Light-Duty Vehicle Fuel Consumption Displacement Potential up to 2045

Energy Systems Division
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Light-Duty Vehicle Fuel Consumption Displacement Potential up to 2045

EXECUTIVE SUMMARY

by
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July 2011
1. EXECUTIVE SUMMARY

The U. S. Department of Energy (DOE) Vehicle Technologies Program (VTP) supports new technologies to increase energy security in the transportation sector at a critical time for global petroleum supply, demand, and pricing. Consequences of our vehicles’ dependence on oil as their source of energy were shown by the “first oil shock” brought on by the petroleum embargo of October 1973 and the “second oil shock” of 1979. However, this oil dependence continues to increase unabated to the present, and the oil price run-up of July 2008 ($147 per barrel of crude) illustrated the rapidity with which these discontinuities can occur. As such, the lack of widely available and viable alternative non-petroleum-based fueling options for ground transport vehicles constitutes a high risk to stable economic activity. Some means of providing energy to move vehicles that greatly reduces or eliminates petroleum consumption must be developed. This challenge is greatly complicated by the fact that virtually all alternatives have some inherent fossil-fuel component. The U.S. transportation sector used about 13.5 million barrels of oil equivalent per day in 2009. It consumed more oil than the total U.S. domestic oil production. On-highway vehicles (passenger and commercial vehicles) used over 11 million barrels of oil equivalent per day, which accounts for over 79 percent of the total transportation oil use and over 59 percent of total U.S. oil use. The Vehicle Technologies Program focuses on ground transportation vehicles because of their dominant contribution to the nation’s oil use.

VTP works in collaboration with industry to identify the priority areas of research needed to develop advanced vehicle technologies to reduce and eventually eliminate petroleum use, and reduce emissions of greenhouse gases, primarily carbon dioxide from carbon-based fuels. The VTP works on numerous technologies, including the following:

- Development of hybrid electric vehicles (HEVs) and plug-in HEVs (PHEVs) can provide significant improvement in fuel economy and petroleum displacement. This research supports President Obama’s goal of 1 million plug-in hybrid vehicles (PHEVs) and electric vehicles (EVs) by 2015.
- Deployment of alternative fuels can rapidly reduce oil imports.
- Reducing vehicle weight directly improves vehicle efficiency and fuel economy, and can potentially reduce vehicle operating costs.
- Improved combustion technologies and optimized fuel systems can improve near- and mid-term fuel economy for passenger vehicles by 25–40% for passenger vehicles by 2015.

The objective of the present study is to evaluate the benefits of the DOE VTP for a wide range of vehicle applications, powertrain configurations and component technologies for different timeframes and quantify the potential future petroleum displacement up to 2045 as well as the cost evolution. More than 2000 light-duty vehicles were simulated with Autonomie, Argonne’s vehicle simulation tool.
Owing to the large number of powertrain and component technologies, only a limited number of combinations were taken into account (i.e., micro or “mild” HEVs were not included), leading to the consideration of more than 2000 vehicles. To address performance and cost uncertainties, three cases were considered: low (10%), average (50%), and high (90%) uncertainty. When available, the high-case assumptions are based on the FreedomCAR and Fuel Partnership program goals. The other assumptions have been developed through discussions with experts from companies, universities, and the national laboratories. While the uncertainties are expected to provide a range, it should be noted that several ongoing research projects or lack of data for specific technologies could lead to significantly higher fuel-efficiency gains than considered in the study. For example, the engine gains could be considered less aggressive than for other technologies, and readers should take this parameter into account during the analysis. More than 400 assumptions are necessary to define each vehicle. Some of the main assumptions are highlighted below:

- The difference in peak efficiency between gasoline and diesel engines is expected to narrow in the future owing to the combination of advanced gasoline engine technologies and the impact of ever more stringent after-treatment for diesel.
- Coupling ultra-capacitors with batteries was not considered, owing to higher cost and expected increase in Li-ion battery life and cold start performance in the short term.
- Because of the drive quality requirements in North America, automated manual transmissions were not included in the study. Continuously variable transmissions (CVT) have also shown issues with reliability and fuel-efficiency gains and are not considered either.
- The peak efficiencies of fuel-cell systems remain constant in the future, as most research is expected to focus on reducing cost and increasing durability. The costs used are based on the assumption that 500,000 units are produced per year.

