Light-Duty Vehicles: A Discussion of the Evolving Engine, Vehicle and Fuel Requirements Context

John B. Heywood

Sun Jae Professor of Mechanical Engineering Emeritus
Sloan Automotive Laboratory
M.I.T.

Abstract

This paper discusses the evolving vehicle context within which assessments and choices of alternative fuels for transportation should take place. The focus is on anticipated engine, powertrain, and other propulsion system improvements (especially their average efficiency) in the context of steadily reducing vehicle driving resistances, and especially weight. The fuel requirements of spark-ignition, diesel, and hybrid engines are discussed and connected to the supply, distribution, and refueling requirements of alternative fuels. An illustrative scenario of alternative fuels is described and used to indicate likely future fuel demand.

1. Background

As the price of oil continues to rise, and the potential for growth of petroleum-based transportation fuel in the longer-term is uncertain, the question of other energy sources and fuels is obviously important. An awareness of the vehicle context, especially the engines or other propulsion system changes in progress, is a necessary preliminary to developing effective alternative fuels strategies. This paper addresses the question of how this engine and vehicle context is likely to evolve over the next twenty years especially in relation to fuel requirements. The focus is on the current state of the in-use light-duty vehicle fleet (cars and light-trucks) in the United States and how, as new and more fuel efficient technology and propulsion systems enter and leave the vehicle fleet or parc through sales and scrappage, the fuel demand and greenhouse gas emissions of this critical component of the total U.S. energy sector will change.

The current U.S. transportation fuels situation from an energy perspective is as follows. Ethanol, made from corn grain is approaching 10 percent of the gasoline market. It is largely blended with and sold as “gasoline.” There are some 2500 refueling stations where ethanol fuel (as E85) can be purchased: there are close to 120,000 re-fueling stations nationwide. A modest amount (or order 1 percent) of biodiesel fuel is blended with regular diesel fuel. In the total in-use fleet of 260 million vehicles there are about 10 million flexible-fuel vehicles in use that can satisfactorily use gasoline, E85, or any mixture of the two. Vehicle models that can use electricity directly (plug-in hybrids, PHEVs, battery electric vehicles, BEVs) are entering the market but as yet sales volumes are very small. There is also modest use of natural gas in vehicles in the U.S.—in buses, and in a small number of dual-fuel and dedicated NG vehicles.
In terms of mainstream technology the dominant propulsion systems are gasoline-fueled spark-ignition engines and diesel engines. While the light-duty vehicle market in Europe is about half gasoline/petrol and half diesel, in the U.S. gasoline engines dominate. The performance and fuel consumptions of these engines has and continues to steadily improve. Table 1 lists the primary nearer-term opportunities for improving the efficiency of gasoline-fueled engine vehicles. They are, in order of importance:

- Turbocharging naturally-aspirated gasoline engines which constitute some 90% of the market, with direct injection of fuel into the cylinder, and significant engine downsizing since the torque per unit of engine displaced volume is substantially increased.

- Improving the base engine efficiency through variable valve timing/control, increasing engine compression ratio, and reductions in powertrain friction, trends that are already underway.

- Introducing engine shut down at idle: so-called engine stop/start. In urban driving this reduces average fuel consumption by up to 5%.

- Steadily reducing the weight of vehicles through substitution of lighter materials, vehicle redesign, and shifting the vehicle size distribution downwards.

Beyond 2016, the auto manufacturers are likely to use these technologies more widely in their sales mix to meet the 2025 CAFE mpg targets now being finalized, step up the pace of ongoing incremental improvements, take additional weight out of vehicles beyond the 5 – 10% reduction expected by 2016, increase the percentage of hybrids, and introduce some electrified vehicles (PHEVs and BEVs) to gain the miles-per-gallon credits these alternative energy vehicles are being awarded.

