/thousand BTU for rail and shipping.

Previously, Greene and Plotkin extrapolated the results to 2050 (Greene and Plotkin, 2011). Those results showed increased CO_2e emissions from 2010 to 2050 of 69.5%. Rail, domestic shipping, and air showed increases of 39%, 23%, and 31% respectively. Clearly, from the EIA projections, trucks are expected to continue to dominate freight energy use in the United States.

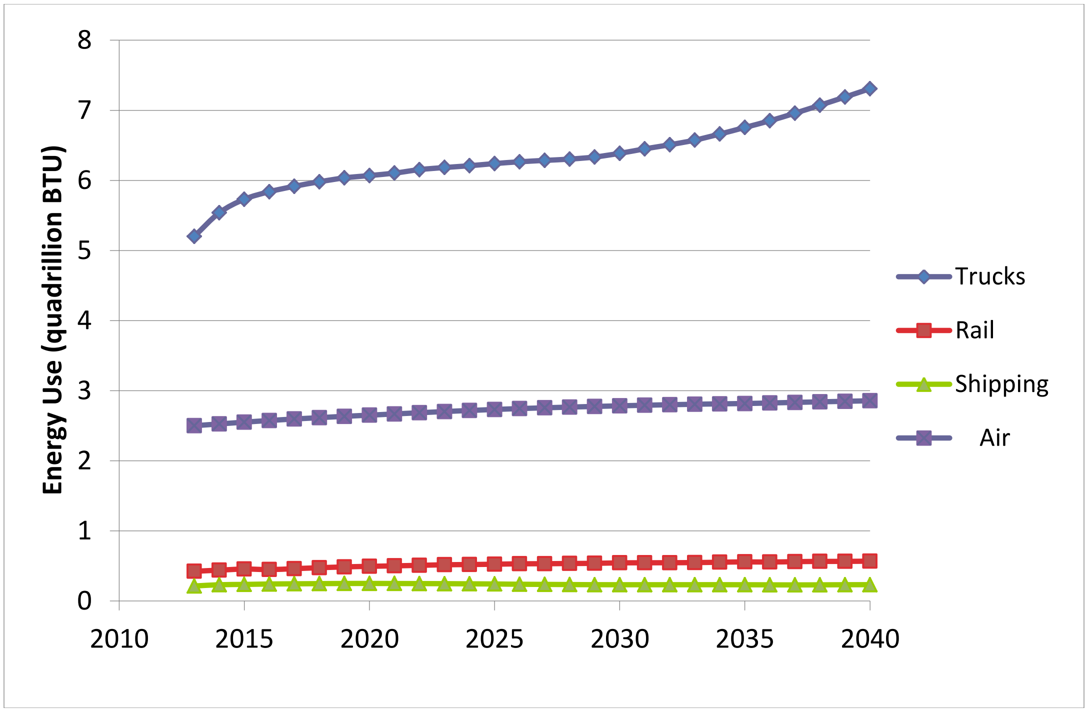

Figure 1. AEO 2015 projection of energy use by mode to 2040

3. Technologies and Fuels for Trucks

There are several types of trucks with a range of usage and travel characteristics. Different studies and reports often do not use the same groupings. In the U.S. Department of Transportation (USDOT) classification system, all medium-duty and heavy-duty trucks are given a Class between 2 and 8, but some trucks in the same class might be driven in very different ways. For example, a truck in the heaviest class, Class 8, may be used as a long haul truck that might drive 125,000 miles/year mostly at high speeds on highways or as a short haul truck driving less than 50,000 miles/year with significant urban driving at low speeds. These differences also affect fuel economy and fuel consumption, vehicle range and fuel storage requirements, and subsequent vehicle cost, and help guide the identification of the most appropriate technologies for reducing CO_2e. Table 3 lists trucks according to the type of work they perform along with characteristics of those trucks.

Table 3. Truck vehicle type with associated characteristics

Truck Type	Description or Example	Average Mileage/Year	Relative Fleet Size
Long haul	Class 8 long distance travel	Very high ~100,000	Medium
Short haul	Class 7, 8 regional travel	High ~50,000	Low
Heavy-duty vocational	Refuse truck	Medium 20,000 – 30,000	Medium
Medium-duty vocational	Trash compactors, bucket trucks	Medium 20,000 – 30,000	Medium
Medium-duty urban	Delivery trucks (UPS, FedEx)	Medium 20,000 – 30,000	High
Buses	Transit buses, shuttles, coaches	Medium ~30,000	Medium
Heavy-duty vans and pickup trucks	Class 2B and 3 > 8,500 lbs. GVWR	Medium 20,000 – 30,000	Very high

The medium- and heavy-duty truck sector is a complex and very heterogeneous sector with many stakeholders making decisions using different rational choices (Winebrake et al, 2012). For example, some short haul trucks primarily serve ports; whereas, others may deliver goods from distribution centers. Port trucks must comply with all port regulations and generally spend significantly more time idling or at low speeds (e.g. on the port property). Those trucks are both classified as short haul but may vary in mileage-fuel economy due to different drive cycles, regulations, and other potential factors. Short haul trucks can be purchased by owner-operators (those who own one or only a few trucks) as well as companies that own hundreds of trucks. These owners can differ markedly in how they make purchasing decisions. This paper does not attempt to address these factors or to utilize a rational choice model in determining how new technologies enter the fleet.

Currently, the overwhelming number of trucks in all classes are conventional trucks using diesel or gasoline fuel with diesel fuel dominant in the larger classes. Some classes have a small to moderate number of alternative fuel or new technology vehicles such as natural gas. The vehicle drivetrain and fuel technologies that could play a significant role in the trucking sector are:

- Conventional diesel and gasoline – Vehicles using spark ignition and compression ignition engines and running on either diesel or gasoline.
- Hybrid and plug-in hybrid – Vehicles that use both gasoline or diesel engines and batteries for propulsion.
- Natural gas – Vehicles that use liquid natural gas (LNG), or compressed natural gas (CNG) for fuel, with either a spark-ignition (SI) or compression-ignition (CI) engine.

- Fuel cell – Vehicles that use a fuel cell in place of an engine. Usually these vehicles operate on hydrogen fuel.
- Battery electric – Vehicles that use electric motors for propulsion with battery storage of electricity.

Table 4 lists the commercial status of these technologies along with barriers or other issues.

Table 4. Vehicle technologies, commercial status, and barriers to commercialization

Vehicle Technology	Commercial status	Efficiency, Range, and Vehicle Cost	Barriers/issues
Conventional diesel/gasoline	Presently dominate all truck types	(baseline technology)	Relatively heavy emitters of GHGs
Hybrid, plug-in hybrid	Commercial in heavy-duty pickups and buses. Expected to play a significant role in all types.	Increased efficiency. Increased range. Increased cost.	Reduce GHGs but reductions are modest compared to fuel cell and electric.
LNG/CNG	Commercial in almost all types. CNG has significant market in buses, medium-duty urban.	With SI, slight decrease in efficiency. No efficiency penalty with CI (HPDI) engine, but increase in cost.	Little reduction in GHGs except with a transition to RNG. Infrastructure not fully mature.
Fuel cell	Extensively tested in buses and cars. Timeline for commercialization in other vehicle types could be 10-20 years.	Large increase in efficiency. Decreased range. Significant cost increase.	Shorter life than diesel engines for the foreseeable future. Hydrogen infrastructure lacking.
Battery electric	Near commercial in some applications.	Large increase in efficiency. Significant decrease in range. Increase in cost.	Only suitable for short-range vehicles. Battery life may not last expected truck life.

Presently diesel fuel dominates all other fuels used in trucking with heavy-duty pickups and vans using gasoline and other applications (i.e., buses and delivery trucks) using modest amounts of natural gas. In order to reach climate change goals, alternative fuels that can provide zero or near-zero emissions must replace a large percentage of truck fuel. For each of these different powertrain types, a range of fuel and/or feedstock options exist. This paper focuses on the major fuel pathways as shown in Table 5. Other fuel/feedstock types, such as RNG (natural gas from biomass rather than fossil sources), are possible. Biofuels, hydrogen, and electricity can all be produced from a wide range of feedstocks; a detailed treatment of the many different pathways is beyond the scope of this paper, but those included here cover the major types and categories available.

For the analysis presented in this paper, a comparison of vehicle costs and fuel costs was made, with estimates for LNG and liquid hydrogen (LH2) based on providing these at a scale typically provided at truck stops. Table 5 lists fuels that are expected to play a significant role in the trucking sector and gives costs and potential issues associated with those fuels. For other years, a linear interpolation was made between the 2010 and 2030 costs, and the 2030 costs are assumed to apply generally between 2030 and 2050 in the projections provided further below. The table shows costs per energy content (not per mile). For example, while electricity costs more than diesel based on energy content, electric vehicles are much more efficient than diesel vehicles and therefore have a lower cost per mile. More details on this cost analysis are available in the paper's Appendix.

Table 5. Present and potential fuels for truck applications, near-term and future costs (retail price equivalents, dollars per diesel gallon equivalent (dge) based on average estimates)

Fuel	**Fuel Cost per dge, circa 2014**	**Projected Cost, 2030**	**Source/Comments**
Diesel	$2.71	$4.01	AEO 2015 (fuel taxes removed)
LNG	$2.75	$3.21	Based on UCD NG model estimates (STEPS 2015). Infrastructure must be built out and has high near-term capital cost
Renewable diesel	$5.31	$3.87	NREL, 2013; near term from hydrotreated oils; long term from thermo-chemical process such as Fisher-Tropsch
Liquid hydrogen (LH2) from natural gas	$5.92	$4.39	LH2 derived from natural gas reforming, followed by liquefaction
LH2 from electrolysis	$11.08	$6.97	Electrolysis from average electricity mix, followed by liquefaction
Electricity	$3.80	$4.22	EIA AEO 2015 average U.S. transportation retail price

Notes: Table is further detailed in Table A-3 in the Appendix. Diesel price does not reflect recent reductions due to the crude oil price reductions during 2014.

Each of the vehicle technologies and technology/fuel combinations has advantages and drawbacks compared to today's conventional vehicles. Most notably, today's diesel trucks benefit from very long driving range (over 1,000 miles on a single refueling), using a very durable and reliable type of engine that can often last well over 500,000 miles of truck use for long haul trucks. Transitioning to any other propulsion system (e.g. motors with batteries, fuel cells running on hydrogen) is likely to require compromises in these regards. In addition, long haul trucks with fuel cell/hydrogen and motor/battery systems will likely suffer from driving range compromises compared to today's (and future) diesel trucks. Table 6 shows the efficiency and thus fuel storage volume requirements for several options.

Table 6. Vehicle efficiency and range/fuel storage requirements for long haul trucks

	Diesel	**Hybrid**	**Diesel**	**Diesel Max Tech**	**LNG-CI**		**CNG-SI**		**Fuel Cell / LH2**	
	2014	2014	2030	2030	2014	2030	2014	2030	2014	2030
MPG (diesel equivalent)	6.5	6.9	9.3	11.2	6.5	9.3	5.7	8.1	10.9	13.3
Gal/100 miles (own fuel units)	15.3	14.5	10.7	8.9	15.3	10.7	17.6	12.3	9.2	7.5
Fuel storage requirement (volumetric gallons for 500 mile range)	77	73	54	45	131	92	332	233	300	225

Based on a range of sources: see Appendix

As shown, in order to deliver 500 miles of range per refueling, the CNG SI and fuel cell/LH2 options require much larger onboard fuel storage than conventional diesel, and LNG with CI would require somewhat more. In this analysis, CNG is assumed to be coupled with SI since the combination is the cheapest and has the best pollutant emissions characteristics; LNG is coupled with CI because this combination provides the longest range (and thus is only considered for long haul trucks). Biodiesel isn't shown since it is assumed to have similar characteristics and requirements as diesel engines, particularly when in the form of renewable diesel (drop-in biodiesel). Battery electrics also are not shown, because these are not considered for long haul due to severe range limitations. It is worth noting that long haul trucks can accommodate fairly large fuel tanks, so, even for batteries there may be fairly large spaces available on tractors; and if trailers are used for battery storage, it is possible that systems could be developed that achieve the 500 mile target. The weight penalty, however, could also be substantial, and recharge times will also be much longer than refueling times for today's vehicles.

4. Cost and CO_2e Comparison across Technologies and Fuels

New vehicle technologies generally are more expensive when they are first commercialized, with costs decreasing over time due to increased production volumes and improvements in design and manufacturing. As shown in Table 7 (and in the Appendix, Tables A-1 and A-2) the costs for present and future heavy-duty trucks are estimated to vary significantly by technology and fuel type. Mature technology costs, such as the purchase price of diesel trucks, are held constant through 2030 under the assumption that incremental technology advances may cost more when introduced but volume sales will then reduce these costs. Fuel cell trucks are estimated to be the most costly, though their price drops substantially by 2030 due to fuel cell cost reductions related to scale and technology learning (modest production scales are assumed even in current costs, though larger scales are assumed for 2030). Electric short haul trucks with reasonable range (e.g. 400 miles) are more expensive still, and are not included in the long haul truck analysis (which assumes 1,000-miles range) due to their range limitations. Given battery cycle limitations, some BEVs may eventually require a replacement battery pack. More data from commercial electric trucks will better determine expected battery life, and future battery research likely will extend cycle life. This analysis does not consider the possibility of needing a replacement battery during vehicle life. Several potentially important but uncertain factors that affect the cost were not included in this analysis. These factors include vehicle maintenance, potential additional downtime, possible loss of payload due to increased vehicle weight, impact of more frequent fueling, financing of new technologies, and infrastructure requirements.

Table 7. Purchase cost estimates for various technology trucks for 2014 and 2030 ($ thousands)

	Diesel		**Hybrid**		**Natural Gas (LNG/CNG)**		**Biofuels**		**Fuel Cell**		**Electricity**	
	2014	2030	2014	2030	2014	2030	2014	2030	2014	2030	2014	2030
Long Haul	160	160	185	177	224/ 183	187/ 183	160	160	255	216	NA	NA
Short Haul	145	145	170	162	209/ 168	172/ 168	145	145	240	201	466	309

Based on a range of sources; see Appendix

Truck purchase cost and fuel cost were then combined to estimate the present value of the cost to own and operate a truck over a given period of time (this does not include non-fuel operating and maintenance costs). We conduct this analysis for long haul and short haul heavy-duty trucks. We consider two time periods—the present and 2030. The 2030 vehicles are assumed to be fully commercial and sold in large volume such that capital costs have benefitted from learning curves and significant sales. The technologies and fuels considered are diesel, advanced diesel, hybrid, LNG, biofuels, and hydrogen fuel cells. The lifecycle CO_2e emissions from both upstream and vehicle operation described above are used for the cost-per-ton estimates. Finally for each type of vehicle, a value for average payload is taken from U.S. EPA data (Long haul – 16.87 tons, Short haul – 11.95 tons) (U.S. EPA 2011).

