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Fuel-Cycle Energy and Emissions Impacts of Tripled Fuel Economy Vehicles*

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Fuel-Cycle Energy and Emissions Impacts of Tripled Fuel Economy Vehicles

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M. Mintz, M. Wang, and A. Vyas

Abstract

This paper presents estimates of the full fuel-cycle energy and emissions impacts of light-duty vehicles with tripled fuel economy (3X vehicles) as currently being developed by the Partnership for a New Generation of Vehicles (PNGV). Seven engine and fuel combinations were analyzed: reformulated gasoline, methanol, and ethanol in spark-ignition, direct-injection engines; low-sulfur diesel and dimethyl ether in compression-ignition, direct-injection engines; and hydrogen and methanol in fuel-cell vehicles. The fuel efficiency gain by 3X vehicles translated directly into reductions in total energy demand, petroleum demand, and carbon dioxide emissions. The combination of fuel substitution and fuel efficiency resulted in substantial reductions in emissions of nitrogen oxide, carbon monoxide, volatile organic compounds, sulfur oxide, and particulate matter smaller than 10 microns, particularly under the High Market Share Scenario.

[Keywords: PNGV, 3X vehicles, light duty vehicle energy, vehicle emissions]

Background

This paper summarizes a portion of ongoing analyses in support of the Partnership for a New Generation of Vehicles (PNGV). Formed as a joint government-industry research and development effort, the PNGV aims to develop vehicles that can achieve up to three times the fuel economy of today's vehicles, about 80 miles per gallon (mpg) for six-passenger automobiles. These three-times-efficient (often called 3X) vehicles are intended to meet the safety and emissions requirements expected to be in place when they are introduced, as well as to maintain the performance, size, utility, and cost of ownership/operation of the vehicles that they replace.

To achieve the 3X goal, the PNGV program is focusing on the development and use of advanced automotive technologies and lightweight materials. To meet the emissions goal or to provide the optimum fuel for new propulsion systems, new fuels (e.g., hydrogen, methanol, ethanol, or dimethyl ether) could also be necessary. New materials and fuels would inevitably require changes in automotive manufacturing, materials production, and fuel production and distribution. Those changes, in turn, will affect energy consumption and emissions.

As part of its oversight of the PNGV, the National Research Council (NRC), a part of the National Academy of Sciences, has created a standing committee to review the PNGV research program. In its report, the NRC Peer Review Committee raised concerns about the potential for "substantial discontinuities" in vehicle manufacturing and the transportation system and identified a need for in-depth assessment of changes that could occur in "infrastructure, capital requirements, shifts in employment, total environmental consequences, alternative safety strategies, and total cost of operation associated with each technology being explored in the PNGV program" (NRC 1994). In response to these concerns, the U.S. Department of Energy's Office of Advanced Automotive Technologies commissioned Argonne National Laboratory (ANL) to analyze energy and emissions impacts and the infrastructure consequences of new vehicle fuels and Oak Ridge National Laboratory (ORNL) to analyze the impacts of light-weight vehicle materials and their infrastructure consequences. This paper summarizes the first phase of the ANL analysis. A more detailed discussion of the analysis methodology and results is contained in the full Phase 1 report (Wang et al. 1997).

Scope and Approach

As a point of departure, this analysis assumed that the 3X goal will be achieved for each of the fuel/engine combinations being considered, that each combination will be an equally feasible 3X alternative, and that assessment of the energy and emissions impacts of the 3X alternatives should include the examination of upstream as well as operational energy use and emissions (i.e., a full fuel-cycle approach should be used). Fuel-cycle energy and emissions for each 3X fuel/engine combination were calculated using a combination of the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) and IMPACTT (Integrated Market Penetration and Anticipated Cost of Transportation Technologies) models. Impacts were estimated for each year between 2007, three years after completion of research and development for 3X vehicles, and 2030, when a significant portion of the light-duty fleet could be expected to be composed of these highly efficient vehicles.

For a given fuel/engine combination, per-mile fuel-cycle energy and emissions were first estimated with the GREET model (Wang 1996). Per-mile energy and emissions results were then fed into the IMPACTT model to estimate energy use and emissions per year (Mintz et al. 1994). In the end, energy savings and emissions reductions of the given technology were estimated for the complete fuel cycle, including both vehicle operation and upstream fuel production processes.

GREET

The GREET model calculates full fuel-cycle emissions and energy use rates in grams-per-mile (g/mi) and Btu-per-mile (Btu/mi) for various transportation fuels. For each fuel-cycle activity, GREET first calculates energy use by various process fuels per unit of fuel throughput, and then calculates emissions associated with combustion of process fuels and emissions from chemical processes and other sources. GREET includes emissions of volatile organic compounds (VOC), carbon monoxide (CO), nitrogen oxides (NO_x), particulate matter with size smaller than 10 microns (PM_{10}), sulfur oxides (SO_x), methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2). GREET calculates energy consumption for three types of energy: total energy (all energy sources), fossil energy (petroleum, natural gas [NG], and coal), and petroleum only.

For gasoline and diesel vehicles, emissions from vehicle operations are first estimated with EPA's Mobile5 and Part5 models and are then input to GREET. For this analysis, it was assumed that 3X vehicles would meet the federally proposed Tier II standards for exhaust VOC, CO, and NOx emissions. Since there is no Tier II PM emission standard for diesel vehicles, the current 0.08 g/mi standard was assumed for diesel-powered 3X vehicles.

IMPACTT

The IMPACTT model was used to estimate annual energy and emissions of conventional and 3X vehicles. IMPACTT incorporates a vehicle stock model that adds new vehicles (3X or conventional) and retires old vehicles from an initial population profile to produce annual profiles of the auto and light-truck population by age and technology; a usage module to compute VMT, oil displacement and fuel use by technology; and an emissions module to compute upstream and downstream emissions of criteria pollutants and CO_2 for autos and light trucks, again by technology. The usage module computes the petroleum that would have been consumed by conventional vehicles in the absence of 3X vehicles, the energy consumed by 3X vehicles, and the net savings due to the presence of 3X vehicles in the fleet.

Emissions of NO_x, CO, VOC, and PM_{10} are computed separately for autos and light trucks using age-based tailpipe emission rates obtained from EPA's Mobile5a and Part5 models for conventional SI and CI engines operating on gasoline and diesel fuel and average tailpipe and upstream emissions rates for nonconventional engines and fuels obtained from GREET.

