Evaluating automobile fuel/propulsion system technologies

Heather L. MacLean\textsuperscript{a,}\textsuperscript{*}, Lester B. Lave\textsuperscript{b}

\textsuperscript{a}Department of Civil Engineering, University of Toronto, 35 St George Street, Toronto, Canada M5S 1A4
\textsuperscript{b}Graduate School of Industrial Administration, Carnegie Mellon University, Tech and Frew Sts, Pittsburgh, PA 15213-3890, USA

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Abstract

We examine the life cycle implications of a wide range of fuels and propulsion systems that could power cars and light trucks in the US and Canada over the next two to three decades (1) reformulated gasoline and diesel, (2) compressed natural gas, (3) methanol and ethanol, (4) liquid petroleum gas, (5) liquefied natural gas, (6) Fischer–Tropsch liquids from natural gas, (7) hydrogen, and (8) electricity; (a) spark ignition port injection engines, (b) spark ignition direct injection engines, (c) compression ignition engines, (d) electric motors with battery power, (e) hybrid electric propulsion options, and (f) fuel cells. We review recent studies to evaluate the environmental, performance, and cost characteristics of fuel/propulsion technology combinations that are currently available or will be available in the next few decades. Only options that could power a significant proportion of the personal transportation fleet are investigated.

Contradictions among the goals of customers, manufacturers, and society have led society to assert control through extensive regulation of fuel composition, vehicle emissions, and fuel economy. Changes in social goals, fuel-engine-emissions technologies, fuel availability, and customer desires require a rethinking of current regulations as well as the design of vehicles and fuels that will appeal to consumers over the next decades. Only options that could power a significant proportion of the personal transportation fleet are investigated.

The almost 250 million light-duty vehicles (LDV; cars and light trucks) in the US and Canada are responsible for about 14\% of the economic activity in these countries for the year 2002. These vehicles are among our most important personal assets and liabilities, since they are generally the second most expensive asset we own, costing almost $100 000 over the lifetime of a vehicle. While an essential part of our lifestyles and economies, in the US, for example, the light-duty fleet is also responsible for 42 000 highways deaths, and four million injuries each year, consumes almost half of the petroleum used, and causes large amounts of illness and premature death due to the emissions of air pollutants (e.g. nitrogen oxides, carbon monoxide, hydrocarbons and particles).

The search for new technologies and fuels has been driven by regulators, not the marketplace. Absent regulation, most consumers would demand larger, more powerful vehicles, ignoring fuel economy and emissions of pollutants and greenhouse gases; the vehicles that get more than 35 mpg make up less than 1\% of new car sales. Federal regulators require increased vehicle safety, decreased pollution emissions, and better fuel economy. In addition, California and Canadian regulators are concerned about lowering greenhouse gas emissions. Many people worry about the US dependence on imported petroleum, and people in both countries desire a switch from petroleum to a more sustainable fuel.

The fuel-technology combinations and vehicle attributes of concern to drivers and regulators are examined along with our final evaluation of the alternatives compared to a conventional gasoline-fueled spark ignition port injection automobile.

When the US Congress passed laws intended to increase safety, decrease emissions, and increase fuel economy, they did not realize that these goals were contradictory. For example, increasing safety requires increasing weight, which lowers fuel economy; decreasing emissions generally decreases engine efficiency. By spending more money or by reducing the performance of the vehicle, most of the attributes can be improved without harming others. For example, spending more money can lighten the vehicle (as with an aluminum frame with greater energy absorbing capacity), improving performance and safety; a smaller engine can increase fuel economy without diminishing safety or increasing pollution emissions, but performance

\textsuperscript{*} Corresponding author. Tel.: +1-416-946-5056; fax: +1-416-978-3674.