Table 8 gives the financial parameters used in the analysis. Figures 2 and 3 show the present value for the annual cost including purchase cost and fuel costs over 15 years (discounted to present value at a societal 4%) for each vehicle, technology and fuel type for both long haul and short haul trucks. Other costs (such as operations and maintenance) are not included since there are not sufficiently good estimates of these costs and how they may vary across technology/fuel type to warrant their inclusion.

Table 8. Financial parameters for cost effectiveness analysis

Parameter	Long Haul Truck	Short Haul Truck
Lifetime of vehicle (years)	15	15
Annual travel (miles)	125,000	50,000
Years amortized	10	10
Interest rate for amortization (%)	10	10
Discount rate for present value calculation (%)	4	4

As shown, there is not a great deal of difference in the “ownership” (purchase plus fuel) cost of most of the options within the given time frame. The most expensive option in the near term is fuel cell trucks operating on hydrogen, with a high purchase cost that is projected to decline over time. Advanced biofuels are also expensive in the near term and thus are not expected to be used in the absence of policy; bio-oil based fatty acid methyl esters (FAME) are assumed more likely to be the main diesel replacement fuel. In the longer run, advanced biofuels have a reasonable chance to reach a similar cost level if produced at large volume, with technology learning.

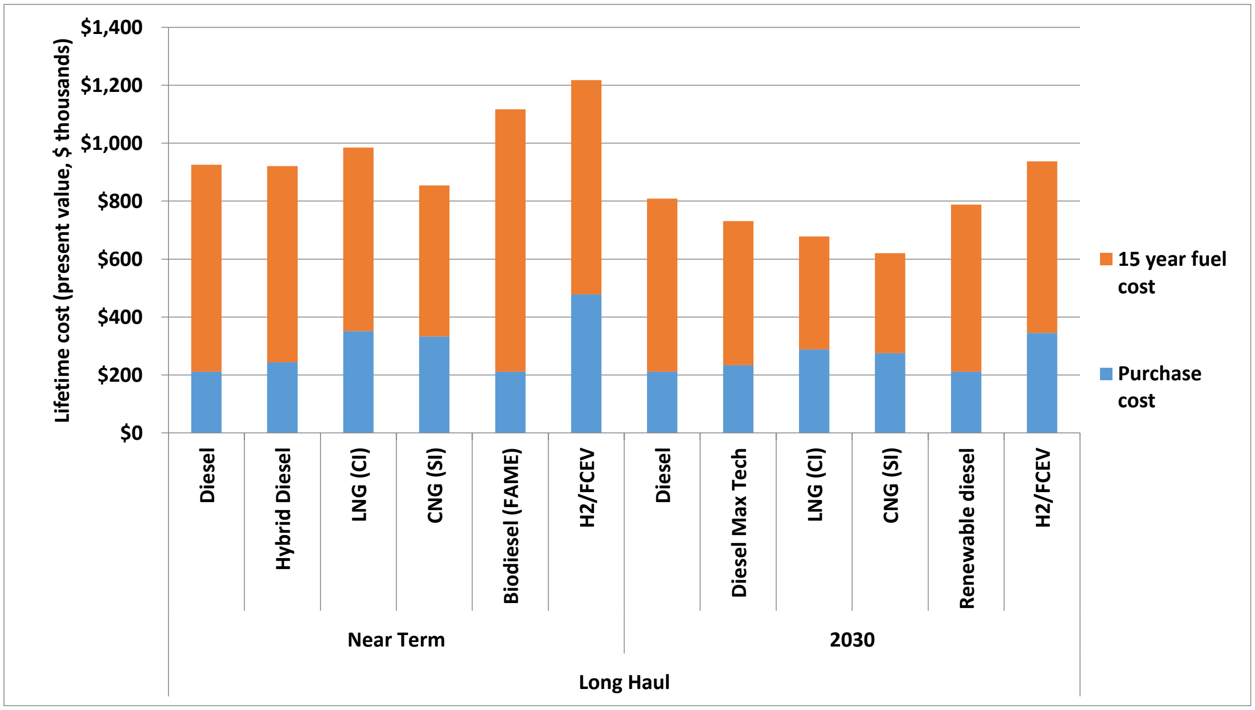

Figure 2. Lifetime vehicle plus fuel cost (present value) for various long haul technology vehicles. Note: Fuel costs for 2014 vehicles are an average of 2014 and 2030 costs to reflect an average over 15 years of fuel use. Biofuels in 2014 are FAME from oil-seed crops and in 2030 are advanced biofuels from dedicated biomass crops such as switchgrass, so a transition is assumed. Hydrogen derives from natural gas in 2014 and from low-carbon electrolysis or natural gas with carbon capture and storage (CCS) in 2030.

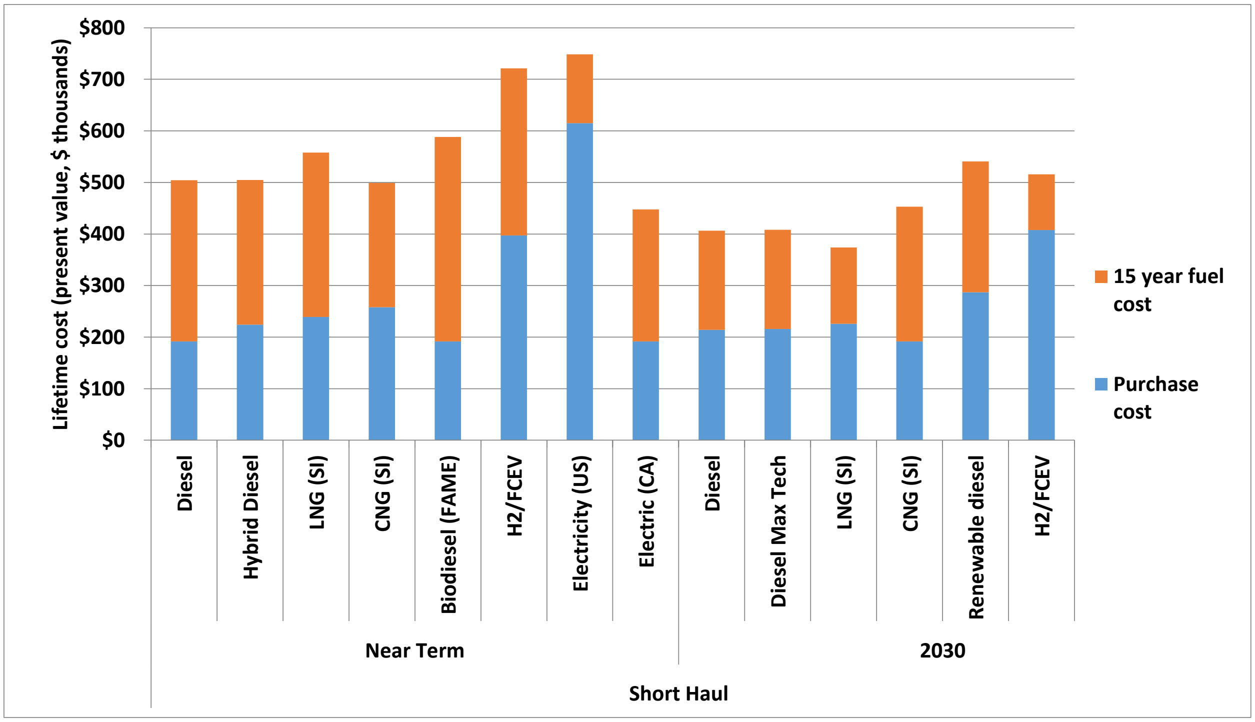

Figure 3. Lifetime vehicle plus fuel cost (present value) for various heavy-duty short haul technology vehicles

Figure 4 provides a comparison of average CO_2e intensity of different fuels used by trucks in the near term and in 2030, based primarily on GREET (2014) model runs, using averages of typical pathways. There are wide variations off these averages depending on the specifics of a fuel pathway and various uncertainties, such as from land-use change. Thus these averages should be considered very rough, but provide a general sense of GHG emissions from using these fuels and these pathways.

Compared to 2014, there are two significant changes in average GHG in the 2030 pathways. First, biodiesel shifts from primarily oil-seed based FAME to primarily advanced drop-in diesel replacement fuel from thermochemical process or upgraded pyrolysis oils derived from cellulosic biomass resources. Either of these pathways will release relatively little fuel-cycle CO_2e. Second, hydrogen production shifts from being primarily from natural gas via steam methane reformation (SMR) to much lower carbon pathways such as electrolysis from electricity, benefiting from grid decarbonization. It is also possible that hydrogen could be produced using “excess” electricity from renewables (i.e., solar, wind power). Other pathways are certainly possible and the transition implied here may be challenging, but the 2030 electrolysis/wind pathway offers a view of the likely long-term approach to producing clean hydrogen.

The electricity available for making hydrogen or for charging truck batteries is shown for both a U.S. and California mix of generation. The 2014 estimates are mainly from the ANL GREET model (ANL, 2014) while for 2030 a 20% reduction in grid carbon intensity is assumed as part of a general program to cut CO_2e emissions in the United States or California. Since some grid decarbonization targets exceed this level, it is possible that deeper cuts will be made, improving the performance of electricity compared to what is shown here.

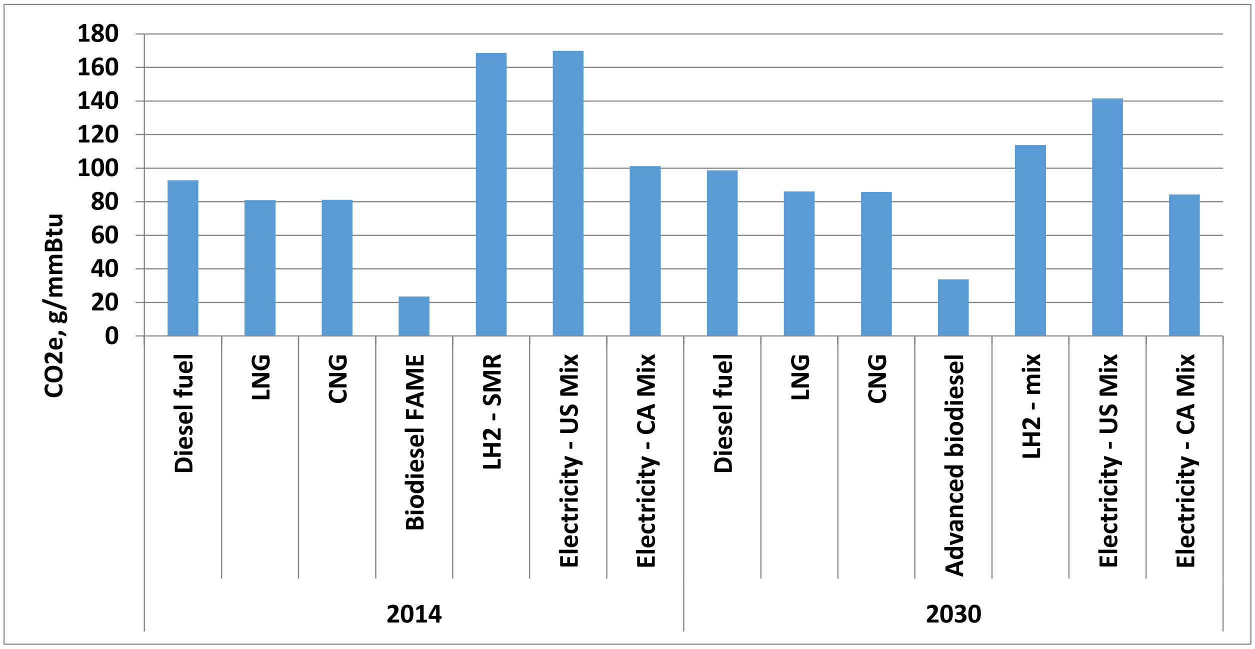

Figure 4. Average estimates for fuel CO_2e emissions per unit energy (carbon intensity), well-to-wheel, 2014 and 2030 (does not take into account vehicle efficiency)

Figure 5 shows the results of applying the per-unit fuel estimates of CO_2e emissions with the efficiency of different vehicle types, in terms of total CO_2e emitted over 15 years of vehicle life. Compared to the average or even best diesel truck in 2014, nearly all alternatives provide CO_2e reduction benefits. By 2030, several options have achieved very low CO_2e levels. It should be noted that for the 2014 trucks, these will use fuel over the 15 years to about 2030, so the fuel pathway GHG will evolve. We thus use an average of the 2014 and 2030 CO_2e intensity of fuels. For 2030 trucks, the 2030 CO_2e intensity is used, assumed to remain stable to 2045.