The main results related to vehicle sizing, fuel efficiency, and cost are highlighted in the following sections.
1.1. VEHICLE SIZING FINDINGS

Advances in material substitution will play a significant role in reducing overall vehicle weight and, consequently, component power and energy requirements.

- Owing to the impact of the component max-torque shapes, maintaining a constant power-to-weight (P/W) ratio between all configurations leads to an inconsistent comparison between technologies due to different performances. Each vehicle should be sized independently to meet specific Vehicle Technical Specifications (VTS).

- Reducing the vehicle weight ("lightweighting") has greater influence on conventional vehicles than on their electric-drive counterparts.

- While performance (i.e., time for 0-60 mph) is the primary factor used to size components for current technologies, aggressive future lightweighting can make gradeability requirements the critical sizing criteria.

- Vehicle weight decreases in the range from 1 to 51% by 2045 across powertrain configurations. The weight reduction, however, varies with the configuration. For the configurations using an engine, the weight reduction for the gasoline conventional powertrain ranges from 1 to 30%, power-split HEVs from 2 to 33%, low-energy PHEVs (with all-electric ranges, or AERs, of 10 and 20 miles) from 3 to 34%, and high energy PHEVs (30- and 40-mile AERs) from 6 to 37%. Configurations with fuel-cell systems demonstrate a larger weight reduction, with fuel-cell HEV weight reductions ranging from 21 to 51%, low-energy PHEV10s and 20s (i.e., 10- and 20-mile AERs) from 19 to 49% and high-energy PHEV30s and 40s (30- and 40-mile AERs) from 18 to 47%. Finally, battery electric vehicles achieve a weight reduction ranging from 7 to 44%. Overall, significant weight reductions can be achieved compared to current technologies, especially for vehicles with large batteries and/or using hydrogen fuel.

- Most of the component peak powers show a strong linear correlation with the vehicle weight. As a result, it is necessary to include secondary effects when analyzing the lightweighting benefits.

- Owing to lightweighting and component efficiency improvements, the peak power of engine and fuel-cell systems could be significantly reduced over time to meet current Vehicle Technical Specifications. Engine peak power could be reduced by 2045 over a 2-to-28% range for conventional gasoline, 5 to 34% for gasoline power-split HEVs, 4 to 28% for low-energy PHEVs, and 8 to 36% for high-energy PHEVs. As seen for vehicle weight, hydrogen-fueled vehicles demonstrate a larger peak-power improvement than gasoline-fueled vehicles over time, with fuel-cell system power decreasing in the range from 22 to 53% for HEVs, 18 to 48% for low-energy PHEVs and 15 to 38% for high-energy PHEVs.

- Battery peak power is also expected to decrease over time to meet current vehicle performance. The battery power is expected to decrease up to 34% for gasoline-engine HEVs and PHEVs. For fuel-cell systems, the decrease could be as high as 48%.
- Battery total energy will be decreasing significantly owing to other component improvements as well as a wider usable state-of-charge range. The reduction in energy required for PHEVs and battery-powered electric vehicles (BEVs) could range from 4 to 60%.