### Table 1: Opportunities for Improving Powertrain Efficiency

<table>
<thead>
<tr>
<th>Technology</th>
<th>Compared with</th>
<th>% Gain in MPG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel engine</td>
<td>Gasoline engine</td>
<td>25 – 30%</td>
</tr>
<tr>
<td>Gasoline direct injection + Turbo</td>
<td>Multiport fuel injection</td>
<td>Up to 12%</td>
</tr>
<tr>
<td>Dual-clutch transmission</td>
<td>Automatic transmission</td>
<td>Up to 10%</td>
</tr>
<tr>
<td>Cylinder deactivation</td>
<td>Using all cylinders</td>
<td>6%</td>
</tr>
<tr>
<td>Cont. variable valve timing</td>
<td>Fixed valve settings</td>
<td>5%</td>
</tr>
<tr>
<td>Stop-start system</td>
<td>Idling</td>
<td>5%</td>
</tr>
<tr>
<td>5 or 6-speed transmission</td>
<td>4-speed</td>
<td>3 – 5%</td>
</tr>
</tbody>
</table>

Source: Automotive News, May 25, 2009
2. **Evolving Vehicle Context for Alternative Fuels**

To assess the roles that alternative transportation fuels might play in the U.S., we need to extend our planning timeframe form the above nearer-term where impacts will largely come from improvement that can be made in mainstream spark-ignition and diesel engines, and expanding hybrid use, over the next 20 or more years. This evolving powertrain, vehicle, and fuels-requirement context involves both the quantitative performance and efficiency gains that improved mainstream and new technology could provide (at the vehicle level), and the deployment potential over time of these technology changes so their impacts on fleet fuel consumption (and other issues such as greenhouse gas (GHG) emissions) can be assessed.

As described above, in the powertrain arena, we expect that spark-ignition engines (largely gasoline fueled) will improve their efficiency through many advances in their component technologies, and through better optimization. By 2030 it is anticipated that a significant fraction (some 50% ore more) of these spark-ignition engines will be direct-injection, turbocharged, and downsized engines. This improves engine part-load efficiency significantly, largely by reducing the relative (and negative) impact of engine friction. Also, through turbocharging, automakers can continue to offer both enhanced (increasing) vehicle performance and higher fuel economy at the same time. There is a negative trade-off between performance and fuel consumption (1): thus this increased vehicle performance does decrease the fuel economy benefit by some 10-15%.

In terms of engine fuel requirements, this turbocharging trend, and the increasing efficiency trend it enables, is constrained by the abnormal engine combustion phenomenon of knock—the rapid spontaneous release of a portion of the fuel-air mixture's chemical energy inside the engine cylinder towards the end of the normally continuous mixture burning process. This knock constraint depends on the fuel's spontaneous ignition characteristics and is quantified by the fuel's octane number. Use of direct fuel-injection in these turbocharged engines helps with this knock constraint because as the in-cylinder fuel spray evaporates, it cools the unburned mixture and the temperature of that mixture which is a critical controlling variable.

What this says is that alternative liquid fuels with high knock resistance—high octave number—are most desirable. Note that interest is growing in increasing the octane rating of current gasolines, if it can be shown that the higher efficiency of the higher compression ratio gasoline engines these better fuels would enable more than offsets the additional energy used in the production of these higher octane gasolines.

Note also that the volatility—ease of vaporization—of spark-ignition engine fuels is a key characteristic in achieving fast and repeatable engine starting and realizing the very low emission levels of hydrocarbons required now (and more stringent levels in the future). This is another major constraint on the properties of alternative fuels.
Diesel engines will steadily improve also, but their efficiency will not increase as much as gasoline engine efficiency will increase. However, diesels, already some 20% more efficient than non-turbocharged gasoline engines on an energy consumption basis (some 30% more efficient on a fuel volume basis—gallons per 100 miles, liters per 100 km). This gap is expected to narrow over time. However, in the U.S. there is no tradition of extensive diesel use in light-duty vehicles, fuel costs are still relatively low, and diesel (per gallon) is more expensive than gasoline. So, the diesel sales fraction in U.S. is not expected to exceed 5-10% of vehicle sales over the next couple of decades. Hybrid vehicles (see below) appear to be a more attractive option. Also, transmission efficiencies will improve by about 10% as powertrain and vehicle designers incorporate more gears and more efficient shifting mechanisms, or continuously variable transmissions.