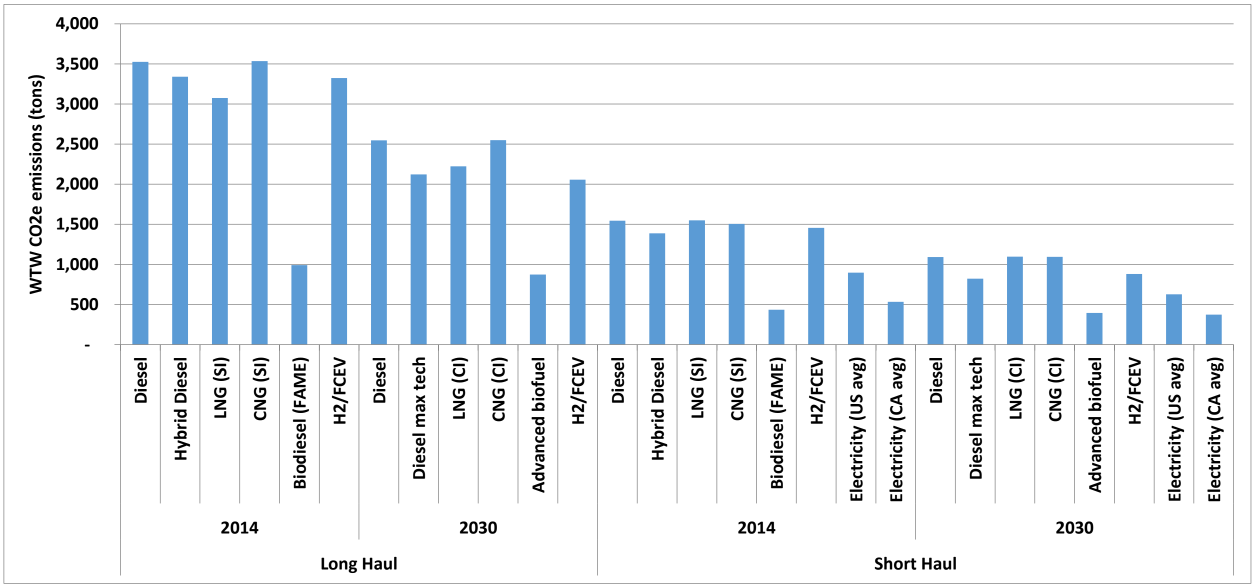

Figure 5. Well-to-wheel CO_2e emissions over vehicle life for long haul and short haul trucks

Figure 6 shows the result of adding vehicle lifetime CO_2e emissions cost to vehicle purchase and fuel cost from previous figures. A $50/ton CO_2e price is used here for illustrative purposes. While the CO_2e cost adds significantly to the total costs for diesel fuel trucks, it does not make these definitively more expensive than other options in the near term or 2030 analysis, but it generally reduces their advantage. For long-haul trucks in 2030, diesel with CO_2e costs is as high or higher than all the other options shown. Notably, fuel cell trucks with low-carbon hydrogen has a very similar cost to diesel. For short haul, electric truck lifecycle plus CO_2e costs are close to diesel.

It is important to be clear that all of the cost and CO_2e estimates are uncertain, in the near term and especially for 2030, and changes in assumptions could change the relative height of bars significantly.

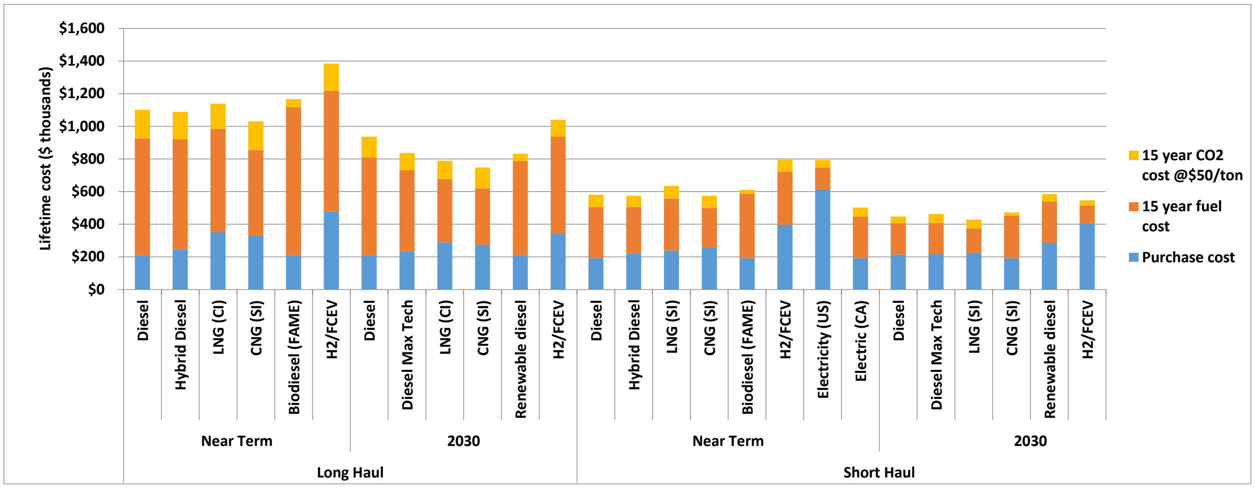

Figure 6. Truck lifecycle costs with GHG emissions cost added ($50/ton CO_2e price assumed)

There are two important considerations in the results shown in Figure 6. First, the results represent a societal cost outcome, not a private cost outcome. Including 15 years of fuel consumption with a 4% discount rate results in fuel savings having a large impact on overall costs compared to a private calculation which might more typically entail a 30% discount rate over just a few years (or a 2- or 3-year payback rate on fuel savings, common among trucking companies in considering more expensive trucks options that save fuel, ICCT, 2013). However, this societal cost perspective is appropriate for making choices and setting policy in a societally optimal manner.

Second, the results in Figure 6, where total costs appear visually to be "close," may relate to very wide swings in cost per ton of CO_2e emissions reduction if plotted as marginal CO_2e costs of reduction of each technology compared to diesel as a base technology (not shown). That approach to showing cost per ton is highly sensitive to small changes in assumptions. For example, if an alternative fuel truck reduces CO_2e by 1,000 tons over vehicle life and the cost swings from 10% more (e.g. $150,000 above a base truck that costs $1.5 million over a 15-year life) to 10% less ($150,000 under the base truck), the cost per ton would swing from $150 to -$150 (negative $150). If that truck cuts CO_2e by only 100 tons instead of 1,000, the cost per ton would swing by a far larger amount: from $1,500/ton to negative $1,500/ton. For these reasons, we prefer to present the costs as wedges based on a $50/ton CO_2e price.

The main takeaway from Figure 6 is that there seems to be a reasonable prospect for all of advanced biofuels, electricity and hydrogen/fuel cells to be competitive with diesel by 2030, taking into account the types of costs considered, and the reductions in costs assumed and described above. In addition, the higher near-term costs of these options will require policies to help overcome barriers and achieve sales volumes and learning that help achieve the future cost reductions.

5. Transition Scenario Comparisons

To understand the potential GHG reductions from the introduction of new technologies and fuels, we review several U.S. studies that have created market penetration scenarios. These scenarios introduce advanced fuels and technologies into the trucking fleet and calculate the effect on GHG emissions. In general, the studies estimate the increase in travel demand, increase in fuel economy, and the decrease in carbon intensity for each vehicle type and for the transportation sectors overall.

McCollum et al, 2010

McCollum *et al* considered three sets of scenarios for the entire U.S. transportation sector (McCollum 2010). The study did not include cost information or dynamic effects in fleet penetration. Their scenarios included a reference scenario to establish a business-as-usual baseline, "silver bullet" scenarios that considered the effect of individual solutions, and multi-strategy scenarios that included mixes of the silver bullet strategies. Table 9 gives a brief description of the scenario components. Since there are indications that biofuels production cannot fuel the entire transportation sector, the study limits overall biofuels use in the U.S. to 90 billion gasoline gallon equivalent (GGE).

Table 9. Scenario descriptions for the McCollum *et al* study

Scenario	Description
Reference	Conventional vehicles and fuels used for all sectors. Energy intensity is reduced significantly (47% overall), but carbon intensities remain high.
Silver bullet	Individual strategies include efficiency increases, biofuels, hydrogen, electricity, and reductions in VMT. No strategy reduces GHGs significantly compared to 1990 levels.
Combination Scenarios	
Efficient biofuels	High efficiency (63% improvement across all transportation sectors). All light-duty vehicles and 20% of buses are fueled by biofuels. Other sectors use conventional fuels. Overall GHG reductions are 50% from 1990.
Electric drive	Light-duty vehicles are entirely electric drive (60% fuel cell, 40% battery electric). Rail and buses are also electric drive. Heavy-duty vehicles use conventional fuels. Energy intensity is reduced 68% and carbon intensity is reduced 41%. Overall GHG reductions are 50% from 1990.
Multi-strategy	Combines electric drive and biofuels. Light-duty vehicles, buses, and rail are mostly electric while heavy-duty vehicles use mostly biofuels. Energy intensity is reduced 68% and carbon intensity is reduced 76%. Overall GHG reductions are 80% from 1990.

Table 10 shows details specifically for the heavy-duty vehicle sector for the three combination scenarios.

Table 10. Heavy-duty vehicle characteristics for the McCollum *et al* combination scenarios

	Share of Miles by Fuel Type (%)					
Scenario	**Conventional**	**Biofuels**	**Hydrogen**	**Electricity**	**Energy Intensity Reduction (%)**	**Carbon Intensity Reduction (%)**
Efficient biofuels	80	20	0	0	32	18
Electric drive	31	35	28	5	34	51
Multi-strategy	0	63	28	9	35	80

The study concluded that baseline GHG emissions from the heavy-duty vehicle sector would increase roughly 175% and overall transportation emissions would increase 82% from 1990 levels. The efficient biofuels and electric drive scenarios are capable of reducing GHG emissions roughly 50%, but to reach a goal of 80% reductions by 2050 in the entire transportation sector, a combination of aggressive strategies are needed.

Pew Research Center Study

A Pew Research Center study considered a large number of potential strategies to reduce GHGs from the transportation sector (Greene and Plotkin, 2011). The study focuses on policies and measures that would cause changes in technologies, fuels, and usage. They created four scenarios—base case, low, medium, and high mitigation cases. Table 11 lists the cases along with descriptions of the policies or measures that define them. The study includes cost effects and assumes new technologies and fuels will enter the fleet when cost effective.

Table 11. Pew Research Center study scenario descriptions

Scenario	Description
Base case	EIA's 2010 reference case extrapolated to 2050. High energy prices, existing emissions regulation, significant renewable fuel usage.
Low mitigation	GHG standards resulting in light-duty vehicles reduction of 2%/year. Energy efficiency user fees, modest increases in efficiency for rail, air, and shipping.
Medium mitigation	More rapid technological progress. Innovative pricing policies. Emissions standards stricter than low mitigation scenario. Land use strategies, feebates, and minimum liability pay-at-the-pump (PATP) insurance are utilized.
High mitigation	Aggressive emissions standards. More land use, congestion pricing, and comprehensive PATP insurance introduced. Transition to electric and hydrogen vehicles well underway by 2050. Automated highways introduced by 2050.

Table 12 shows the changes in fuel economy both from the specific breakthrough technology, automated highways, and from all strategies combined. The table also shows the change in carbon intensity from biofuels usage. Changes are relative to 2010 values.

Table 12. Pew Research Center study indicators for heavy-duty vehicles by scenario. Percent change in fuel economy used in mitigation scenarios, percent change in carbon intensity due to biofuels usage, and percent change in fuel economy due to breakthrough technologies (automated highways)

	2035			**2050**		
	Low	**Medium**	**High**	**Low**	**Medium**	**High**
Total fuel economy (% change in mpg)	15%	25%	30%	25%	35%	40%
Biofuels (% change in carbon intensity)	-2%	-10%	-15%	-10%	-15%	-37.5%
Automated highways (% change in mpg)	0	0	0	0	5%	10%

Table 13 shows the Pew study GHG reductions for the transportation sector in the three mitigation scenarios from vehicle efficiency, vehicle efficiency and low-carbon fuels use, and all strategies combined. All reductions are calculated from 2010 values. The middle scenario only manages to reduce GHGs by 39%, and the high scenario reduces GHGs by 65%.

Table 13. Pew Research Center study results for GHG reductions from energy efficiency gains, low-carbon fuels, and overall reductions for the three mitigation scenarios

	% Reduction in GHGs from 2010 Levels		
	Low Scenario	**Medium Scenario**	**High Scenario**
Vehicle efficiency improvements	-4	-16	-25
Vehicle efficiency plus low-carbon fuels	-10	-25	-54
Overall reductions	-16	-39	-65

The two studies above consider the entire U.S. transportation sector. The strategies attempt to reduce GHG emissions for the entire sector and do not require specific subsectors to reduce GHG emissions a full 80% by 2050. The studies primarily utilize biofuels and increased vehicle efficiency to produce truck reductions, and neither study reaches a full 80% reduction for the trucks they included. In the McCollum et al study, the shortfall in GHG reductions for the trucking sector is balanced by additional reductions in other sectors such as light-duty vehicles such that the overall reductions reach 80% in 2050. The Pew study only reaches 65% reductions in 2050 across all sectors.

California Vision 2050 Report (2012)

In 2012, three California agencies (Air Resources Board, South Coast Air Quality Management District and San Joaquin Valley Unified Air Pollution Control District) prepared a visioning document that covered both GHGs and air pollutant emissions, considering targets out to 2050 and how to achieve these. The report is built on several California targets: an 80% reduction in GHG across energy sectors relative to 1990 levels (or about 85% compared to today), a 2023 NOx target of 80% below 2010 levels and a 2032 NOx target of 90% below 2010. The combination of NOx and GHG targets has a significant impact on the consideration of transportation scenarios in this report.

The “advanced technology” scenario includes deep GHG reduction in all transportation modes, and a strong move toward ZEVs. By 2040, all passenger vehicles sold in California are ZEV; by 2050, for trucks, the average fuel economy doubles and truck NOx emission standards are 80% below the current standards. And as shown in Figure 7, trucks evolve rapidly toward ZEV technologies; by 2030 40% of heavy truck sales are ZEV and 20% more are near-ZEV, and by 2040 all conventional vehicle sales are phased out (with only fuel cell, electric and plug-in hybrid trucks sold). In addition, petroleum fuels across all modes are eliminated—all liquid fuels in 2050 are renewable. For electric vehicles (which include many cars, trucks and rail systems), the electric grid capacity grows to meet new demands, yet is substantially cleaner with heavy reliance on either renewables or carbon capture and storage (CCS).