- While the fuel selection influences the engine size for conventional vehicles (i.e., diesel has lower peak power than gasoline to higher maximum torque at low speed), the power required to meet the Vehicle Technical Specifications for electric-drive vehicles is comparable across all fuels. The different PHEVs show a linear relationship between the usable battery energy and the vehicle mass, with the slope increasing with the All Electric Range.
1.2. VEHICLE FUEL-EFFICIENCY FINDINGS

Overall, the combination of technology improvements leads to significant fuel-consumption reduction across vehicle applications. As a result, significant fuel can be displaced over the next few decades. There is a linear relationship between lightweighting and fuel and electrical consumption. However, as previously discussed, that relationship differs depending on the powertrain configuration.

Evolution of Fuel Consumption Compared to Reference 2010 Gasoline Conventional Vehicle

Table ES-1 shows the adjusted fuel-consumption reduction by 2045 on the combined driving cycle for each powertrain configuration and fuel, compared to the reference gasoline conventional vehicle.

The results demonstrate significant improvements over time across all powertrain configurations and fuels (Table ES-1). When considering the high-uncertainty case across all engines, conventional vehicles can achieve a 41-47% fuel-consumption improvement, engine HEVs, 62 to 67%, engine PHEV10s, 69 to 73%, and engine PHEV40s, 80 to 82%. Fuel-cell vehicles achieve an improvement of up to 70% for HEVs, 75% for PHEV10s, and 84% for PHEV40s.

Table 1 - ES - Percentage Fuel-Consumption Reduction (mi/gal gasoline equivalent or MPGGE) of Each Powertrain by 2045, Compared to 2010 Gasoline Conventional Powertrain. (Electrical consumption is not taken into account for PHEVs)

<table>
<thead>
<tr>
<th>Fuel\Powertrain</th>
<th>Conventional</th>
<th>HEV</th>
<th>PHEV10</th>
<th>PHEV40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>2-43</td>
<td>37-64</td>
<td>49-70</td>
<td>64-81</td>
</tr>
<tr>
<td>Diesel</td>
<td>16-42</td>
<td>42-62</td>
<td>51-69</td>
<td>65-80</td>
</tr>
<tr>
<td>Hydrogen Internal Combustion Engine (ICE)</td>
<td>4-41</td>
<td>50-67</td>
<td>56-73</td>
<td>69-82</td>
</tr>
<tr>
<td>Ethanol</td>
<td>1-47</td>
<td>32-62</td>
<td>46-69</td>
<td>62-80</td>
</tr>
<tr>
<td>Fuel Cell</td>
<td>57-70</td>
<td>62-75</td>
<td>77-84</td>
<td></td>
</tr>
</tbody>
</table>

Evolution of Specific Powertrains

Table ES-2 shows the 2045 adjusted fuel-consumption reduction, on the combined driving cycle, for each powertrain configuration and fuel, compared to each configuration’s current status in 2010 (e.g., the diesel HEV in 2045 is compared to the reference diesel HEV in 2010).
The results demonstrate that the maximum improvement expected for each powertrain technology compared to its current status ranges from 33 to 52%. The range depends on fuels (i.e., diesel vehicles show less improvement than gasoline vehicles) and powertrain (i.e., conventional engines have a lower maximum improvement than PHEV40s). When considering the entire uncertainty range, fuel-cell vehicles show the greatest improvement over time.

Table 2 - ES - Percentage Fuel Consumption Reduction for Each Powertrain by 2045, Compared to the Respective Current Status (Values show uncertainty range)

<table>
<thead>
<tr>
<th>Fuel\Powertrain</th>
<th>Conventional</th>
<th>HEV</th>
<th>PHEV10</th>
<th>PHEV40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>2-43</td>
<td>9-45</td>
<td>8-43</td>
<td>11-49</td>
</tr>
<tr>
<td>Diesel</td>
<td>5-33</td>
<td>10-39</td>
<td>9-39</td>
<td>12-43</td>
</tr>
<tr>
<td>Hydrogen ICE</td>
<td>19-49</td>
<td>24-52</td>
<td>23-50</td>
<td>25-50</td>
</tr>
<tr>
<td>Ethanol</td>
<td>1-41</td>
<td>10-46</td>
<td>8-44</td>
<td>10-50</td>
</tr>
<tr>
<td>Fuel Cell</td>
<td></td>
<td>23-48</td>
<td>20-45</td>
<td>18-42</td>
</tr>
<tr>
<td>Electricity (BEV)</td>
<td></td>
<td>6-41</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Powertrain Comparisons