E-mail addresses: hmaclean@ecf.utoronto.ca (H.L. MacLean), lave@andrew.cmu.edu (L.B. Lave).
<table>
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<tr>
<td>AKI</td>
<td>anti-knock index</td>
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<tr>
<td><strong>Biodiesel</strong></td>
<td>a fuel with characteristics similar to petroleum diesel but which is derived from oils of biological origin (soybean, rapeseed, sunflower). Some oils can be used with minimal processing, others require esterification.</td>
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<tr>
<td><strong>Biofuels</strong></td>
<td>organic materials, such as wood, waste, and alcohol fuels, burned for energy purposes</td>
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<tr>
<td><strong>Biomass</strong></td>
<td>materials that are biological in origin, such as grasses, trees, municipal solid waste, etc.</td>
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<td><strong>BPV</strong></td>
<td>battery-powered vehicle</td>
</tr>
<tr>
<td><strong>CAFE</strong></td>
<td>corporate average fuel economy</td>
</tr>
<tr>
<td><strong>CaRFG2</strong></td>
<td>California Phase 2 reformulated gasoline</td>
</tr>
<tr>
<td><strong>Cetane</strong></td>
<td>colorless, liquid hydrocarbon (C_{16}H_{34}) used as a standard in determining diesel fuel ignition performance</td>
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<tr>
<td><strong>Cetane number</strong></td>
<td>a fuel’s cetane number represents the ability of a fuel to ignite and burn under compression</td>
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<tr>
<td><strong>CFC</strong></td>
<td>chlorofluorocarbons</td>
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<tr>
<td><strong>CH_{4}</strong></td>
<td>methane</td>
</tr>
<tr>
<td><strong>CI</strong></td>
<td>compression ignition</td>
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<tr>
<td><strong>CIDI</strong></td>
<td>compression ignition, direct injection</td>
</tr>
<tr>
<td><strong>CMU-ET</strong></td>
<td>Carnegie Mellon University equivalent toxicity</td>
</tr>
<tr>
<td><strong>CO</strong></td>
<td>carbon monoxide</td>
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<tr>
<td><strong>CO_{2}</strong></td>
<td>carbon dioxide</td>
</tr>
<tr>
<td><strong>CO_{2} equiv.</strong></td>
<td>carbon dioxide equivalent; the amount of carbon dioxide by weight emitted into the atmosphere that would produce the equivalent radiative forcing as a given weight of another greenhouse gas. Carbon dioxide equivalents are the product of the weight of gas being considered and its global warming potential.</td>
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<td><strong>Compression ratio</strong></td>
<td>in an ICE, is the ratio of the volume of the combustion space in the cylinder at the bottom of the piston stroke to the volume at the top of the stroke direct injection mixture of 10% ethanol and 90% gasoline by volume mixture of 85% ethanol and 15% gasoline by volume economic input–output life cycle analysis fuel cell vehicle the activities associated with a fuel; from raw material extraction, through fuel production, and finally to end-use refueling at a refueling station (also called well-to-tank) mixture of 10% ethanol and 90% gasoline by volume (also called E10) gasoline direct injection greenhouse gas (e.g. carbon dioxide, methane, nitrous oxides) Greenhouse gases, regulated emissions, and energy use in transportation, fuel cycle model developed at Argonne National Laboratory global warming potential; an index used to compare the relative radiative forcing of different gases. GWP\text{\textasciitilde}s are calculated as the ratio of the radiative forcing that would result from the emission of 1 kg of a greenhouse gas to that from the emission of 1 kg of carbon dioxide over a fixed time period hybrid electric vehicle internal combustion engine input–output intergovernmental panel on climate change International Standards Organization standard for...</td>
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suffers; modern electronics have improved performance, fuel economy, and lowered emissions, but have increased the price of the vehicle. However, low price and performance are important attributes of a vehicle. To resolve these contradictions, regulators in the US and Canada need to specify the desired tradeoffs among safety, emissions, fuel economy, and cost, and a single agency needs to be designated in each country to oversee the tradeoffs among the regulators’ attributes and those desired by consumers.
We discuss methods needed to evaluate the attractiveness of vehicles employing alternative fuels and propulsion systems including:

1. Predicting the vehicle attributes and tradeoffs among these attributes that consumers will find appealing;
2. assessing current and near term technologies to predict the primary attributes of each fuel and propulsion system as well as its externalities and secondary effects;
3. applying a life cycle assessment approach;
4. completing a benefit–cost analysis to quantify the net social benefit of each alternative system;
5. assessing the comparative advantages of centralized command and control regulation versus the use of market incentives;
6. characterizing and quantifying uncertainty.

An especially important feature of the analysis is ensuring that vehicles to be compared are similar on the basis of size, safety, acceleration, range, fuel economy, emissions and other vehicle attributes. Since it is nearly impossible to find two vehicles that are identical, we use the criterion of asking whether consumers (and regulators) consider them to be comparable. Comparability has proven to be a difficult task for analysts. No one has managed a fully satisfactory method for adjustment, although some have made progress. Absurd comparisons, such as comparing the fuel economy of a Metro to that of an Expedition, have not been made because of the good sense of analysts. However, steps should be taken to achieve further progress in developing methods to address this issue.