Key Analytical Issues

Several key analytical issues had to be addressed before GREET and IMPACTT runs could be completed. These included market penetration of new 3X vehicles, selection of the fuels and engine technologies to be considered in the analysis, and specification of fuel pathways.

3X Vehicle Market Penetration

Since the impacts of 3X vehicles are dependent not only on engine technology and fuel choice, but also on how quickly and completely they penetrate the light-duty vehicle market, market penetration was a key issue. In order to explore a range of 3X impacts, three market penetration scenarios were postulated. The scenarios included a reference or base scenario depicting a future without 3X vehicles and two market share scenarios bracketing a range of 3X vehicle sales.

The Reference Scenario was taken from the Energy Information Administration forecast of transportation energy demand through the year 2015 and extrapolated to 2030 (EIA 1996). This forecast assumes 2.0% per year growth in gross domestic product (GDP), slowly rising world oil price (from $16.81 in 1995 to $25.43 per barrel by 2015 [all in 1994 dollars]), continued growth in the number of licensed drivers, and moderate increases in new light-duty-vehicle sales and fuel economy. Under the Reference Scenario, new car sales increase from 8.92 million with a rated fuel economy of 27.5 mpg in 1995 to 13.13 million units rated at 35.4 mpg in 2030; new light-truck sales increase from 5.53 million rated at 20.2 mpg in 1995 to 7.89 million vehicles rated at 25.1 mpg in 2015.

The 3X vehicle market share scenarios retain the basic parameters of the Reference Scenario but allow such market factors as the level of technology maturity and consumer preferences to vary. Since each of these factors is subject to some uncertainty, two extreme sets of conditions could materialize. Under one set, every factor favorable to 3X vehicles' market success could occur, resulting in rapid consumer acceptance and high sales of new 3X vehicles. Alternatively, some factors may not be as favorable to market success, resulting in slower early consumer acceptance and low-to-moderate sales of new 3X vehicles. Figure 1 illustrates the two market share scenarios developed for this analysis.

The High Market Share Scenario is based on the mid-case for 3X vehicle sales established by DOE's Policy Office for the Policy Dialogue Advisory Committee (the "Car Talk" Committee) (Resolve, Inc. 1995). Under that case, 3X vehicle sales climb rapidly, perhaps too rapidly in terms of the adaptation of the vehicle manufacturing industry. For this reason, the mid-case was modified slightly for this analysis, extending the timeframe over which the market penetration target is achieved. Thus, 3X vehicles enter the new vehicle market in 2007 and take over 20 years to achieve a 60% market share.

The Low Market Share Scenario assumes that 3X vehicles enter the market in 2013, six years later than in the High Market Share Scenario, and capture a 30% share of the new vehicle market by 2030.

For both market share scenarios, each PNGV fuel/engine combination is assumed to have the same market penetration, to compete solely with conventional vehicles (not with one another) and, thus, to account for all of the impacts identified. Because competing technologies are set aside for separate fuel/engine comparisons, this assumption provides the basis for analyzing the maximum impact of each technology.

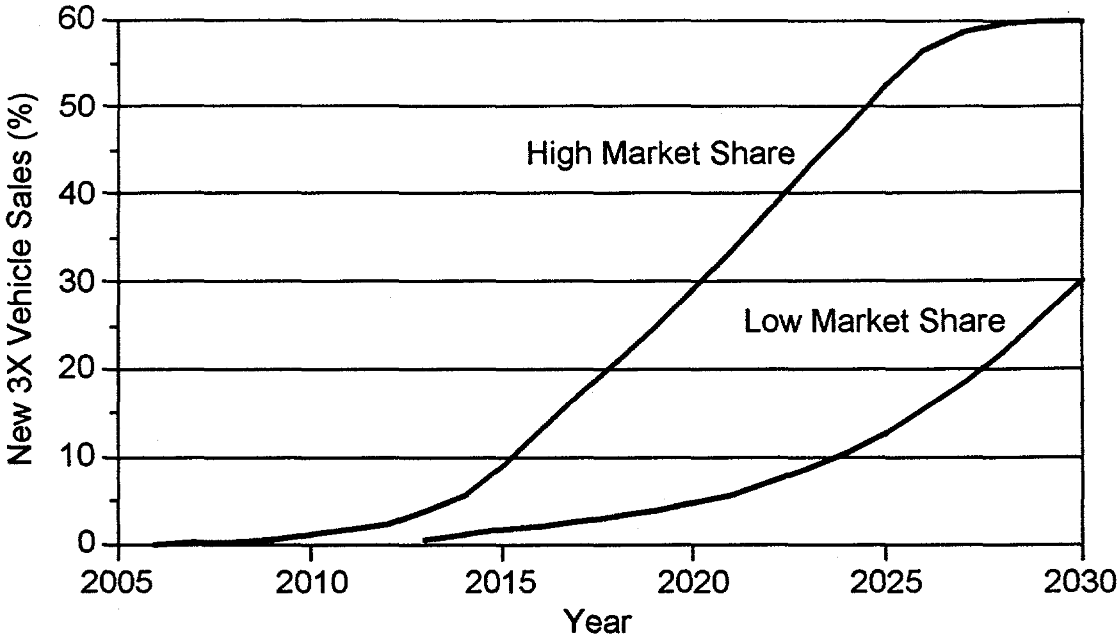

FIGURE 1 3X Vehicle Market Share Scenarios

Fuels and Propulsion Technologies

The PNGV is considering the following candidate propulsion technologies: 4-stroke, direct-injection, spark-ignition (DISI) engines (stand-alone or hybrid-electric configuration); 4-stroke, direct-injection, compression-ignition (DICI) engines (stand-alone or hybrid configuration); gas turbine/series-configured electric hybrids; and proton exchange membrane (PEM) fuel cells/hybrid configuration. Because this study focused on the energy and environmental effects, propulsion technologies were aggregated into five groups: stand-alone SI engines, hybrid SI engines, stand-alone CI engines, hybrid CI engines, fuel cells, and hybrid gas turbines. Direct injection technologies were assumed to be applied to both SI and CI engines. Because gas turbines do not offer a clear advantage vis a vis PNGV goals, they were not considered in the Phase 1 analysis. Six fuels were analyzed:

- Reformulated gasoline (RFG) which served as the Reference Scenario fuel, the fuel for conventional vehicles in both 3X market share scenarios, and a possible fuel for stand-alone SI or hybrid SI 3X vehicles. Reformulated gasoline was assumed to be federal phase 2 RFG.
- Low-sulfur diesel (LSD) which was assumed to have sulfur content below 0.05% by weight (current highway diesel) and to be used in stand-alone CI or hybrid CI vehicles. In Phase 2 of this study, LSD will be replaced with reformulated diesel provided that EPA provides the necessary guidance on future diesel fuel specifications.
- Dimethyl ether (DME) which was assumed to be used in stand-alone CI or hybrid CI vehicles. Although expensive and requiring changes in fuel storage and injection

systems, DME may offer significant environmental benefits while exploiting the high thermal efficiency of a CI engine system.