- Conventional Gasoline Vehicles vs. Engine HEVs
  - The comparison between these powertrains shows that the fuel-consumption reductions due to hybridization stay fairly constant over time for all power-split HEVs.
  - For gasoline HEVs, fuel-consumption reductions range from 36 to 40% for compact cars, 34 to 40% for midsize cars, 60 to 36% for small sport utility vehicles (SUVs), 29 to 35% for large SUVs and 28 to 33% for pickup trucks.

- Conventional Gasoline Vehicles vs. Engine PHEVs
  - As is the case for power-split HEVs, the fuel-consumption reduction observed for PHEVs relative to conventional gasoline vehicles remains fairly constant over time, ranging from 59 to 71%.
  - However, while the percentages decreased for higher vehicle weight classes, the benefits remain fairly constant across platforms, with 63 to 69% fuel consumption reduction for compacts, 65 to 71% for midsize cars, and 59 to 64% for small SUVs, large SUVs and pickup trucks.

- Conventional Gasoline Vehicles vs. Fuel-Cell HEVs
The current fuel-consumption reductions for fuel-cell HEVs compared to conventional gasoline vehicles are 45% for compacts, 43% for midsize cars, 39% for small and large SUVs, and 30% for pickups.

Owing to the expected improvements in fuel-cell system and hydrogen-storage technologies, the fuel-consumption percentage improvements are expected to increase over time. By 2045, the benefits increase from 5 to 20%, depending upon the vehicle class and uncertainties considered.

- Engine HEVs vs. Fuel-Cell HEVs
  - Fuel-cell system technology offers consistently lower fuel consumption than power-split HEV technology.
  - The current fuel-consumption benefits of fuel-cell HEVs compared to gasoline power-split HEVs are fairly constant across all vehicle classes, ranging from 12 to 14%.
  - Owing to the engine and fuel-cell system operating conditions for HEVs, the fuel consumption improvement remains constant across all vehicle classes. However, owing to the expected improvement of hydrogen technologies, the percentage is expected to increase by 18 to 26% by 2045.

- Conventional Hydrogen Engines vs. Fuel-Cell HEVs
  - The percentage of fuel-consumption reduction for fuel-cell vehicles compared to hydrogen conventional vehicles remains at around 50%.
  - The percentage of fuel-consumption reduction remains fairly constant over time for each vehicle class: 50 to 52% for compacts, 50 to 55% for midsize cars, 46 to 48% for small SUVs, 44 to 47% for large SUVs, and 42 to 46% for pickup trucks.

- Hydrogen Engine HEVs vs. Fuel Cell HEVs
  - The fuel-consumption reduction for fuel-cell HEVs compared to hydrogen engine HEVs remains fairly constant across vehicle classes for the reference case ranging from 13 to 17%.
  - The percentage decreases over time owing to the faster improvement of hydrogen engine performance compared to fuel-cell system performance, reaching 8 to 15% by 2045.

Evolution of Fuel Comparisons

- Gasoline vs. diesel
  - The differences between gasoline and diesel-engine fuel consumption for conventional vehicles will tend to decrease in the future.
  - For conventional vehicles, the fuel consumption advantage of diesel engines, when considering MPGe, goes from 11–15% in 2010 to -1–15% by 2045.
For HEVs, the fuel consumption benefit of diesel is smaller than for conventional vehicles, ranging from 5 to 8% in 2010. However, the gap between these fuels is also expected to decrease over time, with gasoline achieving lower fuel consumption for high-uncertainty cases.