Comparing fuels and propulsion systems require a comprehensive, quantitative, life cycle approach to the analysis. It must be more encompassing than ‘well-to-wheels’ analysis. Well-to-wheels is comprised of two components, the ‘well-to-tank’ (all activities involved in producing the fuel) and ‘tank-to-wheel’ (the operation/driving of the vehicle). The analyses must include the extraction of all raw materials, fuel production, infrastructure requirements, component manufacture, vehicle manufacture, use, and end-of-life phases of the vehicle. Focusing on a portion of the system can be misleading. The analysis must be quantitative and include the array of environmental discharges, as well as life cycle cost information, since each fuel and propulsion system has its comparative advantages. Comparing systems requires knowing how much better each alternative is with respect to some dimensions and how much worse it is with respect to others. Since focusing on a single stage or attribute of a system can be misleading, e.g. only tailpipe emissions, we explore the life cycle implications of each fuel and propulsion technology. For example, the California Air Resources Board focused on tailpipe emissions in requiring zero emissions vehicles, neglecting the other attributes of battery-powered cars, such as other environmental discharges, cost, consumer acceptance and performance. The necessity of examining the whole life cycle and all the attributes is demonstrated by the fact that CARB had to rescind its requirement that 2% of new vehicles sold in 1998 and 10% sold in 2003 be zero emissions vehicles.

No one fuel/propulsion system dominates the others on all the dimensions in Table 8. This means that society must decide which attributes are more important, as well as the tradeoffs among attributes. For example, higher manufacturing cost could be offset by lower fuel costs over the life of the vehicle. Changes in social goals, technology, fuel options, customer desires, and public policy since 1970 have changed vehicle design, fuel production, manufacturing plants, and infrastructure. In particular, gasoline or diesel in an internal combustion engine (ICE) is currently the cheapest system and is likely to continue to be the cheapest system through 2020. These vehicles will continue to evolve with improvements in performance, safety, fuel economy, and lower pollution emissions. However, if society desires a more sustainable system or one that emits significantly less greenhouse gases, consumers will have to pay more for an alternative fuel or propulsion system.

We review a dozen life cycle studies that have examined LDV, comparing different fuels and/or propulsion systems. The studies are summarized in Tables 4 and 5. The studies vary in the fuel/propulsion options they consider, the environmental burdens they report, and the assumptions they employ, making it difficult to compare results. However, all of the studies include the ‘well-to-tank’ and ‘tank-to-wheel’ activities and the majority of the studies include a measure of efficiency and greenhouse gas emissions associated with these activities. We limit our comparison to these activities and measures. The life cycle studies match most closely for the well-to-tank portion and for conventional fossil fuels. See Table 6 for a summary of the ranges of efficiency and greenhouse gas emissions reported in the studies for the well-to-tank portion for the various options. For the well-to-tank portion for the production of electricity, renewable fuels, and hydrogen, differing fuel production pathways are most important. Due to the range of different production options for these fuels (as well as other issues such as study assumptions), results are much more variable. In addition, there is less experience with producing these fuels, resulting in more uncertainty. It is important to distinguish between total and fossil energy required for production when comparing efficiencies among the fuels. Petroleum-based fuels have the highest efficiency for the well-to-tank portion when total energy is considered. However, if only fossil energy is considered, biomass-based fuels such as ethanol become more attractive.
The tank-to-wheel portions are more difficult to compare. Each study uses its selected vehicle (e.g. conventional sedans, light-weight sedans, pickup trucks); many present assumptions regarding the vehicle efficiencies. However, the studies do not generally report the range of assumptions or test conditions.

The well-to-wheel results (the sum of the well-to-tank and tank-to-wheel activities) of the studies are still more difficult to compare. The baseline vehicle (with a few exceptions) is a current gasoline fueled ICE port fuel injection vehicle; it combines an efficient well-to-tank portion with a relatively inefficient tank-to-wheel portion. A direct injection diesel vehicle is considerably more efficient and therefore results in lower emissions of carbon dioxide even though the carbon content in the diesel is higher than that in gasoline. Fuel cell vehicles have a high theoretical efficiency but generally a low efficiency well-to-tank portion, which offsets some of the vehicle efficiency benefits.

Table 7 shows the ranges of values reported in the life cycle studies for the well-to-wheel greenhouse gas emissions. All of the fossil fuel options result in emissions of large amounts of greenhouse gases. Ethanol and hydrogen have the potential to reduce greenhouse gas emissions significantly. However, this is highly dependent on the pathways for ethanol and hydrogen production, especially the amount of fossil fuel inputs during production. Some of the hydrogen options result in higher greenhouse gas emissions than those of a gasoline ICE vehicle. Results for hybrid electric vehicles (HEVs) are dependent on the efficiency improvements over conventional vehicles that are assumed.

As noted above, Table 8 summarizes our best judgment as to how each fuel/propulsion system combination would be evaluated on each attribute desired by consumers or society. No one system beats the alternatives on all dimensions. The most desirable system is defined by the properties that the evaluator thinks are most important.

Despite the many difficulties and complexities, there are some broad conclusions regarding LDV for the next two to three decades. The vehicle options likely to be competitive during the next two decades are those using improved ICES, including HEVs burning ‘clean’ gasoline or diesel. An extensive infrastructure has been developed to locate, extract, transport, refine, and retail gasoline and diesel. Any alternative to petroleum would require a new infrastructure with attendant disruption and costs running to trillions of dollars. The current infrastructure is a major reason for continuing to use gasoline and diesel fuels.