- Methanol which was considered in pure form (M100) for both internal combustion engines (in a hybrid electric vehicle [HEV] or stand-alone) and as a hydrogen carrier for fuel cells.
- Ethanol which was included because it, alone among the fuels considered, is currently made from renewable resources. Pure ethanol (E100) was assumed to be burned in stand-alone SI or hybrid SI engines.
- Hydrogen which was considered in gaseous form for use in fuel-cell vehicles.

These fuels were not intended to represent a comprehensive picture of available and potential 3X transportation fuels. In each case, their selection (and that of the vehicle technologies with which they were paired) was based on a specific advantage of the fuel-vehicle system relative to PNGV program goals. Note that liquefied petroleum gas (LPG), compressed natural gas/liquefied natural gas (CNG/LNG), biodiesel, and Fischer-Tropsch diesel made from coal or natural gas were not included in the Phase 1 analysis. However, these fuels are being considered in the Phase 2 analysis now underway.

Fuel Pathways

For a given transportation fuel, a fuel cycle includes the following chain of processes: primary energy recovery; primary energy transportation and storage; fuel production; fuel transportation, storage, and distribution; and vehicular fuel combustion. Fuel-cycle activities before vehicular fuel combustion are usually referred to as upstream activities; vehicular fuel combustion is sometimes referred to as a downstream activity. Energy is consumed and emissions are generated during each of these activities. Emissions may be coincident with the activity or occur somewhat later, as in the case of fuel leakage and evaporation. GREET calculates fuel-cycle energy use and emissions by taking into account all these sources (Wang 1996).

In order to estimate upstream energy and emissions, a fuel cycle path from primary energy recovery to fuel combustion in vehicles was specified for each technology option. The base case or benchmark fuel-cycle path was petroleum to gasoline for conventional vehicles. In this study, eight fuel cycle paths were analyzed. RFG and LSD were assumed to come from petroleum, and methanol and DME were assumed to come from natural gas. Prior to 2020, hydrogen was assumed to be produced from natural gas via steam reforming and ethanol was assumed to be produced from corn; beginning in 2020, hydrogen was assumed to be produced from solar energy through water electrolysis and ethanol was assumed to be produced from biomass (both woody and herbaceous).

Petroleum to RFG. This path includes crude oil recovery in oil fields; crude oil transportation and storage; crude oil refining; and gasoline transportation, storage, and distribution.

Petroleum to Diesel. This path includes crude oil recovery, transportation, and storage; diesel production in crude refineries; and diesel transportation, storage, and distribution.

NG to DME. This path includes NG recovery and processing; DME production; and DME transportation, storage, and distribution. Because the carbon ratio of DME is higher than that of NG, the process of converting NG to DME results in a net carbon absorption which was subtracted from the CO_2 emission value calculated for NG combustion in DME plants.

NG to Methanol. This path includes NG recovery and processing; methanol production; and methanol transportation, storage, and distribution. As with DME, the process of converting NG to methanol results in a net carbon absorption which was subtracted from the CO_2 emission rate calculated for NG combustion in methanol plants.

NG to H_2. For gaseous H_2, the path from NG includes NG recovery, and processing; H_2 production, transportation via pipeline, and storage; and H_2 compression at service stations. Because H_2 contains no carbon, H_2 production generates substantial CO_2 emissions which were estimated in the model. No CO_2 sequestration in hydrogen plants was assumed.

Solar Energy to H_2. Production of H_2 from solar energy via water electrolysis offers large energy and environmental benefits, and would permit the transportation sector to use a practically unlimited energy source. In this analysis, H_2 was assumed to be produced in centralized facilities in the southwestern U.S. or other regions where solar energy is abundant, compressed moderately (to about 100 psi) and transported to H_2 refueling facilities via pipeline. At the refueling facility, gaseous H_2 was assumed to be compressed to 5,000-6,000 psi before being dispensed to H_2-powered FCVs. Electricity was assumed to be used for H_2 compression and transportation. Greenhouse gas emissions attributable to H_2 compression and transportation were estimated using national average emission rates for electricity generation.

Corn to Ethanol. This path includes corn production and transportation; ethanol production; and ethanol transportation, storage, and distribution. GHG emissions from corn production come from fuels used for farming, harvesting, and corn drying, together with the amount used to produce fertilizers and herbicides. GREET accounts for all these activities in calculating GHG emissions.

Corn-to-ethanol production was assumed to use wet-milling technology with coal as the process fuel. A bushel of corn was assumed to produce 2.5 gallons of ethanol, as well as other co-products. Thus, emissions from ethanol plants and from upstream corn production had to be allocated between ethanol and co-products. For this analysis, an ethanol co-product credit of 30% was used.

Biomass to Ethanol. This path includes biomass production and transportation; ethanol production; and ethanol transportation, storage, and distribution. Energy and emissions from biomass production were calculated in the same way as from corn production. In this study, biomass was assumed to be burned in biomass-to-ethanol plants to provide process heat. While biomass combustion undoubtedly produces CO_2 emissions, these emissions originally came from the atmosphere through the process of photosynthesis. Thus, CO_2 emissions from biomass combustion were treated as being zero. For the same reason, CO_2 emissions from ethanol combustion by ethanol-powered vehicles also were treated as being zero.

Combustion of biomass in biomass-to-ethanol plants which are cogeneration facilities generated electricity as well as process heat. The electricity generated was assumed to be exported to the electricity grid. Emissions credits for the cogenerated electricity were calculated in GREET by estimating the quantity of electricity produced via cogeneration and the average emissions associated with electricity generation in electric utility systems.