For PHEVs, the benefits of diesel compared to gasoline are minimal, ranging from 1 to 2% in 2010.

However, the diesel engine retains the best fuel consumption for the vast majority of uncertainties and timeframes.

- Ethanol
  - In most cases, ethanol-engine vehicles have the highest fuel consumption among conventional vehicles.
  - Ethanol-fuel conventional vehicles are expected to narrow their fuel consumption penalty over gasoline engines with time. In 2010, the penalty ranges from 7 to 8%; it could be lowered to 5-7% by 2045.
  - The fuel-consumption penalty for ethanol decreases for increased hybridization degree and battery energy

- Hydrogen Engine
  - The hydrogen-engine conventional vehicle shows the greatest improvements in fuel consumption over time, owing to the introduction of direct injection. The fuel penalty compared to its gasoline counterpart is 10-17% in 2010; by 2045, hydrogen-fueled conventional vehicles could range from a fuel-consumption penalty of 3% up to an advantage of 12%.
  - By 2045, the hydrogen-fueled engine configurations consistently achieve the lowest fuel consumption of any configuration.
1.3. MANUFACTURING COST FINDINGS:

Overall, the combination of technology improvements leads to significant manufacturing cost reduction across vehicle applications. As a result, advanced technologies are expected to have significant market penetration over the next decades.

Cost Evolution Compared to Reference 2010 Gasoline Conventional Vehicle

Table ES-3 shows the additional manufacturing cost by 2045, compared to the reference gasoline conventional vehicle. The table shows a significant uncertainty range for the additional manufacturing cost across all technologies. This high uncertainty highlights the need to pursue aggressive research over the next decades to bring the cost of advanced technologies to a level that will favor high market penetrations.

<table>
<thead>
<tr>
<th>Fuel\Powertrain</th>
<th>Conventional</th>
<th>HEV</th>
<th>PHEV10</th>
<th>PHEV40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>584-1240</td>
<td>560-3091</td>
<td>1029-4086</td>
<td>2188-8402</td>
</tr>
<tr>
<td>Diesel</td>
<td>1782-2609</td>
<td>2037-4831</td>
<td>2290-5543</td>
<td>3700-10159</td>
</tr>
<tr>
<td>Hydrogen ICE</td>
<td>452-951</td>
<td>828-2706</td>
<td>1099-3500</td>
<td>2432-7935</td>
</tr>
<tr>
<td>Ethanol</td>
<td>511-1209</td>
<td>583-3111</td>
<td>802-3695</td>
<td>2205-8426</td>
</tr>
<tr>
<td>Fuel Cell</td>
<td>-264-1812</td>
<td>-186-2661</td>
<td>721-6035</td>
<td></td>
</tr>
<tr>
<td>BEV</td>
<td>1446-10649</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Evolution of Costs for Specific Powertrains

Table ES-4 compares the percentage change in the manufacturing cost between 2010 and 2045 for each configuration relative to its current value.

Vehicle manufacturing costs for gasoline, diesel, and ethanol conventional vehicles increase over time because of several factors, including lightweighting (vehicle body mass decreases up to 37% by 2045 and its cost increases owing to the use of aluminum or carbon fiber) and advanced component technologies such as direct injection. In
contrast, the greatest reductions are noticed for the vehicles with high-energy batteries, fuel-cell systems and hydrogen storage.

Owing to the expected improvements in batteries, the higher the battery energy, the greater will be the manufacturing cost reduction. As a result, PHEV40 demonstrates a larger cost reduction than PHEV10 across all fuels. PHEV40s with gasoline engines show cost reductions ranging from 32 to 41% from 2010 to 2045, while PHEV10s only show a cost reduction ranging from 11 to 18%.

The fuel-cell vehicle manufacturing costs decrease significantly over time. From 2010 to 2045, the manufacturing for the fuel-cell HEV decreases by 29 to 41%, for the fuel-cell PHEV10 by 30 to 42%, and for the fuel-cell PHEV40 by 35 to 45%.