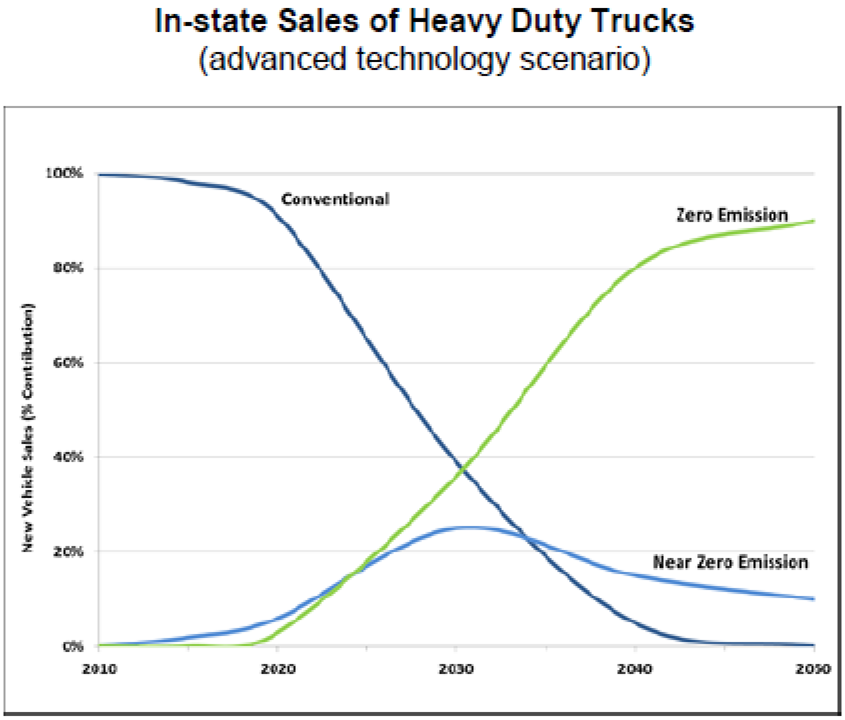

Figure 7. Vision 2050 scenario for heavy-duty truck sales

Rather incredibly, while all of these changes are sufficient to meet the GHG target in 2050, for NOx emissions the scenario falls short—it hits the 2032 target well after 2040. For trucks the target NOx emissions levels for 2032 are not met until 2050. Thus an even faster move to ZEVs would be desirable if it were deemed feasible.

The report does not estimate the costs of these scenarios, but acknowledges that the advanced technologies it relies on are currently expensive. It relies on efficiency gains and cutting fuel costs dramatically to help offset higher vehicle purchase costs.

6. New Projections with the TOP-HDV Model

One additional low CO_2e truck study was recently undertaken by Ben Sharpe, who developed projections of truck CO_2e emissions for his UC Davis Ph.D., completed in 2014. For this he developed the TOP-HDV model, which focuses on the trucking sector in California and includes several scenarios using different technologies and fuels (Sharpe 2013, and briefly described in the appendix). For purposes of this white paper, his work has been updated and modified to match various assumptions and inputs described in sections above. While his research focuses on a subset of the U.S., namely California, it contains a detailed year-by-year calculation of the trucking fleet, vehicle technology, fuels, CO_2e emissions, and costs with an 80% reduction scenario that provides some insights also applicable to a U.S.-wide truck CO_2e strategy. While scenarios do not show what is likely to occur in trucking fleets (rather they simply build plausible scenarios), they can demonstrate what is required to meet various goals. For example, one TOP-HDV scenario shows a ramp-up of ZEV trucks that could achieve an 80% reduction target if ZEVs are the primary path to GHG reductions. A second scenario shows how this rapid fleet penetration could be alleviated through significant increase in production and use of advanced, very-low-carbon biofuels.

The scenarios in TOP-HDV were also used to build a simplified model for the U.S. and project the same scenarios at a national level. The same technologies, efficiencies and assumed travel per truck for different truck types is assumed in the U.S. scenarios, but the total VMT and number of trucks is adjusted using EIA AEO 2015 data and projections.

The TOP-HDV model includes the vehicle types and technologies listed in Tables 3 and 4, and breaks trucks into many more types and sizes than considered in the other studies (or any other known truck CO_2e study). Sharpe's dissertation includes six scenarios, but this paper will emphasize two—baseline and 80-in-50—adjusted from his work as described below. The model is a "what if" and back-casting type of model; it does not have endogenous determination of vehicle sales or use. It has been calibrated to California Energy Commission (CEC) and California Air Resources Board (ARB) projections of truck stocks and travel in California, with baseline projections of technology and fuel shares made on an "expert judgment" basis, and low-carbon scenarios designed to meet specific targets.

The baseline scenario assumes that conventional vehicles dominate the market. But natural gas vehicles are adopted due to favorable economics (assuming ongoing low natural gas prices) and hybrid electric vehicles (HEV) play a significant role as they become more cost-effective over time. Natural gas vehicles play a large role in the urban bus, medium-duty urban, medium-duty vocational, and heavy-duty vocational markets. HEVs play a large role in the other categories.

The following figures contrast the baseline and several 80-in-50 scenarios showing the transition from 2010 through 2050 for such fleet characteristics as, truck sales, truck stock, VMT by vehicle/fuel type, fuel consumption compared to the 2010 average, and GHG emissions by vehicle/fuel type. Figures 8 and 9 show fleet sales for long haul and short haul heavy-duty trucks as a function of vehicle type for the baseline and 80-in-50 scenarios respectively (similar transitional projections are made for other trucks but not shown).

For heavy-duty long and short haul vehicles, Figure 8 shows a heavy dependence on diesel trucks in the baseline scenario with a modest number of natural gas and hybrid trucks in the fleet by 2030 and significant numbers by 2050. These shares are even higher for medium- and light-duty trucks. It is worth noting that, for long haul trucks, a new white paper on long haul natural gas trucks from the UC Davis Institute of Transportation Studies suggests that even the modest natural gas penetrations shown here may be optimistic. They are based on the assumption of ongoing low natural gas prices and rising oil prices, but even if this occurs, that study has found that long haul natural gas trucks may not penetrate the market to a significant degree without supporting policies. That study has not looked at other truck types, which mostly operate in metro areas rather than on highways, and may have less trouble shifting to natural gas, for example if they are centrally refueled.

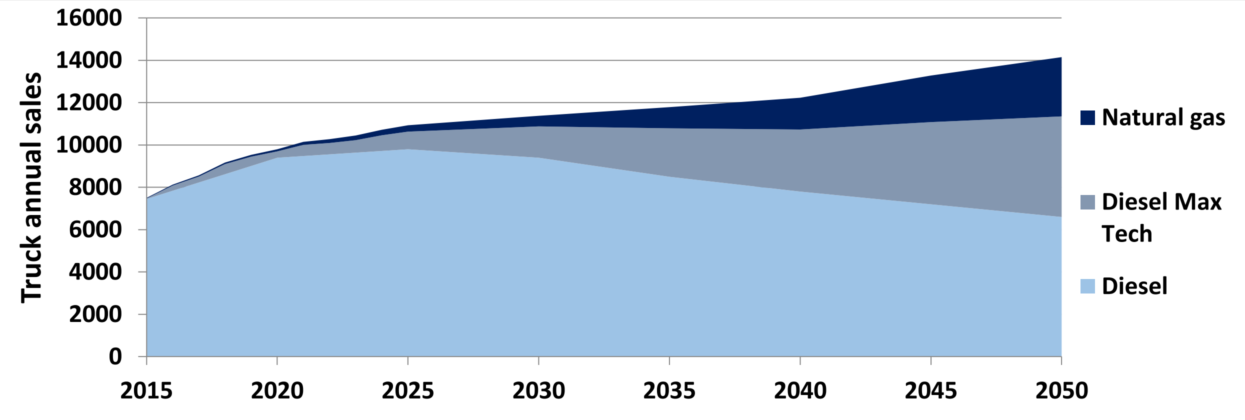

Figure 8. Heavy-duty vehicle sales by vehicle type in the baseline scenario

Two 80-in-50 scenarios are presented for heavy-duty trucks. The first of these (Figure 9 top), the High ZEV scenario, features very rapid penetration of ZEV trucks after 2025, along with massive efficiency improvements in conventional trucks leading to hybridization of most new remaining internal combustion engine (ICE) trucks after 2025. In order to hit an 80% CO_2e reduction target, the sales share of fuel cell vehicles must be nearly 100% by 2040, in order for their stock share to approach 100% by 2050. There must also be a rapid shift to very low GHG hydrogen over the projection period (starting from methane reforming and shifting to pathways such as electrolysis or natural gas with CCS). This allows fuel cells to reach about an 80% reduction in CO_2e, and along with a 95% penetration of the total stock by 2050 (and lower overall fuel use due to the efficiency benefits), the overall 80% target can be met.

The second 80-in-50 scenario (Figure 9 bottom), the “Mixed” scenario, explores the effect of adding large volumes of very low-GHG advanced biofuels to diesel fuel used by conventional and hybrid diesel trucks (and to gasoline for those trucks using that fuel). As the blend share of these biofuels rises, this allows fewer fuel cell trucks to be sold, and potentially starting later. Mathematically, reaching a 100% biofuels share with an 80% GHG reduction per unit energy, and no more fuel use in 2050 than in the base case, would result in an overall 80% reduction. Here we show a case where biofuels “only” reach 90% diesel blends, possible given the large numbers of ZEVs that remain in this scenario.

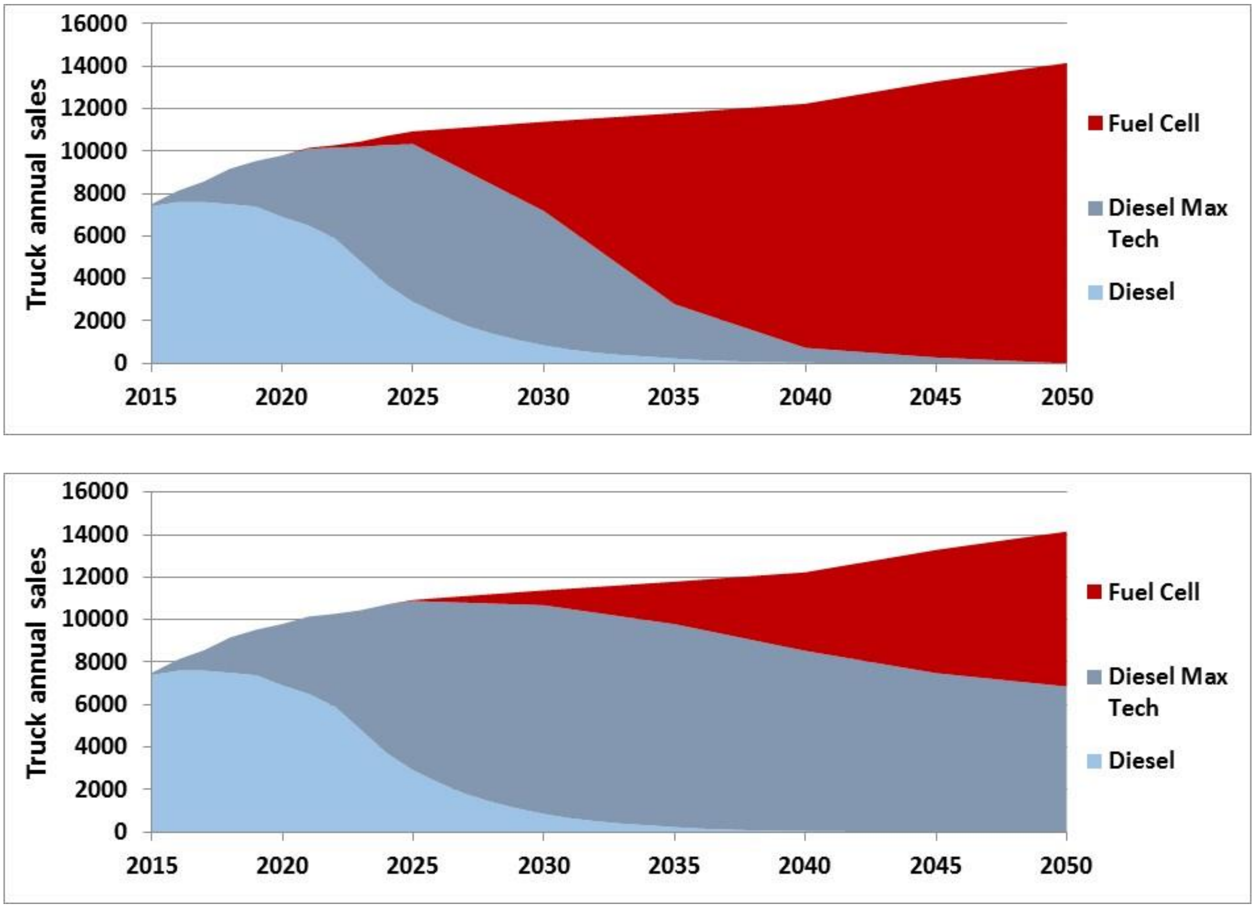

Figure 9. Heavy-duty vehicle sales by vehicle type in the 80-by-50 High ZEV scenario (top) and Mixed scenario (bottom)

Many other scenarios are possible based on varying the VMT projection, the GHG-intensity of fuels and the biofuel blend level, and these should be taken as two examples among an even wider spectrum of possibilities. It should be noted that a 100% biofuels scenario (with no ZEVs) would require twice as much biofuel as shown in the Mixed scenario, so the availability of advanced biofuels would be an important consideration in attempting to follow a ZEV-free scenario. Further, the air quality implications of such a scenario in non-attainment areas may be an important consideration. Overall, given the uncertain nature of both biofuels and ZEV technologies, following a path that includes a combination of different approaches (strong conventional vehicle efficiency improvement, low-carbon hydrogen and electricity, and large volume production of low-carbon biofuels) appears the most robust and flexible pathway to achieving an 80-in-50 target.

For medium- and light-duty trucks (all non-Class 8 trucks), a combined baseline projection is shown in Figure 10 and a “High ZEV” 80-in-50 scenario in Figure 11. (For the remainder of this presentation, the “Mixed” scenario is not shown since the differences are similar to those shown for long-haul trucks.) For medium- and light-duty trucks (mainly commercial pickups), both strong electricity and hydrogen fuel cell truck penetration are assumed. This reflects the expectation that both battery electric and hydrogen trucks appear viable for many of these types of vehicles. These are assumed to have roughly equal market shares in the 80-in-50 scenario, though the shares vary somewhat by specific market class. In a manner similar to the biofuels/hydrogen scenario for heavy trucks, this “hedges the bet” regarding which technology will prove superior for different applications, which can achieve an 80% GHG reduction, and whether costs come down faster for fuel cell or battery systems. In any case the rate of market penetration of these ZEVs must be very rapid if starting from 2025, reaching 80% within about 10 years and 100% within about 15 years (by 2040), in order to achieve the 80-in-50 target (taking into account fleet turnover).