Impact Estimation

In order to assess the energy and emissions impacts of 3X vehicles, the total volume of fuel consumed and emissions produced with and without 3X vehicles was estimated by the IMPACTT model. Using the Reference Scenario forecast of new light-duty-vehicle sales and fuel economy, and the 3X market share assumptions described above, the number of conventional and 3X vehicles, their VMT and gasoline-equivalent fuel use were determined for each year between market introduction (2007 in the High Market Share Scenario and 2013 in the Low Market Share Scenario) and 2030. Note that 3X vehicle market penetration was assumed to have no effect on light-duty-vehicle sales, scrappage or utilization (i.e., mi/year). Thus, total vehicles and VMT did not differ by scenario despite large differences in the number of 3X vehicles and 3X VMT. As compared to the Low Market Share Scenario, the High Market Share Scenario had nearly three times as many 3X vehicles on the road in 2030, accounting for nearly three times as much VMT and consuming nearly three times as much fuel.

Differences in g/mi operational emissions, as well as in upstream energy and emissions rates of the various fuels (as computed by the GREET model) produced even more substantial differences in total fuel use and emissions between the reference and market share scenarios, as well as among the seven fuel/technology alternatives.

Figures 2-6 display fuel-cycle energy and emissions arising from upstream activities and vehicle operation (i.e., downstream activity) for the Reference Scenario and for each of the fuel/technology combinations under the High Market Share Scenario. For all figures, the Reference Scenario is shown as the first member of a series of bars, each of which represents an alternative fuel/technology combination. Upstream and downstream totals are shown separately to more clearly illustrate how the alternative differs from the Reference Scenario distribution (upstream vs. downstream), as well as to indicate where impacts are likely to occur. Since upstream and downstream emissions often have very different spatial locations, the breakout also provides additional policy guidance for considering the impacts of the several alternatives. Although both market share scenarios had similar results, the patterns were much more striking under the High Market Share Scenario which, by definition, is a more extreme example of possible market penetration. Thus, the figures and discussion presented here are limited to the High Market Share Scenario. It should also be noted that even under the High Market Share Scenario, conventional vehicles still comprised more than half of all light-duty vehicles on the road in 2030. Since the values shown are actually totals for a vehicle fleet consisting of each of the technology/fuel alternatives and conventional light-duty vehicles, the results are less striking than would be the case if results were reported for any of the 3X technologies alone.

Energy Impacts

Total Energy. Figure 2 illustrates total fuel-cycle energy use by light-duty vehicles under the Reference and High Market Share Scenarios. Total energy rose to 20.2 quads in 2030 under the Reference Scenario, with vehicle operations (downstream energy) accounting for 78% (approximately 15.7 quads). The 3X alternatives reduced total energy use by 20-25%. Since, by definition, all fuel/technology alternatives achieved 3X fuel economy, the upstream energy requirements of the various fuels accounted for all the variation in total energy use.

Petroleum. Figure 3 displays petroleum use by technology/fuel alternative for the Reference and High Market Share Scenarios. By 2030 each of the nonpetroleum alternatives (i.e., hydrogen, methanol, ethanol, and DME) reduced total petroleum use by approximately 45% relative to the Reference Scenario.