<table>
<thead>
<tr>
<th>Fuel\Powertrain</th>
<th>Conventional</th>
<th>HEV</th>
<th>PHEV10</th>
<th>PHEV40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>-9 to 4</td>
<td>-1 to -2</td>
<td>-18 to -11</td>
<td>-41 to -32</td>
</tr>
<tr>
<td>Diesel</td>
<td>1 to 4</td>
<td>-12 to -5</td>
<td>-20 to -13</td>
<td>-40 to -33</td>
</tr>
<tr>
<td>Hydrogen ICE</td>
<td>-10 to 7</td>
<td>-21 to -5</td>
<td>-27 to -14</td>
<td>-45 to -35</td>
</tr>
<tr>
<td>Ethanol</td>
<td>4 to 9</td>
<td>-10 to -2</td>
<td>-18 to -11</td>
<td>-40 to -33</td>
</tr>
<tr>
<td>Fuel Cell</td>
<td>-41 to -29</td>
<td>-42 to -30</td>
<td>-45 to -35</td>
<td></td>
</tr>
<tr>
<td>Electricity (BEV)</td>
<td>-66 to -55</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4 - ES - Percentage manufacturing cost Reduction for Each Powertrain by 2045, Compared to the Respective Current manufacturing cost, for Compact Cars

Powertrain Comparison

- The manufacturing cost differences between different powertrain options tend to decrease over time. In 2010, for midsize cars, the gasoline power-split HEV is 26% more expensive than the conventional vehicle, the PHEV10 45% more expensive and the PHEV40 150% more expensive. By 2045, these percentages are 8-13% for HEVs, 11-17% for PHEV10s, and 32-50% for PHEV40s.

- While vehicles with hydrogen engines will remain more expensive than fuel-cell vehicles, the technology will become more cost-competitive with the fuel-cell system over time. By 2045, conventional hydrogen-engine vehicles will be slightly cheaper to manufacture than their gasoline counterpart.
Fuel-Comparison Evolution

- Gasoline vs. diesel
  - The conventional diesel vehicle manufacturing cost will remain between 10 and 13% more expensive than gasoline vehicles.
  - The diesel HEV is between 10 and 14% more expensive to manufacture than the gasoline vehicle, but this difference tends to decrease after 2010.

- Ethanol
  - Gasoline and ethanol vehicles have similar manufacturing costs across timeframes. Their manufacturing cost increases between 4 and 8% between 2010 and 2045, whereas the diesel-vehicle manufacturing cost increases by only 1 to 5% in that timeframe.
  - From 2010 forward, the relative cost of ethanol vehicles decreases, reaching almost the same level as gasoline HEVs in 2045.

- Hydrogen Engine
  - Vehicle cost for the hydrogen engine decreases as the additional cost of reducing the vehicle weight ("lightweighting") is compensated by larger cost reductions in the hydrogen storage system.
1.4. CONCLUSION

The combination of the technology improvements leads to significant fuel consumption and cost reduction across light duty vehicle applications. Due to the uncertainty of the evolution of the technologies considered, research should continue to be conducted in the different area showing high fuel displacement potential.

Due to expected improvements, advanced technologies are expected to have significant market penetration over the next decades. In the short term, both engine HEVs and PHEVs allow for significant fuel displacement with acceptable additional cost. While electric vehicles do provide a promising solution, they are likely to remain expensive and range limited in the near future. In the medium term, hydrogen engine HEVs will offer significant fuel improvements and could potentially offer a bridging technology that would help establish the infrastructure required for fuel cell vehicles. For the long term, fuel cell vehicles demonstrate very high fuel displacement potential at a competitive cost.

This research will be updated on a yearly bases to include the latest powertrain technologies (i.e., multi-mode HEV, E-REV...), component technologies, as well as additional timeframes (i.e., 2020) and vehicle applications.