Alternative propulsion systems are already in production though still at modest levels. Hybrid sales (HEVs) are expected to grow steadily from today’s 3% level to 10-20% of new vehicles in 2030, as the HEV cost premium above a conventional engine vehicle is reduced. Use of electricity in light-duty vehicles, in PHEVs and BEVs, will grow more slowly. Sales of such vehicles in 2030 might reach 10% if the battery cost premium falls sufficiently, though there is a growing consensus that the necessary cost reductions will need the successful development of new battery chemistries, a research and development task that would take at least 15 years.

From 2020 to 2030, the use of natural gas as a vehicle fuel may well grow, but prospects are uncertain. In the light-duty vehicle area its use is likely to be largely confined to localized fleets. Natural gas vehicles, either as single-fueled vehicles or as dual fuel—with both natural gas and gasoline fuel systems on the vehicle—are significantly more costly and a readily and broadly available distribution and refueling system for natural gas does not yet exist. Thus, at present the use of natural gas as a vehicle fuel is “inconvenient” though natural gas per unit energy content is significantly cheaper than petroleum-based fuels and is expected to remain so.

Fuel-cell hybrid systems, which many view as a promising longer-term option for the larger end of the light-duty vehicle size distribution, will continue to be developed and tested under real world conditions essentially as “production prototypes.” Sales volumes in the 2020-2030 timeframe might be several percent. The deployment of a widespread hydrogen distribution system will be a critical constraint, and at best will take time to develop. However, the cost premium of the fuel-cell propulsion system has been substantially reduced, and that cost reduction trend continues.

There will be vehicle changes, too. A steady reduction in vehicle weight, up to some 10-15% by 2030, from vehicle design changes and use of lighter-weight materials is anticipated. A comparable weight reduction (by 2030) is likely to occur in parallel due to downsizing of the U.S. new vehicle size distribution. This downsizing is starting as gasoline prices steadily rise, and due to consumer’s caution in the current economy. A 10% reduction in vehicle weight results in about a 6% reduction in fuel consumption.
An important “less obvious” trend is the ongoing negative impact of increasing vehicle performance on fuel consumption. An average vehicle acceleration performance escalation of some 10% where it eventually levels out by about 2030 is anticipated for an average car value of about 9 seconds today to about 8 seconds). Some 15% degradation of the anticipated potential 2030 fuel consumption benefit will result as a consequence. Note that smaller lighter vehicles with less powerful engines may compromise vehicle drivability, performance up a grade, vehicle towing capability, load-carrying capacity, etc., especially in certain important categories of vehicles where one or more of these capabilities is critical.

What will be the fuels requirements of these evolving future vehicles? Multi-component hydrocarbon fuels closely comparable to what we have today would be the “best solution.” Such fuels would have a high octane rating and appropriate wide volatility range: liquid fuels are obviously the most desirable. It will be challenging to replace petroleum-based fuels as their supply, though pulled by increasing demand, over time will become limiting. Oil sands and heavy oil are a growing source of liquid fuels: currently supplying some 10% of demand in the U.S. Global supply projections of petroleum and oil sands/heavy oil based fuels, out to 2030, suggest modest growth of order 1% (at best) with a gradual leveling-off and then decline thereafter.

Ethanol, which at present is an easier end-product to produce than many of the alternatives, is about 7% (on an energy basis) of U.S. transportation fuel supply. 10% corn-based ethanol is a likely upper bound in the U.S. Other biomass sources and fuel production approaches are moving toward pilot production but are not yet at that stage. Currently, plausible best fuel choices from biomass are unclear.

Methanol, from energy density (half that of gasoline) and toxicity perspectives, is not an ideal end product, and the broader motivation in the U.S. for methanol, beyond its potential for lower cost, is unclear.