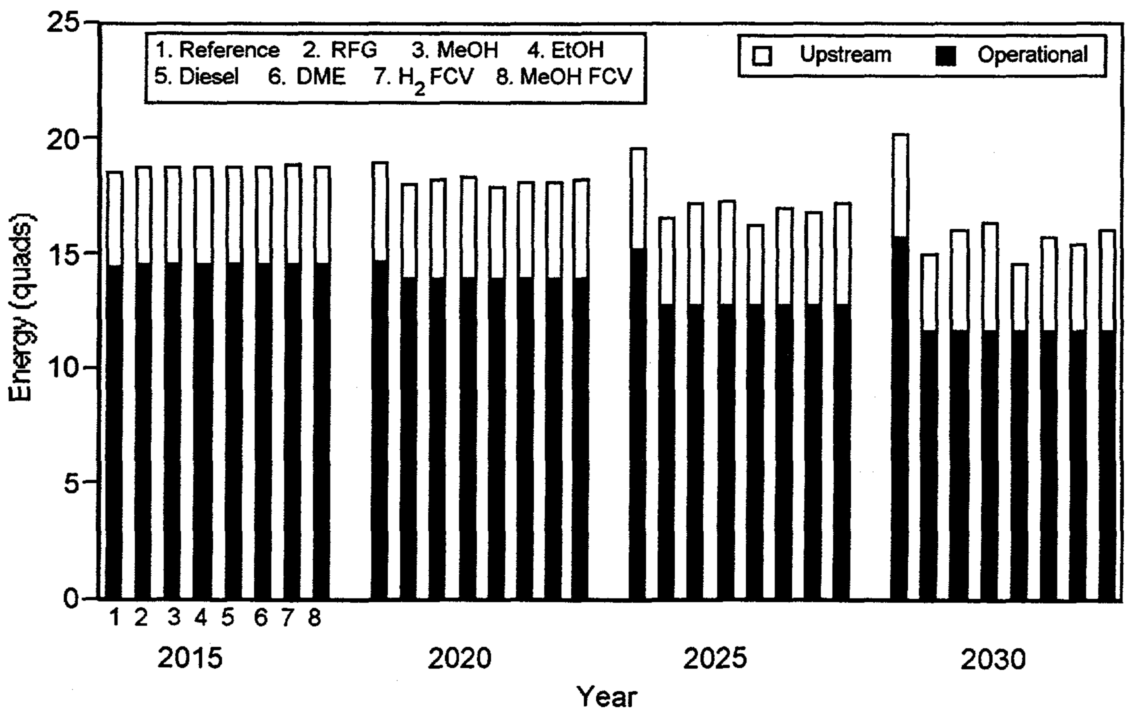

FIGURE 2 Fuel-Cycle Total Energy Use by Light-Duty Vehicles

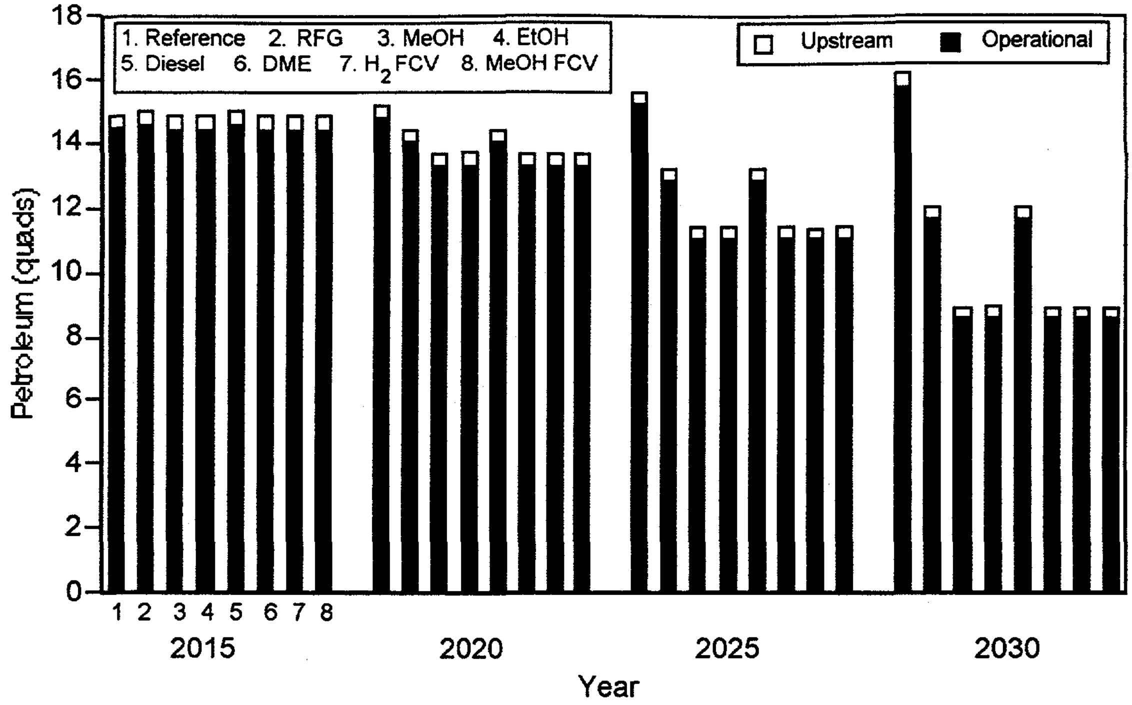

FIGURE 3 Total Fuel-Cycle Petroleum Use by Light-Duty-Vehicles

Emissions Impacts

Nitrogen Oxides (NO_X). Because Tier 2 emissions standards were assumed to be in place, Reference Scenario NO_X emissions held relatively steady over the forecast period (Fig. 4). Fuel-cell vehicles (especially those using hydrogen) showed the greatest potential for reducing NO_X emissions (primarily downstream), with RFG- and ethanol-fueled vehicles distant third and fourth place alternatives as a result of reduced upstream emissions. Both diesel- and DME-fueled alternatives increased downstream NO_X relative to the Reference Scenario, clearly illustrating the need for improved NO_X control for CI engines.

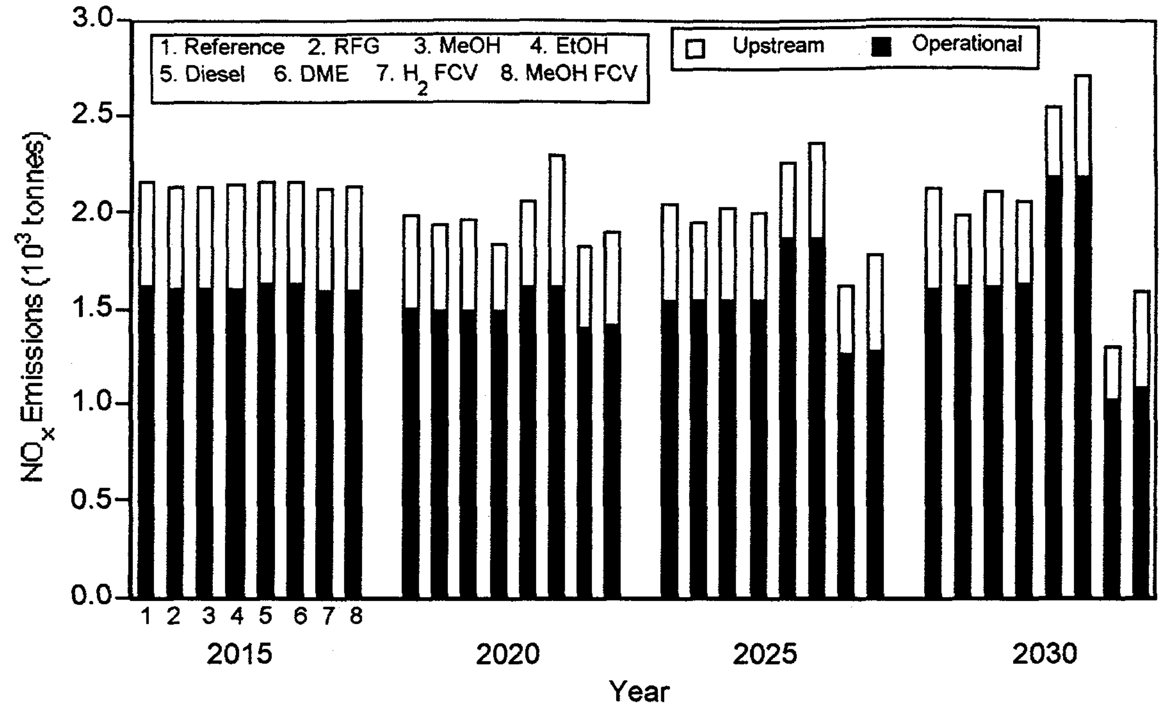

FIGURE 4 Total Fuel-Cycle NO_X Emissions of Light-Duty Vehicles

Carbon Monoxide (CO). As shown in Figure 5, vehicle operations account for nearly all CO emissions. Again, the assumption of Tier 2 emission standards constrained growth in CO emissions, which dropped between 2015 and 2020 and then rose slowly under the Reference Scenario. (The rise is due to the gradual increase in VMT.) Fuel-cell vehicles again showed the greatest potential for downstream emission reduction, followed by diesel- and DME-fueled alternatives. Given the CI engine's proven record of relatively low CO emissions, this result was not unexpected.

Volatile Organic Compounds (VOCs). Unlike NO_X and CO, Reference Scenario emissions of VOCs continued to rise throughout the forecast period (see Figure 6). This rise resulted from increasing travel coupled with Tier 2 controls that applied to only the exhaust portion of VOC emissions. From a VOC emissions-reduction standpoint, hydrogen fuel cells were the clear leader in 2030 since virtually no VOC is generated when hydrogen is produced from solar energy via water electrolysis. With the exception of RFG, all technology/fuel alternatives produced significant reductions in upstream and downstream VOC emissions, primarily because of their fuel properties.

