smaller than 10 μm (PM₁₀), sulfur oxides (SOₓ), methane (CH₄), nitrous oxide (N₂O), and carbon
dioxide (CO₂). The three greenhouse gases (GHGs) (CH₄, N₂O, and CO₂) were weighted by their
global warming potentials to estimate CO₂-equivalent GHG emissions. Emissions of the five urban
air pollutants were further separated into total emissions and urban emissions to provide a better
indication of human exposure to air pollution that would result from a given combination of 3X fuel
and propulsion system technologies.

The IMPACTT model was used to estimate annual energy consumption and emissions
production by conventional and 3X vehicles by considering vehicle stock and usage and emission
rates from GREET runs. In IMPACTT, age-based tailpipe emissions rates were obtained from
EPA’s MOBILE5b and PART5 models for conventional SI and CI engines operating on gasoline
and diesel fuel, respectively. Average operational emissions rates for nonconventional engines and
fuels were estimated on the basis of the assumptions presented below. Although MOBILE5a and
PART5 are under criticism for not predicting emissions accurately, they are still the most widely
used models in the United States.

Emissions standards are an important reason for considering alternative propulsion systems
in the PNGV program. In the United States, new vehicles must meet the federal Tier 1 emissions
standards. Tier 2 standards, requiring a further 50% reduction (beyond Tier 1 standards) in vehicle
emissions for model-year 2004 and beyond, may be adopted in 1999 (vehicles in California must
now meet stricter low-emission vehicle standards). It is generally believed that 3X vehicles will be
subject to Tier 2 standards for VOC, CO, and NOₓ and the ultra-low-emission vehicle standard for
PM. For this study, we assumed that RFG-fueled SIDI engines would meet Tier 2 standards. All
other SIDI engines (fueled with methanol, ethanol, CNG, LNG, and LPG) were assumed to meet
Tier 2 standards. If an alternative fuel offers inherently lower emissions than RFG, emissions
reductions were assumed for that fuel. We further assumed that 3X CIDI engines fueled with RFD
would at least meet Tier 2 standards for NOₓ, CO, and VOC and the ultra-low-emission vehicle
standard (i.e., 0.04 g/mi) for PM. As with SIDI alternative fuels, CIDI fuels that offer inherently
lower emissions were assumed to achieve greater reductions than RFD.

Fuel-Cycle Energy and Emissions Estimates

Figures 2–4 display percent changes in urban emissions of VOC, SOₓ and PM₁₀, for each of
the propulsion system/fuel combinations examined. Each figure depicts results for a single pollutant
as a series of curves showing annual percentage increases or decreases from the reference scenario
forecast. Curves that are all but indistinguishable are combined to aid interpretation. Note that each
propulsion system/fuel alternative was examined in the context of a scenario that contained a
significant portion of conventional vehicles. Thus, emissions were computed for a combination of
conventional and 3X technologies, so results are less striking than would be the case for 3X
technologies alone.

Nitrogen Oxides (NOₓ). Urban NOₓ emissions are not shown because of relatively small
differences among the alternatives. The four CIDI fuels (RFD, DME, FT50, and B20) were
assumed to meet equivalent Tier 2 emission standards and thus were essentially equivalent to results
for RFG, methanol, ethanol, LPG, and the gaseous fuel alternatives. Methanol and gasoline fuel
cells offer the largest reduction in urban NOₓ emissions — 35% in 2030. H₂ fuel cells achieve a
somewhat lower NOₓ reduction because of their relatively higher upstream emissions.

CO. Reductions in urban CO emissions range from essentially zero to about 35% in 2030;
fuel cells achieve the greatest reductions, and SIDI engines on any of six fuels achieve the lowest.
Given the CI engine’s proven record of relatively low CO emissions, it is not surprising that diesel-
lke fuels (RFD, DME, FT50, and B20) achieve the second-best CO reduction, approximately 28%
in 2030.

VOCs. Urban VOC emissions reductions range up to approximately 37% (Figure 2). H₂ fuel
cells are the clear leader in reducing VOC emissions, methanol fuel cells are a close second and
gasoline fuel cells are third. CIDI engines fueled by RFD, DME, FT50, or B20 and SIDI engines fueled by LPG, CNG, or LNG achieve almost half the reduction of H2 fuel cells.

SO2 Urban SO2 emissions are closely related to the volume of fuel used. Thus, all propulsion system/fuel alternatives reduce urban SO2 emissions because of their tripled fuel efficiency (Figure 3). H2 fuel cells, LPG, CNG, ethanol, and DME achieve the greatest reductions, but urban SO2 represents a very small share (on the order of 13%) of the total SO2 attributable to light-duty vehicles. Most SO2 emissions come from upstream fuel processing, which tends to occur outside urban areas.