While we are steadily learning about the environmental and other potential impacts of large-scale use of biomass for transportation, the likely magnitude of these impacts is often uncertain. The issues are: competition with food in agricultural land use, the ecological impacts of large scale biomass production for fuel, the greenhouse gas emissions impacts of increasing and changing land use patterns to produce fuels from biomass, water impacts—the amounts required for this agricultural expansion and the amounts used in biomass processing, and the environmental consequences of increased use of fertilizer, etc.

Increasingly, many professionals in this area, are recognizing the real challenges involved in setting up new fuel distribution and vehicle refueling infrastructures for alternative fuels such as ethanol and methanol, for natural gas, and for hydrogen, and in parallel implementing at scale the propulsion system and on-vehicle fuel storage technology needed to use these fuels. As a consequence, attention at least for the nearer-term, is shifting to whether “drop-in” fuels that are compatible with existing fuels—gasoline and diesel—and thus do not require any major changes on the fuel side and the vehicle side, are a realistic alternative. Given this difficult choice with substantial
uncertainty, it is not surprising that the major growing non-petroleum based fuel supply is “gasoline and diesel” from Canadian tar/oil sands.

3. Illustrative Demand Scenarios

A second part of this evolving context is the anticipated U.S. demand for transportation fuel and how that will change over time. This has been an important focus of my MIT team’s research. Here, I will summarize one of our recent assessments (2). Many others, of course, are active in this area. While different groups make different assumptions, especially about the rates at which we progress to lower fuel-consuming vehicles technology, the general trends in these studies are similar.

Figure 1 shows our recent projections of vehicle fuel consumption (in liters/100 km) of different powertrain technology vehicles into the future. Light-trucks show similar trends but with fuel consumptions some 30-40% higher due primarily to their higher weight. Figure 2 shows the assumed market shares of the various powertrains as a percentage of new vehicle sales in each year, out to 2050. Note that in this study (2), assumed values for the some 40 input parameters required for each simulation were specified by a minimum and maximum value, and a modal value for each triangular distribution. These figures show mean values. A steady transition over time to more efficient propulsion systems (and increasingly lighter vehicles) is assumed. (We update these assumptions periodically. With the 2025 CAFE targets now part of a NHTSA/EPA rulemaking, we are assuming a higher proportion of gasoline engines is likely to be turbocharged (increasing that percentage from 20 or so to approaching 50%. The net impact of this change on fleet fuel consumption and GHG emissions is modest.) Many other assumptions related to the in-use fleet size and turnover, vehicle kilometers traveled, sources of alternative fuels to petroleum-based gasoline and diesel, any electricity and hydrogen used, extent of vehicle performance escalation, are required: see reference (2). Also, a Monte Carlo probabilistic methodology is used to generate a distribution of outputs form the input distributions specified as assumptions (3).

The results for the LDV U.S. in-use fleet’s fuel consumption (in billion liters of gasoline equivalent per year), is shown in Fig. 3. We see that the mean projected fuel consumption changes little over the next decade, and then decreases at some 1 to 1.5 percent per year. By 2040 fleet fuel consumption would be down by about 20% from its 2010 to 2020 value. The U.S. in-use fleets GHG emissions decrease from 2010-2020 levels also by about 20% (note these are life-cycle emissions, and several other fuel-related factors come in). The dashed lines in Fig 3 show the 75% and 25% probability pathways (one standard deviation), and 95% and 5% probability pathways (two standard deviations) in this calculation, which embodies uncertainty. These scenario analyses give us a useful sense of what future demand for transportation fuels is likely to be.
Figure 1. Relative fuel consumption of the average car for the different powertrains, assumed scenario input, over time to 2050. Hybrids and plug-in have the same fuel consumption for liquid-fuel driven miles. (2)

Figure 2. Powertrain new vehicle market share, mean input values 2010-2050. (2)
4. Alternative Fuels: Overall Objectives

Our overall objectives are to displace a significant fraction of the petroleum and oil-sands based fuels we are using at roughly equivalent cost, and do this in ways that also reduce the LDV fleet’s greenhouse gas emissions. Both these objectives are furthered if the powertrain that use these alternative fuels are of equal or higher fuel efficiency than the steadily improving gasoline engine. It is clearly beneficial if vehicle engines can operate satisfactorily on both the alternative fuel and gasoline. Higher compression ratios, higher turbocharger boosting levels and thus greater engine downsizing, all improve powertrain-in-vehicle efficiency. Thus alternative liquid fuels should match or exceed the anti-knock rating (octane number) of gasoline.