Sulfur Oxides (SO_X). Because most SO_X emissions occur upstream in the fuel pathway, SO_X emissions were closely related to the volume of fuel used. Improvements in upstream fuel production activities caused Reference Scenario SO_X emissions to drop between 2015 and 2020, and then to begin rising slowly (with VMT growth) over the forecast period (see Figure 7). Relative to the Reference Scenario, all technology/fuel alternatives produced a decline in SO_X

emissions because of their 3X efficiency improvement. Ethanol-, methanol-, DME-, and hydrogen-fueled alternatives achieved the biggest declines because of the inherently low sulfur content of these fuels. Conversely, diesel showed the least reduction in SO_X emissions relative to the reference scenario, because diesel CI engines were assumed to have high tailpipe SO_X emissions.

Particulate Matter (PM_{10}). For most fuels (ethanol and diesel are notable exceptions) nearly half of all PM_{10} emissions occur upstream. PM_{10} emissions rose slowly under the Reference Scenario due to growth in VMT (see Figure 9). Ethanol- and, to a lesser extent, diesel-fueled alternatives increased PM_{10} emissions, while hydrogen-, methanol-, DME-, and RFG-fueled alternatives reduced PM_{10} emissions. Note that the sharp increase in PM_{10} emissions for the ethanol-fueled alternative occurred upstream, from agricultural operations as well as ethanol production. The increase for the diesel-fueled alternative, (which was expected) occurred downstream (from diesel engine exhaust) since diesels were assumed to meet only the current PM_{10} standard. If a more stringent standard were adopted (and met), diesel PM_{10} emissions would be lower than these estimates.