Figure 2 Changes in Fuel-Cycle Urban VOC Emissions by 3X Technology/Fuel Alternative

Figure 3 Changes in Fuel-Cycle Urban SO2 Emissions by 3X Technology/Fuel Alternative
With the exception of DME, diesel-like fuels increase PM$_{10}$ emissions (Figure 4). Excluding RFG, DME, and LNG, which have little effect on PM$_{10}$, all the other alternatives decrease PM$_{10}$ emissions by approximately 15%. Note that the increase for diesel-like fuels occurs despite the assumption of a “Tier 2 equivalent” exhaust emission standard of 0.04 g/mi.

GHGs. Figure 5 shows that changes in total GHG emissions. Note that because CO$_2$ accounts for the bulk of GHG emissions and all propulsion system/fuel alternatives share the same fuel efficiency, emission reductions from non-renewable fuels are clustered. Chief among the low-GHG alternatives is ethanol-fueled SIDI engines and H$_2$ fuel cells, both of which generate no CO$_2$ from vehicle operations (the carbon in ethanol comes from carbon in the atmosphere via photosynthesis). When combined with the conventional vehicles (and their GHG emissions), these low-GHG alternatives achieve overall reductions (from all light-duty vehicles, both 3X and conventional) of 46% (for ethanol) and 33% (for H$_2$).

Figure 4 Changes in Fuel-Cycle Urban PM$_{10}$ Emissions by 3X Technology/Fuel Alternative

Petroleum. Several of the technology/fuel alternatives consume nonpetroleum fuels (Figure 6). Clearly, the alternatives cluster into three groups: largely petroleum fuels (i.e., RFG, RFD, and B20), part petroleum fuels (i.e., FT50 and LPG), and largely nonpetroleum fuels (i.e., H$_2$, methanol, ethanol, DME, CNG, and LNG). By 2030, the nonpetroleum alternatives achieve an approximately 45% reduction in total petroleum use. The part petroleum alternatives (i.e., FT50 and LPG) achieve the next-best reduction — approximately 35% under that scenario.
CONCLUSIONS

Our study reveals that supplying gasoline-equivalent demand for the low-market-share scenario requires a capital investment of less than $40 billion for all fuels except H₂, which will require a total cumulative investment of $150 billion. By contrast, cumulative capital investments under the high-market-share scenario are $50 billion for LNG, $90 billion for ethanol, $100 billion for methanol, $160 billion for CNG and DME, and $560 billion for H₂. Although these substantial capital requirements are spread over many years, their magnitude could pose a challenge to the widespread introduction of 3X vehicles.
Fossil fuel use by U.S. light-duty vehicles declines significantly with introduction of 3X vehicles because of fuel-efficiency improvements for 3X vehicles and because of fuel substitution (which applies to the nonpetroleum-fueled alternatives). Petroleum use for light-duty vehicles in 2030 is reduced by as much as 45% relative to the reference scenario. GHG emissions follow a similar pattern. Total GHG emissions decline by 25–30% with most of the propulsion system/fuel alternatives. For those using renewable fuels (i.e., ethanol and H₂ from solar energy), GHG emissions drop by 33% (H₂) and 45% (ethanol).

Among urban air pollutants, urban NOₓ emissions decline slightly for 3X vehicles using CIDI and SIDI engines and drop substantially for fuel-cell vehicles. Urban CO emissions decline for CIDI and FCV alternatives, while VOC emissions drop significantly for all alternatives except RFG-, methanol-, and ethanol-fueled SIDI engines. With the exception of CIDI engines fueled by RFD, FT50, or B20 (which increase urban PM₁₀ emissions by over 30%), all propulsion system/fuel alternatives reduce urban PM₁₀ emissions. Reductions are approximately 15–20% for fuel cells and for methanol-, ethanol-, CNG-, or LPG-fueled SIDI engines.

Table 3 qualitatively summarizes impacts of the 13 alternatives on capital requirements and on energy use and emissions relative to the reference scenario. The table clearly shows the trade-off between costs and benefits. For example, while H₂ FCVs have the greatest incremental capital needs, they offer the largest energy and emissions benefits. On the basis of the cost and benefit changes shown, methanol and gasoline FCVs appear to have particularly promising benefits-to-costs ratios.

Table 3 | Impacts of Propulsion System/Fuel Alternatives for 3X Vehicles Relative to the Reference Scenario |
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<sup>a</sup> 0: no change  ++: a little better  +++: best  ++: a little worse  ---: worst

<sup>b</sup> Urban emissions

ACKNOWLEDGMENTS

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REFERENCES