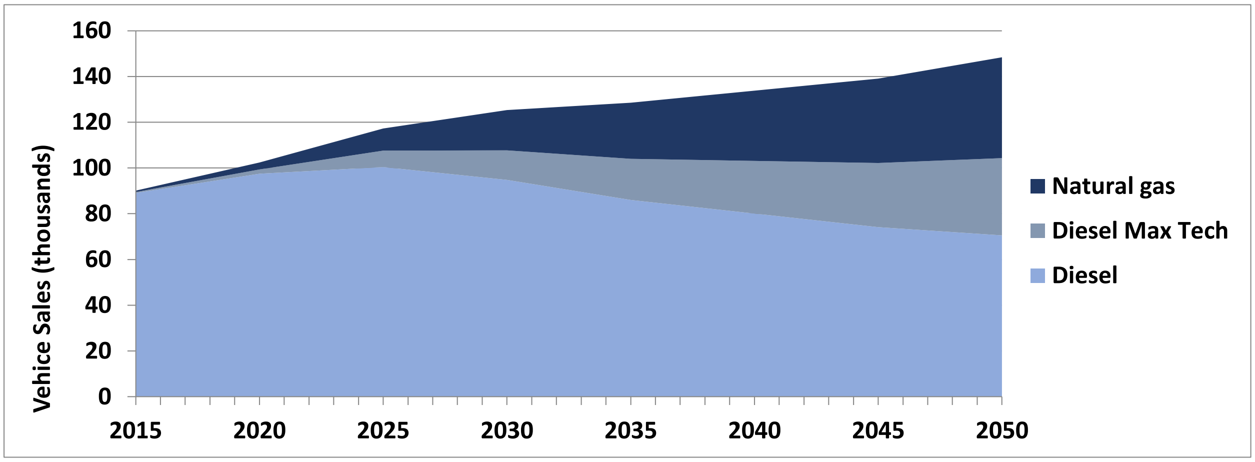

Figure 10. Light- and medium-duty truck sales, baseline scenario

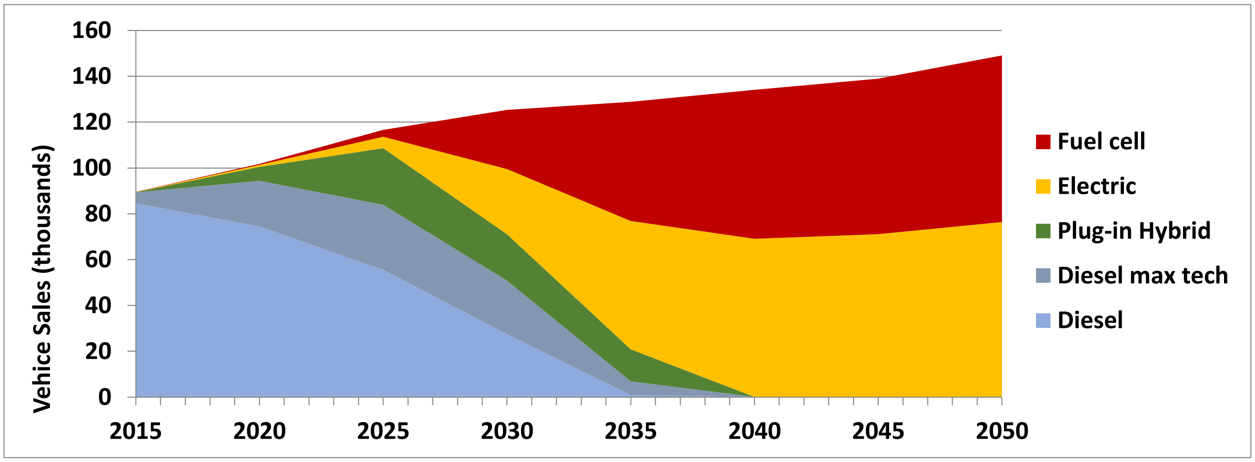

Figure 11. Light- and medium-duty truck sales, 80-in-50 High ZEV scenario

Figures 12 and 13 show our results for total truck stocks for all truck types for the baseline and 80-in-50 High ZEV scenarios respectively. The baseline scenario is very similar to the scenario for long and short haul trucks, but the share of natural gas vehicles is larger for every truck type. The 80-in-50 scenario also requires ZEV trucks to reach 100% of sales in other truck categories by roughly 2040; however, electric vehicles are assumed to have a slightly higher marker share than fuel cell vehicles in many of these, given their urban duty cycles.

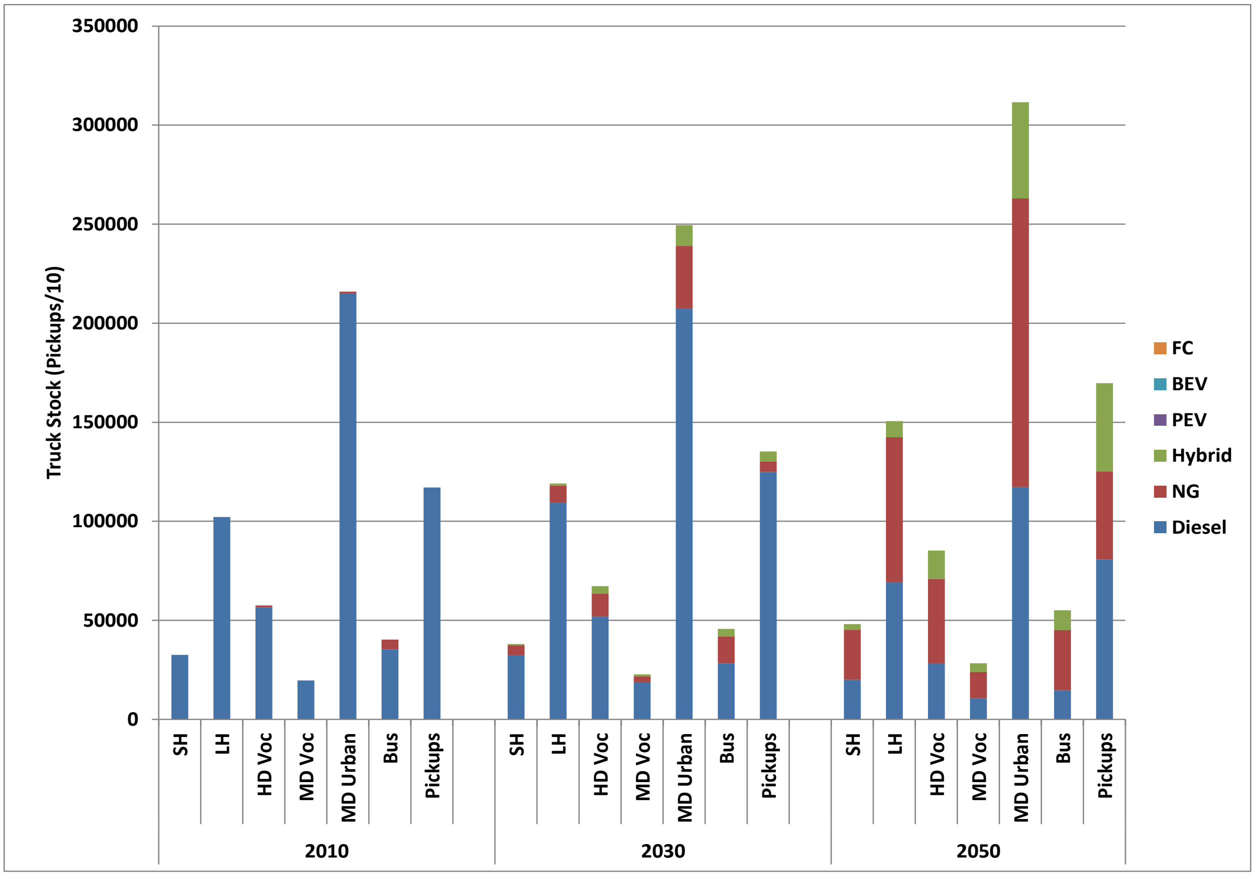

Figure 12. Truck stock for the baseline scenario by vehicle/fuel type for 3 years – 2010, 2030, and 2050 (Pickup stock has been divided by 10 to fit the scale of the figure. SH=short haul heavy-duty; LH=long haul heavy-duty; MD=medium-duty; Voc=vocational; Pickup trucks include commercial "heavy-duty" pickups but exclude lighter pickups often used by households.)

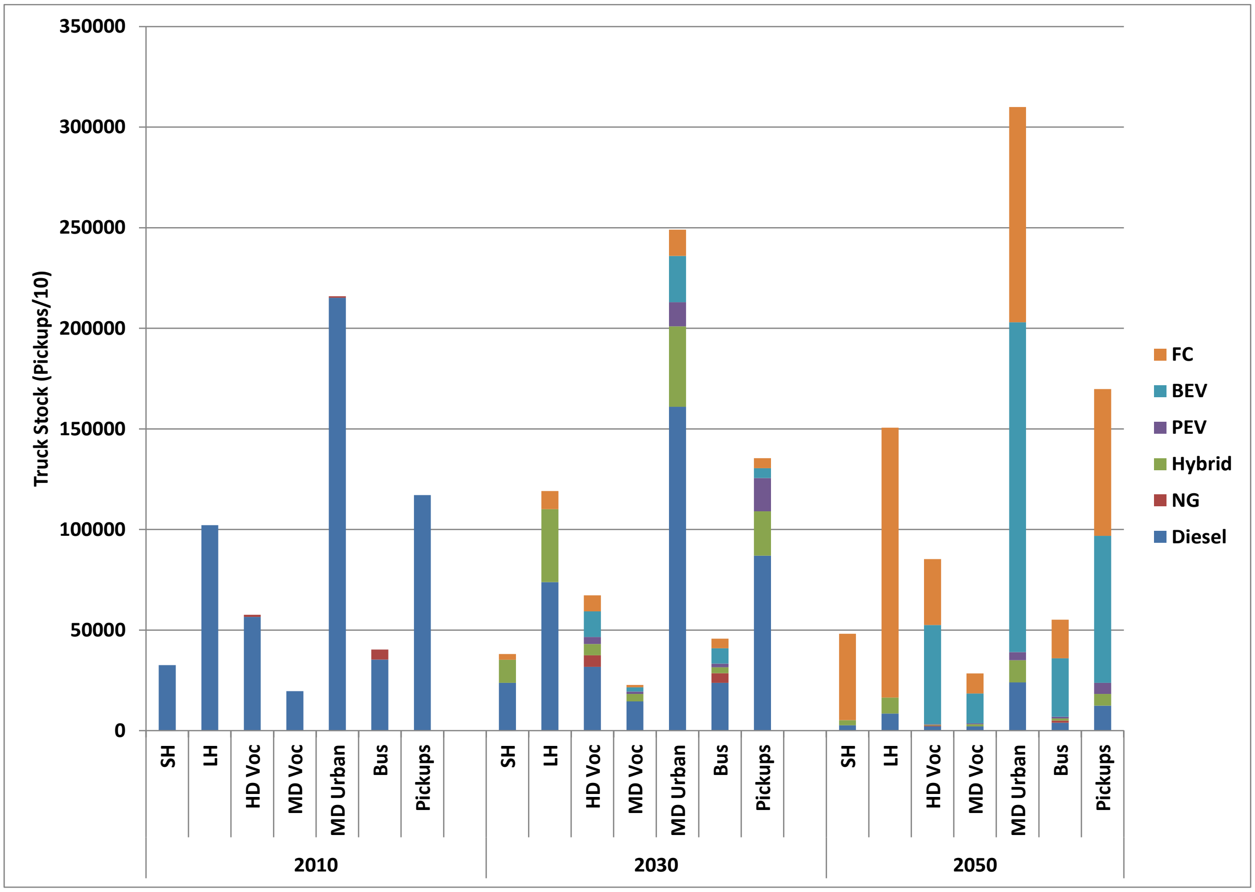

Figure 13. Truck stock for the 80-in-50 High ZEV scenario by vehicle/fuel type for 3 years – 2010, 2030, and 2050

The figures following the stock figures show VMT, fuel consumption and GHG projections by scenario and truck/fuel type. Figures 14 (baseline) and 15 (80-in-50 High ZEV) show VMT as a function of vehicle type and truck type. The results for VMT are closely correlated with the vehicle stock numbers, though they reflect that some truck types travel much farther per year than others—notably long haul trucks and light-duty trucks.

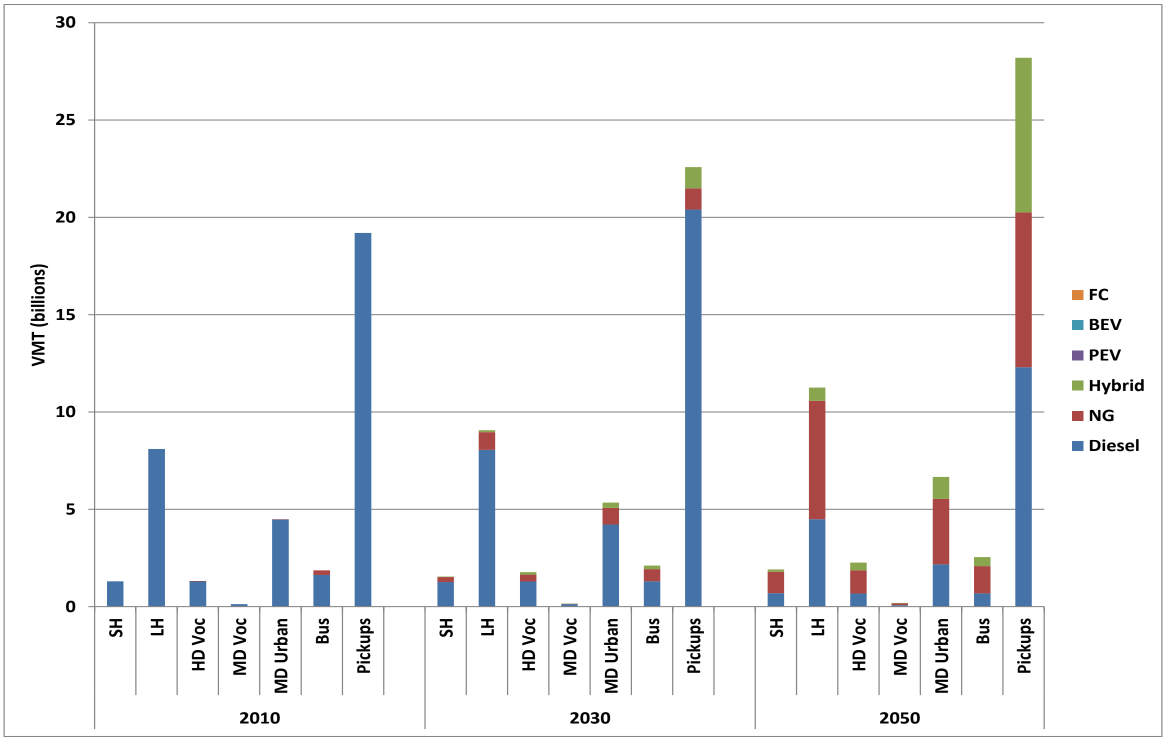

Figure 14. Truck VMT for the baseline scenario by vehicle/fuel type for 3 years – 2010, 2030, and 2050