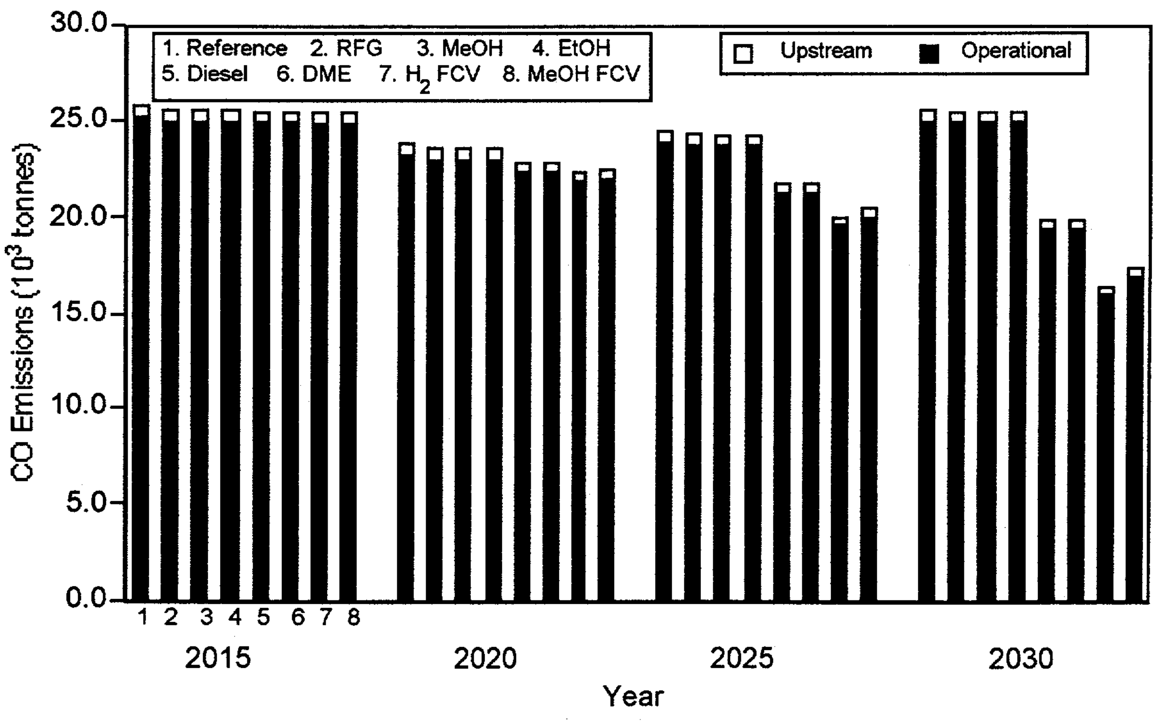

FIGURE 5 Total Fuel-Cycle CO Emissions of Light-Duty Vehicles

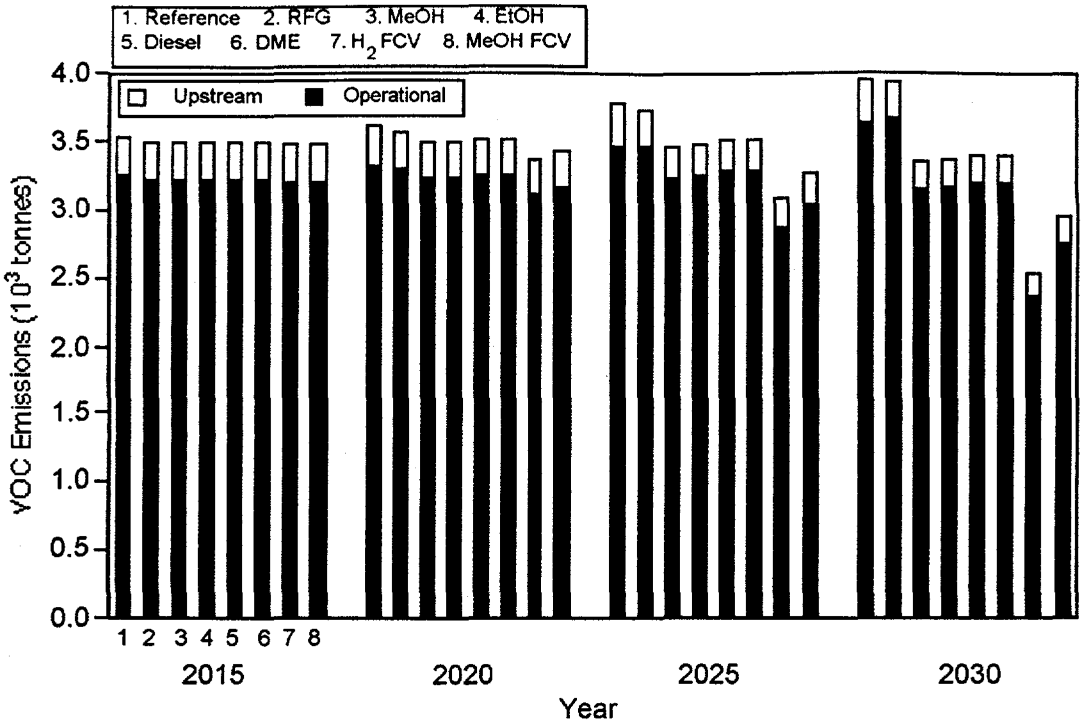

FIGURE 6 Total Fuel-Cycle VOC Emissions of Light-Duty-Vehicles

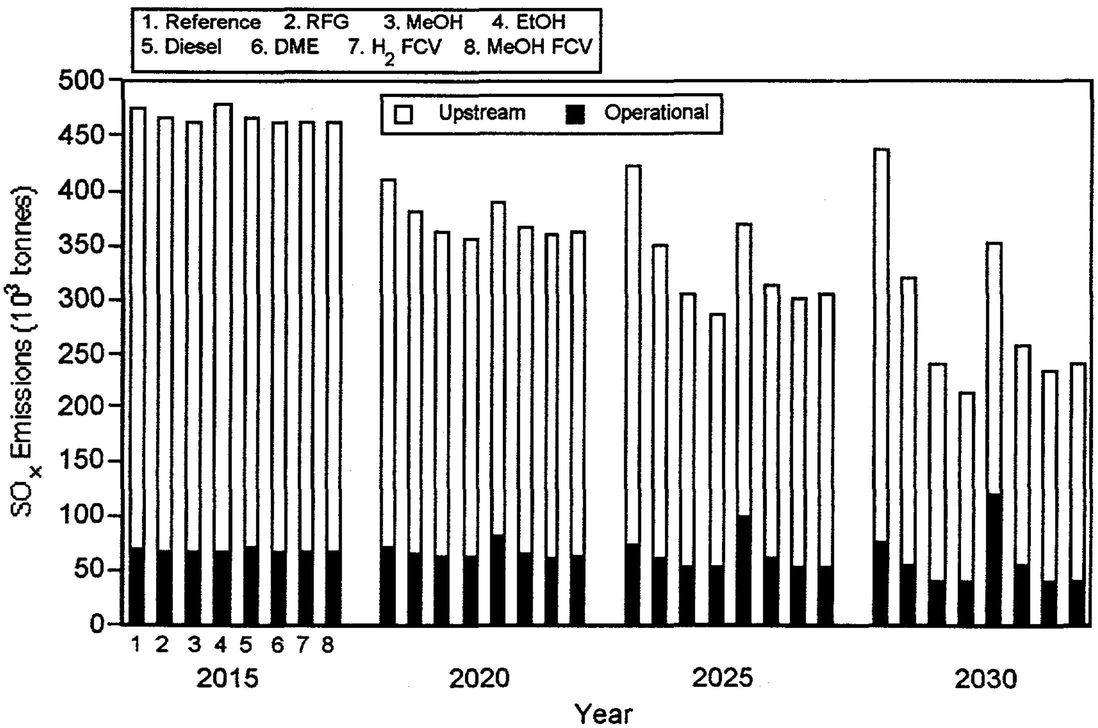

FIGURE 7 Total Fuel-Cycle SO_X Emissions of Light-Duty-Vehicles

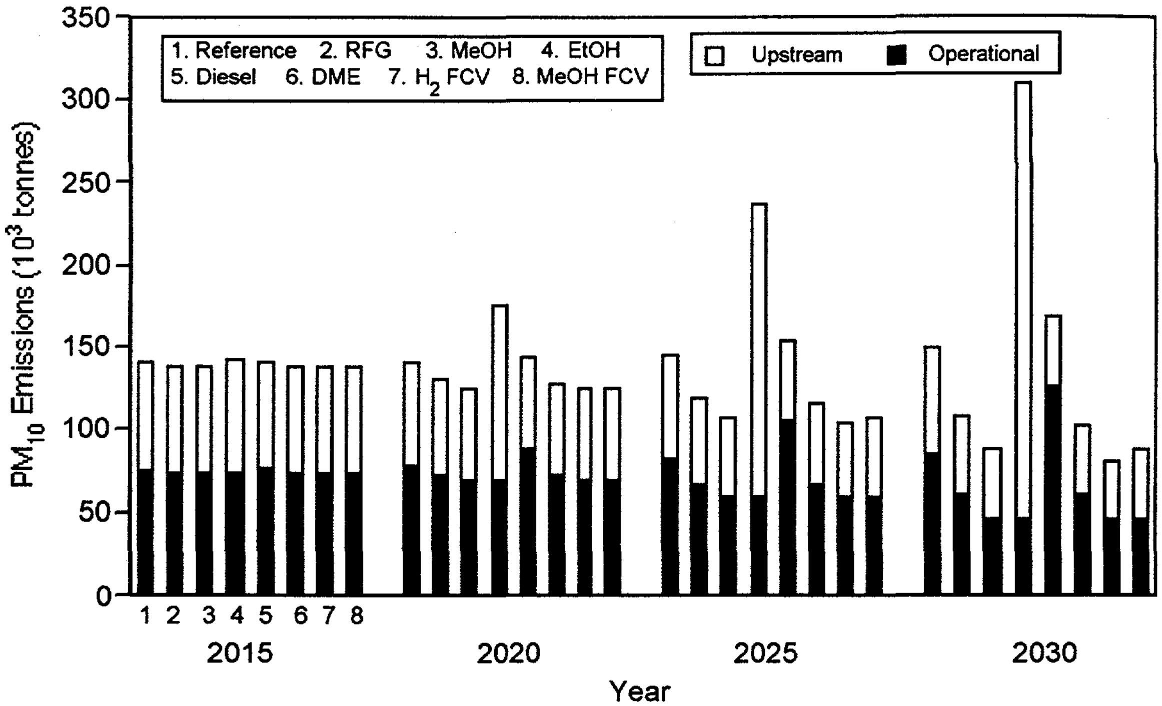

FIGURE 8 Total Fuel-Cycle PM_{10} Emissions of Light-Duty Vehicles

Carbon Dioxide. As shown in Figure 9, Reference Scenario emissions of CO_2 rose steadily over the forecast period. Since the Reference Scenario assumed no significant use of alternative fuels, the CO_2 generated by increased vehicular travel (by conventional vehicles) was moderated only by relatively modest fuel economy improvements (new autos achieved 27.5 mpg in 1995 vs. 35.4 mpg in 2030; light trucks rose from 20.2 mpg in 1995 to 26.5 mpg in 2030). Because of their 3X efficiency improvement, all technology/fuel combinations achieved significant reductions in CO_2 emissions relative to the Reference Scenario.