Light-duty vehicles must, of course, meet current and future vehicle air-pollutant requirements. Future standards will be lighter than today’s requirements and, the most demanding requirement, the HC emission standards (emissions must be less than 1/10,000 of the vehicle’s fuel usage), are expected to be further reduced. Thus the volatility/evaporation characteristics of alternative fuels will need to be comparable to those of gasoline (which also need to be tightly controlled as well), to ensure very clean engine start-ups. Note that deployment of engine start/stop technology makes this even more important.

Obviously, a high specific energy density (per unit mass and per unit volume) is important in fuel production, distribution, storage, and refueling at the service station, and for fuel storage on the vehicle. Here the alcohols, ethanol and methanol, are at a
disadvantage because they are partly oxidized already (they have specific chemical energy densities of 0.7 and 0.5 relative to gasoline, respectively).

The above summary indicates that drop-in fuels—hydrocarbons with properties little different from petroleum-based gasoline, maybe with higher octane ratings, are an attractive option if the availability of primary energy sources of such fuels and their processing technology indicates their potential for large-scale production at marketable prices. If alternative fuels can be produced that are fully miscible with gasoline or diesel, and could even enhance the characteristics of these petroleum-based fuels (for example through higher octane) they would have a significant advantage.

Alternative fuels that would need a separate (and therefore new) supply, and distribution, and refueling system, and which would need vehicle modifications to use these fuels would be disadvantaged.

The anticipated future prices of these different alternative fuels relative to the prices of petroleum-based gasoline and diesel, is clearly a major factor in choosing among the alternatives.

5. Vehicle and Fuel Options

Here I list and briefly describe our vehicle and fuel options, with the next 20 years as the timescale. Table 2 summarizes the several alternatives.

We can blend these new fuels with conventional fuels. We are already doing this with ethanol as E10 and we may move to E15. With ethanol and methanol, which is not fully miscible, there is an upper bound on the amount that can be absorbed by blending.

Thermochemical conversion of biomass and other sources to gasoline-like fuels has the potential for producing drop-in fuels—end products fully miscible with gasoline and diesel. As discussed previously, should the cost of producing these fuels prove to be competitive, their development and use would be an especially attractive option because propulsion system and vehicle technology changes, and fuel distribution and refueling infrastructure changes would be minimum.

Flex-fuel vehicles that can operate with any mixture of gasoline and ethanol have been brought into the vehicle fleet over the past decade or so. The auto manufacturer's incentives were the government's CAFE credit incentive that this approach (with its low costs—some $100 per vehicle) could open the LDV fuel market to growing ethanol use, and there are currently about 10 million flex-fuel vehicles in use in the U.S., about 4% of the in-use fleet. E85 refueling stations have spread and there are now about 2500 such stations, about 2% of the 120,000 U.S. refueling stations. Only about 500,000 of the 10-million flex-fuel vehicles regularly use E85. Barriers to increased ethanol use are the fuel's cost, its availability (production and retailing are currently concentrated in the U.S. Midwest) and limited supply (most of the available ethanol is blended).
Table 2: Vehicle/Alternative Fuels Options

(a) Blend new fuels with existing fuels: e.g., E10, maybe E15. Upper bound on penetration.

(b) Produce new fuels that are fully miscible with gasoline and diesel.

(c) Expand production of flex-fuel vehicles; achieve adequate distribution of alternative-fuel refueling stations.

(d) Produce dedicated optimized alternative-fuel-vehicles: e.g., natural-gas vehicles.

(e) Dual-fuel vehicles: e.g., both gasoline and natural gas fuel tanks and fuel-injection systems on the vehicle.

(f) More focused approaches: Separate on-board tank for “anti-knock” fuel (e.g., ethanol): suppresses knock with gasoline and increases gasoline engine efficiency.