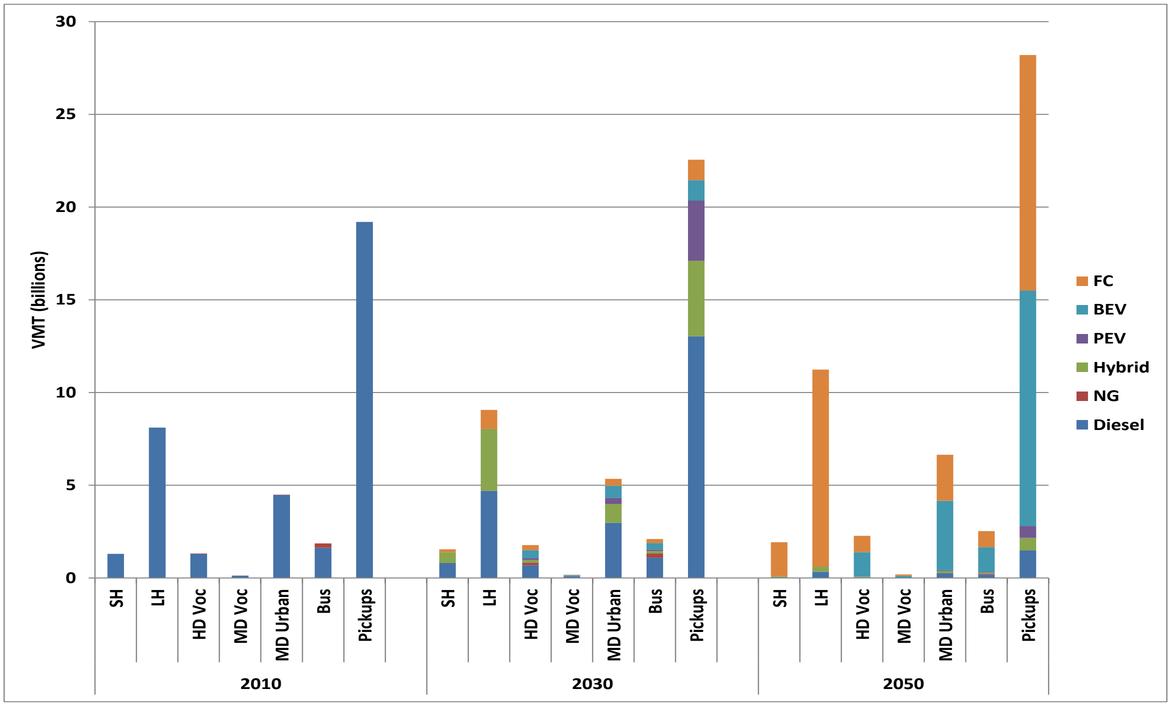

Figure 15. Truck VMT for the 80-in-50 High ZEV scenario by vehicle/fuel type for 3 years – 2010, 2030, and 2050

The fuel efficiency figures (Figures 16 and 17) show the future trend in average fuel consumption per mile for new trucks relative to 2010 model year trucks as a function of vehicle type. These figures show strong reductions in truck fuel intensity given the expected impacts of the federal truck fuel economy standards and underlying trends. Even steeper reductions are achieved in the 80-in-50 High ZEV scenario, reflecting projected technology potentials estimated in the NAS (2010) and CalHEAT (2013) roadmap studies.

These fuel economy improvements translate into more efficient diesel trucks, an increase in the number of advanced technology (e.g. hybridized) diesels, and other changes including trailer designs for long haul trucks. They are separate from the inherent efficiency differences across different propulsion systems (electric, fuel cell) and in some cases lower the advantage of some of these technologies. (For example, as shown above in Table 6, fuel cell trucks in 2030 have a smaller advantage compared to the base diesel vehicle in 2030 than they do today.) These efficiency improvements help to reduce the fuel required in the future and provide important benefits particularly through 2030, since relatively few alternative fuel trucks are projected to be sold by then. Ultimately though, to achieve 80-in-50, a high share of trucks by 2050 must be alternative fueled, as described above.

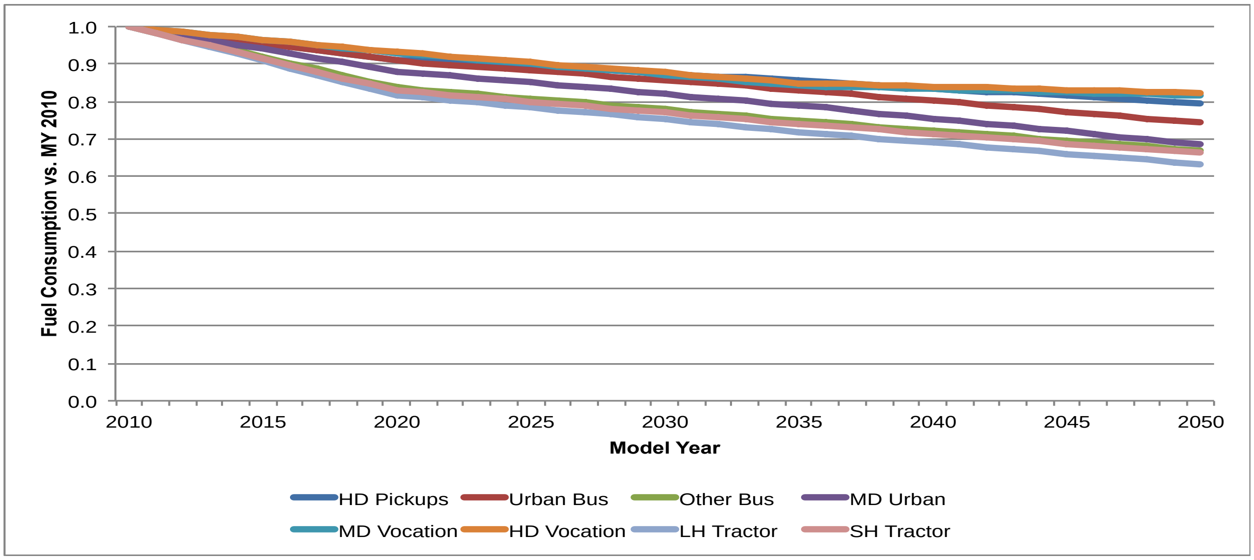

Figure 16. Truck fuel consumption per mile for the baseline scenario by vehicle type through 2050

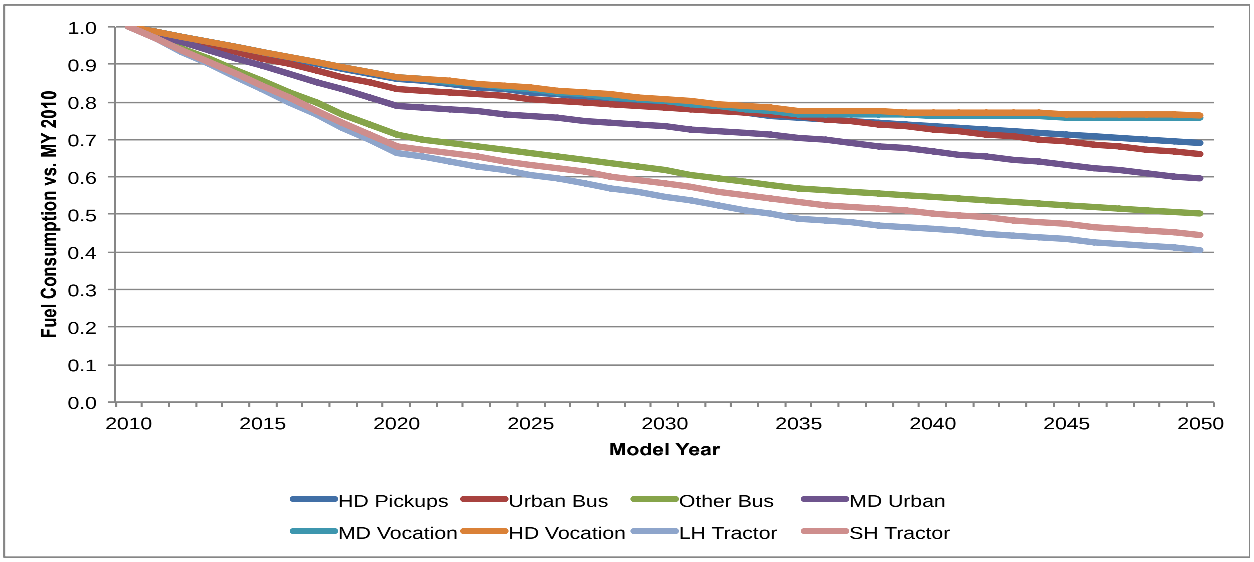

Figure 17. Truck fuel consumption per mile for the 80-in-50 High ZEV scenario by vehicle type through 2050

Figures 18 (baseline) and 19 (80-in-50, High ZEV scenario) show GHG emissions as a function of vehicle type and truck type. The baseline scenario shows relatively modest reductions in GHGs due primarily to fuel efficiency improvements in the overall fleet. The 80-in-50 scenario shows slightly over a 30% reduction in GHGs from 2010 to 2030. This reduction comes primarily from fuel efficiency improvements. The large reductions in 2050 stem from the combination of significant fuel efficiency improvements and the almost complete fleet penetration of ZEVs.

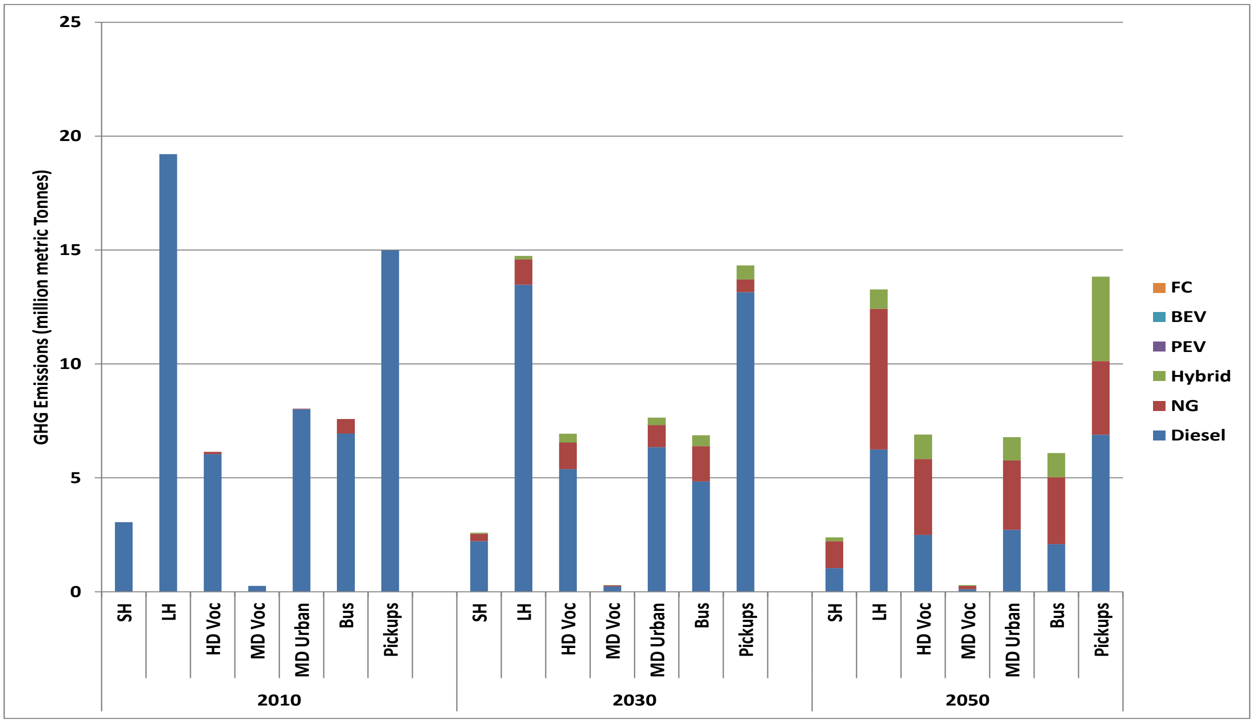

Figure 18. Truck GHG emissions for the baseline scenario by vehicle/fuel type for 3 years – 2010, 2030, and 2050

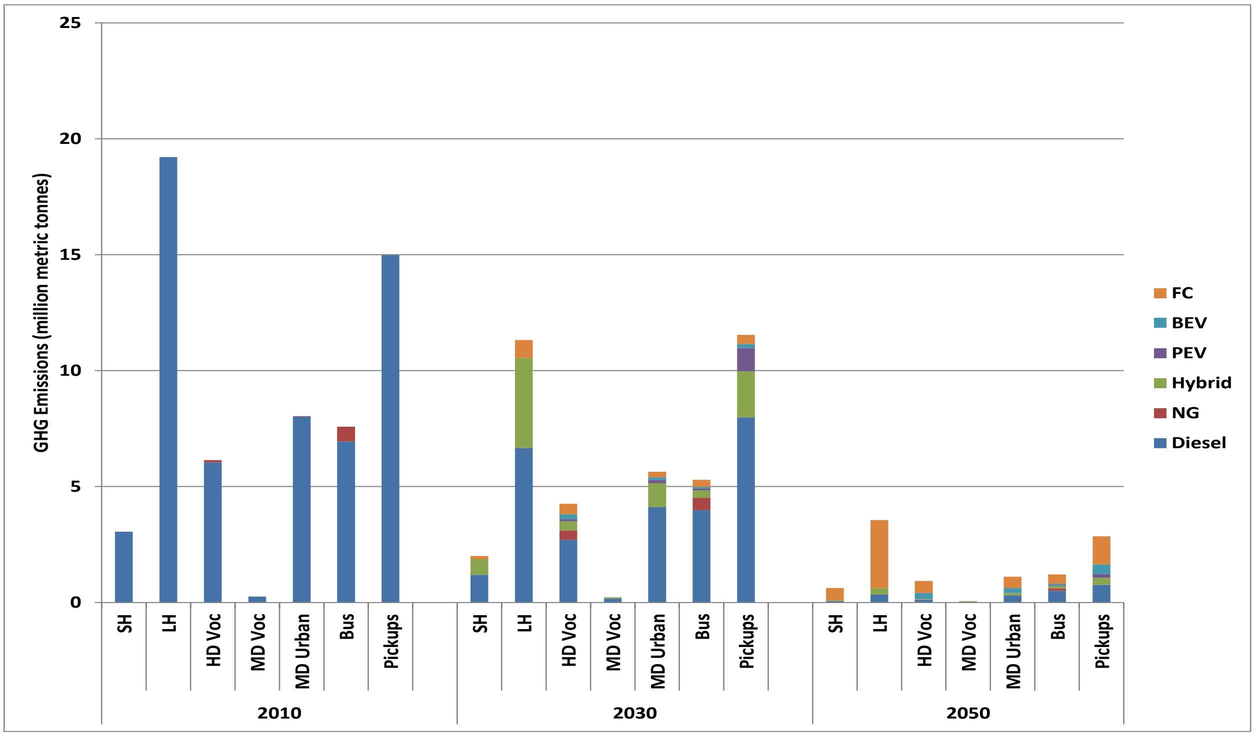

Figure 19. Truck GHG emissions for the 80-in-50 High ZEV scenario by vehicle/fuel type for 3 years – 2010, 2030, and 2050

The GHG results are driven by the fuel consumption results shown in Table 14. This shows the results in fuel use for both the detailed California scenarios and also for the U.S., based in EIA projections of truck VMT, and applying the same efficiency and fuels changes that are applied above for the California scenarios. Both the High ZEV and the Mixed scenario (lower ZEVs, higher biofuels) are shown.