Under the High Market Share Scenario, several of the alternatives produced dramatic reductions in CO_2 emissions. Chief among these low-CO_2 alternatives were ethanol-fueled IC engines and hydrogen fuel cells, both of which generated no CO_2 from vehicle operation. Hydrogen-fuel-cell vehicles generated no CO_2 because there is no carbon in the fuel. Ethanol-fueled SI engines were assumed to generate zero CO_2 because the carbon in ethanol comes from carbon in the atmosphere via photosynthesis. When combined with the conventional vehicles in the High Market Share Scenario, these low-CO_2 alternatives achieved an overall reduction in fuel-cycle CO_2 emissions (from all light-duty vehicles, both PNGV and conventional) of nearly 50%. Due to higher upstream emissions, hydrogen fuel cells achieved somewhat less overall reduction; however, they were still far superior to the next best alternatives, DME- and methanol-fueled IC engines and methanol-fuel-cell vehicles.

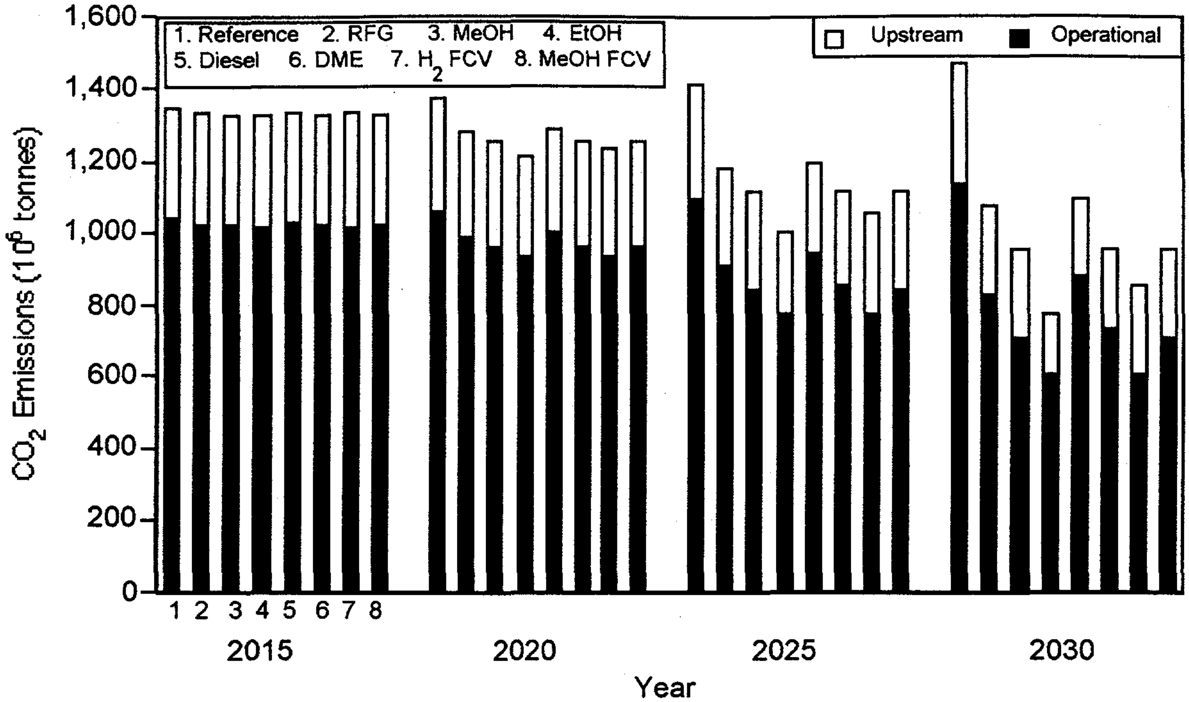

FIGURE 9 Total Fuel-Cycle CO_2 Emissions of Light-Duty-Vehicles

Conclusions

Energy and emissions impacts of 3X vehicles are highly dependent on market penetration and thus differed substantially between the two market share scenarios examined in this study. Impacts were relatively small under the Low Market Share Scenario. Under the High Market Share Scenario, total energy and petroleum use by light-duty vehicles declined significantly for all PNGV fuel/engine technologies relative to Reference Scenario estimates for 2030. Petroleum savings occurred as a result of fuel efficiency improvements, which applied to all 3X technologies, and which reduced transportation petroleum use by more than a quarter, as well as fuel substitution, which applied to the nonpetroleum-fueled alternatives studied. Together, the two effects reduced transportation petroleum use in 2030 by nearly half relative to the Reference Scenario. CO2 emissions were reduced by about half with biomass-based ethanol and solar hydrogen, somewhat less with the other alternatives.

As far as criteria pollutants are concerned, diesel- and DME-fueled alternatives increased NO_X emissions and decreased CO emissions; FCVs reduced emissions of all criteria pollutants; all PNGV fuel/engine technologies reduced SO_X emissions; and diesel- and (especially) ethanol-fueled alternatives increased PM_{10} emissions. Generally speaking, NO_X, CO, and VOC impacts occurred downstream, while SO_X and PM_{10} impacts occurred both upstream and downstream.

The air quality implications of these results are somewhat problematic, since impacts are affected by the location as well as the amount of emissions. Upstream emissions usually occur outside urban areas, while vehicular emissions usually occur within urban areas. These latter emissions generate far greater damage than the former. Full assessment of the damage caused by emissions from each fuel requires air quality modeling and risk assessment beyond the scope of this analysis.

The overall study on which this paper is based estimated energy and emissions impacts as well as capital needs for fuels infrastructure. The study showed the tradeoff between costs and benefits, a tradeoff which is particularly crucial for hydrogen FCVs which were found to offer the largest energy and emissions benefits, but with the greatest incremental capital need. This paper does not address the cost side of the equation, nor technological readiness which is another area where FCVs may lag behind the other alternatives examined.

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