An approach to expand this ethanol path under consideration is to require all vehicles sold be made bi-flex-fuel (gasoline and ethanol) or tri-flex-fuel (gasoline, ethanol, and methanol). Thus, over time, use of these alcohol fuels—which do have attractive combustion and knock-resisting characteristics—could then expand. An important question is whether uncertainly as to the long-term potential for these two alcohol fuels relative to other options such as producing drop-in fuels thermochemically from biomass and other sources, makes it premature to attempt a mandate.

Development and limited production of dedicated fuel vehicles is occurring. Honda is selling a natural-gas-fueled LDV. Also, in other parts of the world (Sweden, Brazil) E100, ethanol-fueled vehicles, have been offered. The latter usually require a small gasoline tank on-board to achieve adequate low-emissions engine starting.

Another option is dual-fuel vehicles such as natural gas and gasoline. These vehicles require two on-board fuel storage systems and fuel injection systems. Dual fuel vehicles, as with the flex-fuel vehicles, may not be able to get the optimum use out of each of the two fuels due to their different characteristics. Each of the fuels in these two pairs—natural gas and gasoline, or gasoline and ethanol—has different knock resistance and thus octane rating. The engine compression ratio is fixed by the basic geometrical design of the engine, so it has to be set (more or less) at a value determined by the lower octane rating fuel (gasoline, compared to natural gas; gasoline, compared with ethanol). So optimum efficiency in the absence of variable compression ratio engines is not obtained with each fuel. Variable valve control can help here but at a loss in power. The added costs of dual-fuel spark-ignition engines involving natural gas are substantial.
In addition to the broader options outlined above, there are some more specific engine-fuels opportunities. One concept that I, with Dan Cohn and Leslie Bromberg here at MIT are exploring uses direct-injection of ethanol (or methanol) into the cylinders of a gasoline engine when that engine (with gasoline) is about to knock. Thus the major efficiency constraint on compression ratio and high turbocharger boost pressures is removed, the engine can be downsized substantially, and its efficiency significantly increased (doubling the benefits that a direct-injection, turbocharged and downsized standard gasoline engine achieves). This can be done with modest amounts (5% or less) of ethanol but a small additional tank and fuel pump for this anti-knock fuel are required. This approach to constraining or removing knock is also applicable to flex-fuel vehicles and natural gas vehicles to optimize their operation and performance. It can utilize more than a modest amount of the “alternative fuel,” if more is available. This concept is being explored by some industrial groups. There are several potential refueling options: one is to distribute the anti-knock fuel (say ethanol plus some water) in a manner analogous to how windshield washer fluid is distributed.

6. Key Questions

This Symposium is taking place because developing a significant supply of alternative fuels is important as the cost of petroleum-based transportation fuels rises, and (in due course) their availability becomes a serious constraint. Our discussions today are also important because we have yet to identify clearly the most advantageous and viable path towards this goal—a substantial supply of one or more alternative fuel that is cost effective as it is used in light-duty vehicles. We need to acknowledge that our knowledge base for identifying the more promising fuel options (along with the vehicle propulsion systems these fuels require) is currently insufficient.

The challenge of building-up significant supply of these fuels can usefully be separated into two steps. First, how can we best “get started” on exploring the various options in ever-greater depth and thus narrowing our many possible choices in a rational way? Second, we need to explore how to grow the supply of the most promising of these options, to significant scale, as we steadily become “wiser.” A key piece of these questions is what the appropriate role of our Federal Government in this process should be. The basic question is how do we break out of the “chicken and egg” constraint circle—fuels first or vehicles first: how can we best grow both together?

One approach to moving us forward would be to identify the (limited number of) promising options, gaining real-world experience with the required vehicle technology, fuel supply and distribution, in a step-by-step manner. Some of this is already happening with limited fleet studies that are “localized” so that fuel supply and distribution, and actual vehicle use, are not severely constrained. A steadily expanding set of fleet studies, which may well need to be incentivized by Federal funding, may be a promising way to get us started more seriously towards our broader goal. At present, our progress is limited.
References


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