As shown in the bottom row, fuel efficiency gains are critical for both scenarios. Total fuel use is cut by about half in 2050 in the California ZEV scenario compared to 2010, even after about a 50% increase in VMT in this scenario. This occurs because conventional vehicle efficiency improves by up to twice the miles per gallon (50% lower energy per mile) and additional improvements occur in electric and fuel cell trucks. Total fuel use is cut by about 30% in the Mixed scenario. In the U.S. the same changes are applied to a higher VMT growth—about 80% between 2010 and 2050 (EIA AEO 2014 base projection)—so total energy use in the two 2050 scenarios is closer to 2010 than in California, though still significantly lower than 2010.

Another striking result is that the use of hydrogen (in both the High ZEV and Mixed scenarios) is far higher than electricity, which is mainly because long haul trucks account for a high share of VMT and use hydrogen rather than electricity. Still, a significant amount of electricity is used in urban vehicles in these scenarios. For all three of hydrogen, electricity and biodiesel, the 2050 demand is far higher than today's levels; for example, biodiesel use nationally is close to 25 billion gallons (diesel equivalent), about 25 times higher than today's usage for all transportation modes. The implications for producing these fuels are important; however, they are beyond the scope of this paper. An important complement would be to add in the potential demand of these fuels from other modes and sectors in an 80-in-50 scenario in order to fully estimate the potential demand for each type of fuel.

Table 14. Fuel use in the baseline and 80-in50 scenarios, California and U.S. (billion dge)

	California			**U.S.**		
	2010	**2050 High ZEV**	**2050 Mix**	**2010**	**2050 High ZEV**	**2050 Mix**
Diesel fuel	4.7	0.1	0.2	46.6	1.2	1.3
Biodiesel	0.1	0.1	1.8	1.0	1.8	24.4
Natural gas	0.1	0.0	0.0	1.3	0.3	0.3
Electricity	0.0	0.7	0.4	0.0	7.1	3.6
Hydrogen	0.0	1.5	0.7	0.0	21.9	11.0
Total	4.8	2.4	3.1	48.9	32.3	40.5

7. Policy Discussion

Successfully introducing ZEV trucks and expanding their market shares in the medium- and heavy-duty segments will likely require strong policy initiatives. Achieving the types of penetration rates and overall market shares by 2050 that are shown in the 80-in-50 scenario will depend on a steady uptake of fuel cell and/or electric technologies (most likely both), beginning very soon, and overcoming a range of barriers to full commercialization and market competitiveness that eventually leads to high market shares. Given the high capital cost and lack of refueling infrastructure of these technologies, along with other issues (such as range for electric vehicles), policies will need to encourage early adopters to use these options in enough volume to eventually eliminate the barriers (e.g. by providing enough refueling infrastructure and reducing the initial cost of vehicles via volumes and optimization-related cost reductions).

Currently at a national and state level, virtually no policies are in place to encourage the uptake of ZEV medium- and heavy-duty trucks. The main CO_2e reduction policy in place is fuel economy/GHG standards, and while these will be tightened in 2016, they will not likely promote the adoption of ZEV trucks without additional supporting policies. This policy and possible additional supporting policies are described below.

Truck Fuel Economy Standards

In 2011 the U.S. National High Traffic Safety Administration (NHTSA) and Environmental Protection Agency (EPA) implemented complementary fuel economy/GHG emissions standards for heavy-duty trucks covering 2014-2018 models (and tailored to each of three main regulatory categories: combination tractors, heavy-duty pickup trucks and vans, and vocational vehicles) (EPA, 2014). The standards are based on energy and CO_2e emissions per mile, as well as grams of CO_2e per ton-mile and gallons per 1,000 ton-miles. (Engine standards use another metric: grams of CO_2e per brake horsepower-hour or gallons per 100 bhp-hr.) Overall they are expected to cut fuel use per mile by between 9% and 23% depending on truck type, via the adoption of a range of technologies including engine and drive train improvements, light weighting, aerodynamics, tire improvements, and auxiliary improvements such as more efficient air conditioning systems. EPA estimates that this standard will save 530 million barrels of oil and reduce GHG emissions by approximately 270 million metric tons, saving vehicle owners and operators an estimated $50 billion in fuel costs over the lifetimes of the vehicles covered (EPA, 2014). For example, an operator of a new 2018 Class 8 long-haul truck could pay for the technology upgrades in under a year and realize a net savings of $73,000 through reduced fuel costs over the truck's useful life.

These standards are scheduled to be revised during 2015/2016 for trucks sold beginning in 2019. Although the rulemaking process is complex, there will be changes in the way that trucks and truck engines are tested and the standards are expected to be tightened. This process is a critical part of maintaining a strong rate of fuel economy improvements in trucks and reaching the efficiency improvement potential out to 2025 and beyond. Since this process is well developed, it is not clear that further actions are needed in this area. However, to the extent that alternative powertrains are needed to hit an 80-in-50 target, particularly ZEVs, and given the interim sales levels that would be needed to get there that are shown in the above scenarios (e.g. high sales shares by 2030), it is not clear that the national truck fuel economy standards program will ensure this will occur. Additional policies may be needed, as described below.

RD&D Efforts

Major research, development and demonstration efforts into advanced truck technologies and fuel systems are underway and have been at least for the past decade. These including U.S. Department of Energy (DOE) programs, state programs such as the California Energy Commission (CEC) and California Air Resources Board (ARB) research/demonstration grants, and truck manufacturer programs.

The DOE has been operating advanced truck programs such as the 21st Century Truck and "SuperTruck" research programs over a number of years, with targets in terms of specific technologies and overall truck efficiency and CO_2e reduction. The SuperTruck program has targeted a 50% improvement in efficiency of Class 8 trucks by 2015, and indeed has achieved demonstration trucks as of 2014 that have been tested at over 10 MPG, well more than 50% better than a base Class 8 long haul truck (White House, 2014b). However, while this program's achievements will no doubt support the rulemakings for increased truck fuel economy standards, it does not specifically include new non-diesel propulsion systems.

The DOE also has a research program into fuel cells including truck applications (DOE, 2014). This program has been focused on achieving ambitious targets such as a reduction in the cost per kilowatt of fuel cell stacks (and claims an achievement by 2014 of $55/kw under high volume production, down from $124 in 2006). Achieving a truck driving range of more than 300 miles is another target, with validation of 250 miles already achieved via demonstration vehicles. Remaining challenges mentioned in their progress report include more durable systems, further cost reductions, and more compact, lightweight and low-cost hydrogen storage systems.

Regarding electric trucks, the DOE runs a range of relevant programs including battery technology programs, hybrid and plug-in hybrid and electric vehicle programs, and electric auxiliary programs for trucks. However, it does not have any research focused on dedicated long haul battery-electric trucks. This suggests that DOE has made a determination that such a truck is not viable and is not worth the allocation of research funding.

In California there are a number of important research/demonstration efforts underway, funded by agencies such as CEC, ARB and the South Coast Air Quality Management District (SCAQMD). For example the ARB-funded Hybrid Truck and Bus Voucher Incentive Project (HVIP) reduces the purchase price of these vehicles in California. HVIP is managed by CALSTART and works through a series of authorized dealers. All fleets are eligible for HVIP funding on a per-vehicle basis, with vouchers of up to $110,000 for the purchase of a ZEV truck in disadvantaged communities.

Another innovative demonstration project is underway at the California Ports of Los Angeles and Long Beach, implemented by the SCAQMD (SCAQMD, 2014) with funding from the CEC and others. This program is focused on catenary electric trucks, covering a one-mile stretch of highway that is heavily operated by drayage trucks taking goods out of the ports. The trucks will be capable of operating beyond the one-mile stretch either on battery electric power or other system.

Overall there are important and in many ways successful ZEV truck research programs in the United States that are ongoing. It is beyond the scope of this paper to assess these programs or recommend whether additional resources are needed to speed progress. But there is no question that further RD&D to achieve the types of targets mentioned above are an essential part of the policy mix.

Additional Potential Policies

A range of additional policies to promote (or require) ZEV trucks are possible, with experience gained from light-duty ZEV promotion serving as one guide to what is possible. Several potential policies are described below. Assessing the potential impacts of each policy would depend on the stringency of the policy, the way policies are combined, and the manner that consumers (e.g. trucking companies) and manufacturers react to these. Such an analysis is beyond the scope of this paper.

ZEV Standards

While fuel economy standards require manufacturers to achieve a target level of fuel use (or CO_2e) per mile, a more directed “ZEV standard” would encourage sales of ZEVs by explicitly targeting sales requirements for such vehicles. California and other states currently have such a ZEV standard for light-duty vehicles. In the case of California, all major automobile manufacturers must achieve a 15% share of their light-duty vehicle sales as ZEVs by 2025, with some averaging components for other low-emission vehicles allowing the gain of credits in the years leading up to this target year.

For trucks, a similar type of standard is imaginable, though there are a range of issues with trucks that do not typically occur with cars. These include the wide range of truck types and small volumes of some truck segments (making the provision of some share that are zero emission burdensome given the small quantities)— and the challenge of meeting truck duty requirements across segments with ZEVs. These are not specifically related to particular policies but must be taken into consideration when setting standards to avoid creating a situation where compliances is very expensive or even infeasible.

Ways to deal with such issues include averaging across truck types, a robust system of credit trading that allows some manufactures in some segments to avoid producing ZEVs while others “over comply,” and long lead times to let manufacturers have enough time to develop models that can compete. This paper does not attempt to design any such ZEV standards for trucks but simply points out that such standards should be feasible, with perhaps an overall ZEV percentage sales target for each major type of truck (e.g. medium-duty, heavy-duty urban, heavy-duty long haul, buses, etc.), and giving an appropriate lead time and flexibility in the policy to allow compliance with a minimum of unnecessary cost.

Hydrogen and Electricity Infrastructure Roll-out

A critical element for the introduction of ZEV truck technology is refueling infrastructure. While electric trucks will benefit from the well-developed grid system, and to some degree from recharging systems being installed for light-duty vehicles, recharging stations dedicated and suitable for their needs (geared toward high capacity battery systems, fast charging needs) and in suitable locations (e.g. industrial areas, truck stops) will be needed, and should become more of a priority as the light-duty vehicle recharging infrastructure system becomes adequate. As mentioned, truck catenary systems are emerging and if this technology proves likely to be cost-effective on a large scale, some larger demonstrations and eventual roll-out of catenary routes should be considered.

Hydrogen refueling infrastructure is at a more nascent stage than electricity, though in 2015 there is a new roll-out effort of hydrogen stations for light-duty vehicles underway in California, with up to 100 stations planned to be installed by 2017 (CEC, 2014). These will be coupled with the sales of several models of ZEV light-duty vehicles, and thus are not directed toward truck refueling. But it represents a beginning that could be used to build out infrastructure within a few years that includes stations designed and located with truck refueling in mind. Scenarios and plans are needed for how hydrogen refueling infrastructure development can occur in a manner that is suitable for both cars and trucks—for example when and how to move from a focus on urban refueling to include more highway refueling. Given the High ZEV scenario presented in this report, such infrastructure planning is needed now, with demonstration projects and roll-outs focused on trucks (along with truck models being introduced)— starting within perhaps three to five years.

Advanced Biofuels

The key challenge for biofuels is ensuring adequate supplies of truly low GHG fuel, taking into account land use change and a range of other factors. Given that light-duty vehicles seem more amenable to electrification than do large trucks (especially long haul trucks), it may make sense to set policies that push available biofuels toward larger trucks. However, similar arguments may be made for other large modes such as ships and aircraft. Ultimately pricing will play a key role; the modes and industries willing to bid highest for the fuels will obtain them. Meanwhile the most important role for policies is to encourage a migration to advanced biofuels, typically from cellulosic feedstocks, and to drop-in biofuels such as renewable diesel fuel that can be used up to 100% in diesel engine trucks. The California Low Carbon Fuel Standard and the national Renewable Fuel Standard both attempt the first of these, with limited success so far. No U.S. policy expressly targets or encourages drop-in fuels at this time, which has become a priority given the limited usefulness and “blend walls” associated with fuels such as ethanol and FAME biodiesel.

RNG is another important pathway, one that has not been addressed in detail in this paper given the lack of clear information on its market potential. But for most RNG pathways (municipal solid waste, wastewater treatment plants, dairy farm bio-digesters, etc.) there is a clear climate benefit, with mainly questions around cost, infrastructure compatibility, and potential scale and contribution to the fuel supply system. The UC Davis STEPS program is currently studying this topic and will have a separate report available by late 2015. In any case, a range of demonstration projects such as those currently being funded by the CEC (2013) are important to help establish answers to fundamental questions and begin to develop needed learning and infrastructure.

Pricing Policies

A complement or alternative to a ZEV standard for trucks mentioned above could be incentives such as the current national purchase price incentive for light-duty ZEVs. Pricing policies can take a range of forms, and these can provide powerful levers to both consumers and producers to move toward adopting ZEV trucks. Forms including fuel taxes, vehicle taxes and tax/rebate (or feebate) systems, and road pricing (differentiated by CO_2e emissions of the truck). In all of these cases, the most effective forms of pricing to promote ZEVs would be those that give a maximum differential between high CO_2e emitting vehicles and low or zero emitting vehicles. Both fuel taxes and road taxes would be paid by truck users during daily truck operation, while vehicle tax or feebate policies would be paid by users when they purchase vehicles, which has the advantage of "front-loading" the tax and making this visible while the purchase decision is being made. It also may have a similar advantage in terms of getting truck manufacturers to notice this market incentive when they offer trucks for sale, modifying their offerings to take advantage of lower taxes if their trucks are low CO_2e emitting (or outright ZEV). The appropriate form and level of incentives to spur significant ZEV sales most efficiently would need to be researched, and a funding mechanism would need to be identified.

8. Conclusions and Recommendations

This paper has explored future low-carbon technology and fuel options for non-light-duty vehicles, primarily for trucks, and assessed the potential and cost of achieving a scenario with deep penetrations of low-carbon vehicles and fuels, including ZEVs (electric and hydrogen fuel cell) and vehicles running on biofuels.

The study creates several scenarios of truck sales and alternative fuel use that could achieve an "80-in-50" GHG reduction target (80% reduction compared to today's levels by 2050) and reviews other recent projections for the United States. It discusses the technical and other challenges in achieving widespread, rapid uptake in the 2020 to 2050 time frame, with market penetration rates that seem very challenging. It also considers the potential societal costs and benefits associated with doing so.

As with light-duty vehicles, the challenges for trucks include achieving a refueling infrastructure that supports widespread adoption of vehicles, and bringing down the cost barriers through scale and learning, all of which require strong policies to achieve. Ongoing RD&D programs coupled with fiscal incentives for low-carbon fuel adoption by trucks appear critical; a ZEV requirement in the truck sector may also be useful but could be more difficult to manage than for cars given the wide range of trucks types and purposes.

Overall, a principal finding of this white paper is that it will likely take a combination of vehicle types and fuel types to achieve a low-carbon future for trucking, with electricity, hydrogen fuel cells and biofuels all likely playing a role. And since the exact role or potential role of each is unclear, it seems wise to pursue all these technologies and strategies in combination, possibly for another 10 years or more, at least until a dominant pathway, or perhaps an equilibrium combination (which may vary by truck type and use), emerges.

Strong policies also will be needed to achieve a low-carbon truck future. This white paper has reviewed a range of existing and potential policies and noted that the main policy in place at this time is the national fuel economy standard for trucks. This will play a role, but to encourage trucking firms to adopt new types of vehicles and fuels, other policies will likely be needed, such as incentive programs and potentially a ZEV target with mandate or incentives.

Additional research is needed in a number of areas, including a more detailed analysis of how trucking companies use different types of trucks, how new truck technologies and refueling transitions could occur, and a better understanding of various pathways. One in particular is RNG, starting with natural gas trucks and leading to RNG, providing a clear pathway for achieving a low-carbon future. The potential availability and cost of RNG, however, are critical uncertainties at this time.

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Appendix

Key Data and Assumptions

The truck and fuel related estimates used in the various comparisons in this report are based on data and estimates in the tables that follow.

For heavy-duty trucks, costs were compared across fuels and technologies based on the estimates in Table A-1 (no cost analysis was conducted for light- or medium-duty trucks). Costs are roughly in 2013 dollars, with diesel truck costs assumed unchanged in constant dollars into the future, a simplifying assumption. The 2014 estimates in the table below are based mainly on recent reports by UC Davis researchers (e.g. Zhao et al, 2013; Burke and Zhu, 2014); projections to 2030 are based mainly on assumptions as outlined in Table A-2, which in turn are based on a range of sources including NRC (2010), Sharpe (2013), and discussions with manufacturers. Some adjustments were made from these sources, notably the use of a heavy-duty fuel cell system with 350 kW rather than 450 kW of power. The future tank storage costs for both natural gas and hydrogen were reduced by 25%. Storage volume for both hydrogen and natural gas was calculated based on ranges of 1000 miles for long haul trucks and 500 miles for short haul trucks.

For fuels, fuel cost assumptions (Table A-3) were based on a range of sources for 2014 and 2030 (with 2014 data from early in the year, before oil prices dropped). For GHG estimates (Table A-4), GREET 2013 was used to generate most estimates, with 2030 values adjusted as indicated.

Table A-1. Heavy-duty truck purchase costs assumed in the analysis

			Diesel		Hybrid		LNG-CI		LNG-SI		CNG-SI	CNG	Fuel Cell		BEV	
			2014	2030	2014	2030	2014	2030	2014	2030	2014	2030	2014	2030	2014	2030
Base truck ("glider") cost																
	Long Haul		145,000	145,000	145,000	145,000	145,000	145,000	145,000	145,000	145,000	145,000	145,000	145,000	145,000	145,000
	Short Haul		130,000	130,000	130,000	130,000	130,000	130,000	130,000	130,000	130,000	130,000	130,000	130,000	130,000	130,000
Component costs																
	Fuel storage (miles)	Long (1000)	1,000	1,000	1,000	1,000	45,872	24,116			61,544	32293.7	68,383	41,942		
		Short (500)							24,079	12,359	33,710	17,316	37,456	22,490		
	Engine (CI)		9,000	9,000	9,000	9,000	35,000	25,000								
	Engine (SI)								10,000	10,000	10,000	10,000				
	Battery				7,500	3,750									200,000	100,000
	Fuel cell												52,500	16,450		
	Motor				7,000	5,600							24,000	19,200	24,000	19,200
	Accessories				2,000	2,000										
	component costs (includes	Long haul	15,000	15,000	39,750	32,025	121,307	73,674			107,317	63,441	217,324	116,388		
		Short haul	15,000	15,000	39,750	32,025			51,118	33,539	65,565	40,974	170,934	87,210	336,000	178,800
Total Purchase Cost																
	Long Haul		160,000	160,000	184,750	177,025	266,307	218,674			252,317	208,441	362,324	261,388		
	Short haul		145,000	145,000	169,750	162,025			181,118	163,539	195,565	170,974	300,934	217,210	466,000	308,800

Table A-2. Heavy-duty truck technology characteristics and costs

	Characteristics			Cost		
Component	2014	2030	Units	2014	2030	Units
Fuel Cell	350	350	kW	150	47	$/kW
BEV battery	400	400	kWh	500	250	$/kWh
Hybrid battery	15	15	kWh	500	250	$/kWh
LH LNG SI tank	176	123	DGE	250	187	$/DGE
LH LNG CI tank	153	107	DGE	300	225	$/DGE
LH CNG SI tank	176	123	DGE	350	262	$/DGE
SH LNG SI tank	96	66	DGE	250	187	$/DGE
SH LNG CI tank	84	57	DGE	300	225	$/DGE
SH CNG SI tank	96	66	DGE	350	262	$/DGE
LH LH2 Tank	104	85	kg	660	495	$/kg
SH LH2 Tank	57	45	kg	660	495	$/kg

Table A-3. Fuel-related characteristics and costs

				FUEL PRICES				
				$/MMBT		$/Gal DE		
Fuel	**Process**	**Feedstock**	**Mode**	**2014**	**2030**	**2014**	**2030**	**Notes, sources**
diesel fuel	Low-sulphur diesel fuel	petroleum	trucks, rail	21.1	31.2	2.71	4.01	EIA AEO 2015 (fuel taxes removed)
Renewable diesel	Hydrotreating	Plant oil		41.4	N/A	5.31	N/A	MIT, 2012, "Techno-economic review of hydroprocessed renewable esters and fatty acids for jet fuel production", Pearlson *et al*
Renewable diesel	Thermochemical (e.g. Fischer Tropsch)	cellulosic	trucks, rail	44.5	30.2	5.71	3.87	DOE, 2013 (NREL report on TEF Series: Projected Biomass Utilization for Fuels and Power in a Mature Market)
biodiesel (FAME)	Esterification	plant oil	trucks, rail	36.2	36.2	4.65	4.65	2014: NREL fuels report; 2030: assumed unchanged
NG	Feedstock price for transportation users	pipeline NG	all	8.5	10.4	1.09	1.34	EIA AEO 2015 commercial natural gas price
CNG	for transportation retail	pipeline NG	trucks, rail	17.5	15.7	2.25	2.02	EIA AEO 2015 transportation natural gas delivered price with compression
LNG	Truck/rail scale, liquefied at point of use	pipeline NG	trucks, rail	26.0	24.4	3.34	3.14	Liquefaction cost from STEPS NG truck study; assumes a 20% reduction in liquefaction costs by 2030
LNG	Truck/rail scale, central production and trucked to point of use	pipeline NG	trucks, rail	21.0	20.4	2.69	2.62	Liquefaction cost from STEPS NG truck study; assumes a 20% reduction in liquefaction costs by 2030
LH2	LH2 with NG feedstock	pipeline NG	trucks, rail	46.1	34.2	5.92	4.39	DOE H2A model
LH2	LH2 with electrolysis	grid electricity	trucks, rail	86.2	54.2	11.08	6.97	Near term based on modest scale, immature market; 2030 based on STEPS runs of DOE H2A model
electricity	average mix, sales to transport	average US mix	all	29.6	32.9	3.80	4.22	EIA AEO 2015 price to transport users
electricity	average mix, sales to industry	average US mix	all	21.1	22.6	2.71	2.90	EIA AEO 2015 price to industrial users

Table A-4. Fuel-related GHG estimates

(CO_2e-eq per mmBtu of fuel provided to vehicles, broken out by well-to-tank [WTT], tank-to-wheel [TTW], and well-to-wheel [WTW])

				Current			2030			Other notes, assumptions	
Type	**Fuel**	**Process, notes**	**Feedstock**	**WTT**	**TTW**	**WTW**	**WTT**	**TTW**	**WTW**	**Current estimates**	**2030 estimates**
Diesel	diesel fuel	CA baseline conv and LS diesel	petroleum	18,718	74,058	92,776	20,497	78,179	98,676	ANL GREET 2014	Assume WTT is 5 % higher than 2014
	biodiesel (FAME)	esterfication	soy	(55,871)	79,340	23,469	(33,438)	79,993	46,555	ANL GREET 2014	Assume 5% better than 2014
	biodiesel (drop-in)	Thermo-chemical	cellulosic (switchgrass)	(46,630)	76,710	30,080	(56,213)	77,346	21,133	ANL GREET 2014	Assume 5% better than 2014
NG	CNG-SI	base CA Greet assumptions	NG	20,350	60,713	81,063	22,359	63,511	85,870	ANL GREET 2014	same as 2014
	LNG-SI	liquifaction at POU	pipeline NG	19,996	60,960	80,956	27,017	59,101	86,117	ANL GREET 2014	same as 2014
	LNG-HPDI	liquifaction at POU	pipeline NG	19,996	63,337	83,333	27,017	59,101	86,117	ANL GREET 2014	same as 2014
RNG	RNG-liquid	Landfill gas to NG	Landfill gas	(44,450)	60,960	16,510	(44,450)	59,101	14,651	ANL GREET 2014	same as 2014
	RNG-Compressed	Landfill gas to NG	Landfill gas	(42,760)	63,337	20,577	(42,760)	59,101	16,341	ANL GREET 2014	same as 2014
H2	CH2	Compressed H2 with reforming, compression at POU	100% pipeline NG	124,700	-	124,700	91,509	-	91,509	ANL GREET 2014	same as 2014
	LH2	Liquified H2 with reforming, Liquifaction at POU	100% pipeline NG	168,714	-	168,714	113,746	-	113,746	ANL GREET 2014	same as 2014
	LH2	Electrolysis, mix of grid and pure renewable	electricity	29,116		29,116	29,116		29,116	NRC 2013	same as 2014
electricity	electricity	average CA mix	average CA mix	101,142	-	101,142	91,658	-	91,658	ANL GREET 2014	2030 uses GREET projectionn
	electricity	average US mix	average US mix	169,836	-	169,836	154,078	-	154,078	ANL GREET 2014	2030 uses GREET projectionn

Description of the TOP-HDV Model

The Technology Options and Pathways for Heavy-Duty Vehicles (TOP-HDV) model was written by Ben Sharpe while completing his Ph.D. at UC Davis (Sharpe 2013). The model calculates emissions, energy use, and costs for trucks in California over the timeframe from 2010-2050. The model uses vehicle population, activity, vehicle efficiency, and vehicle emission factors to estimate fuel use and well-to-wheel emissions. The authors along with Dr. Sharpe updated the model to include more recent data for the trucking fleet and trucking activity. In addition the authors worked with the CalHEAT team to update vehicle fuel economies for the various truck types. (CalHEAT 2013)

The model disaggregates the truck fleet into eight truck types including long haul, short haul, heavy-duty vocational, medium-duty vocational, medium-duty urban, urban buses, other buses, and heavy-duty pickups and vans. The truck types have an associated vehicle lifetime in the fleet and sales-to-scrappage rates determine fleet growth over time. The vehicle stock is taken from the EMFAC 2007 model and the activity matches EMFAC 2007 with slight modifications for the recent recession. Vehicle attributes such as fuel use and costs vary over the model timeframe. The user can determine when and to what extent alternative fuels and technologies enter the fleet. The model handles each of the eight vehicle types separately. TOP-HDV calculates various fleet and truck type characteristics on a year-by-year basis out to 2050.

TOP-HDV allows the user to create scenarios where the truck stock for each truck type can include varying percentages of alternative fuels (diesel, gasoline, natural gas, biofuels, electricity, and hydrogen) and technologies (conventional, natural gas, battery electric, diesel or gasoline hybrid or plug-in hybrid, and fuel cell). These new technologies and fuels enter the fleet over time and change the fleet fuel use and emissions. The TOP-HDV model includes six discrete scenarios: baseline, high efficiency, plug-in hybrids and electric vehicles, fuel cell vehicles, alternative fuels, and 80-in-50. Each scenario focuses on a small set of technologies or fuels that dominate the fleet penetration. This study only considers the baseline and ZEV-dominated 80-in-50 scenarios, with the Mixed scenario added separately.