Absent a breakthrough in electrochemistry, battery-powered vehicles will remain expensive and have an unattractive range. The failure to produce a breakthrough despite considerable research does not give much hope that vastly superior, inexpensive batteries will be produced within our time frame.

Fuel cell propulsion systems are unlikely to be competitive before 2020, if they are ever competitive. Although, fuel cells have high theoretical efficiencies, and do not need a tailpipe and therefore have vehicle emissions benefits over conventional vehicles, generating the hydrogen and getting it to the vehicle requires large amounts of energy. The current well-to-wheel analyses show that using a liquid fuel and onboard reforming produces a system inferior to gasoline powered ICES on the basis of efficiency and environmental discharges. Storage of the hydrogen onboard the vehicle is another challenge.

Fischer–Tropsch liquids from natural gas and ethanol from biomass may become widespread. The Fischer–Tropsch liquids will penetrate if there are large amounts of stranded natural gas selling for very low prices at the same time that petroleum is expensive or extremely low sulfur is required in diesel fuel. Ethanol could become the dominant fuel if energy independence, sustainability, or very low carbon dioxide emissions become important—or if petroleum prices double.

Absent major technology breakthroughs, a doubling of petroleum prices, or stringent regulation of fuel economy or greenhouse gas emissions, the 2030 LDV will be powered by a gasoline ICE. The continuing progress in increasing engine efficiency, lowering emissions, and supplying inexpensive gasoline makes it extremely difficult for any of the alternative fuels or propulsion technologies to displace the gasoline (diesel) fueled ICE.

This conclusion should not be interpreted as one of despair or pessimism. Rather, the progress in improving the ICE and providing gasoline/diesel at low price has obviated the need for alternative technologies. Many of the technologies that we examine, such as cellulosic ethanol or Fischer–Tropsch fuels from natural gas or HEVs are attractive. If there were no further progress in improving the gasoline/diesel fuel ICE or the fuel became more expensive, one or more of these options would take over the market. Thus, the fact that the current fuel and technology is so hard to displace means that society is getting what it wants at low cost.

Extensive progress has been made by analysts in examining the life cycles of a range of fuels and propulsion systems for personal transportation vehicles. The most important contribution of these methods and studies is getting decision-makers to focus on the important attributes and to avoid looking only at one aspect of the fuel cycle or propulsion system or at only one media for environmental burdens. The current state of knowledge should avoid the recurrence of the fiasco of requiring battery-powered cars on the grounds that they are good for the environment and will appeal to consumers.

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1. Introduction: importance of motor vehicles

The economies of rich nations and the lifestyle of most of their residents depend on cars and light trucks (light-duty vehicles [LDV]); LDV are gaining the same role in developing nations. The manufacture, fueling service and repair, and disposal of LDV consume about 14% of economic activity in the United States and Canada. These represent more than 1/7 of total commercial energy use and total materials use. These vehicles contribute most of the carbon monoxide (CO), volatile organic compounds (VOC), and nitrogen oxides (NOx) emitted in cities; counting discharges of engine-coolant, windshield washer fluid, used motor oil, and gasoline, LDV are responsible for a considerable amount of water pollution. Transportation accounts for 30% of total carbon dioxide (CO2) emissions from fossil fuel combustion in the USA, with just under 2/3 resulting from gasoline consumption in motor vehicles [1]. LDV are also responsible for considerable expenditures and environmental disruption due to construction and repair of highways and parking facilities. Finally, in the US, LDV are responsible for approximately 42,000 deaths and four million injuries each year [2] as well as the deaths of untold numbers of rabbits, deer, and other animals.

In 1995, there were about 600 million vehicles worldwide, almost 80% of them passenger cars [3]. The USA has 210 million LDV, more than one for every licensed driver. The fleet uses about 130 billion gallons of gasoline to travel two trillion miles each year [4]. The total expenditures on purchasing, financing, fueling, insuring, maintaining, and repairing the LDV is about $65,000 over the lifetime of a vehicle [5] or almost $1 trillion each year in the US.

Substantial additions to these out-of-pocket costs are the time lost due to congestion and injuries. One study estimates that congestion costs Americans $75 billion each year in delays [6]. The average American will be injured in a highway crash during her lifetime and about 1% of Americans will die in a highway crash; the annual social loss from highway injuries exceeds $200 billion.\footnote{Using EPA's value for a premature death of $5.3 million, the 42,000 highway fatalities cost society $222 billion each year. Adding the social loss from the 4 million highway injuries increases the social loss to about $250 billion per year.}

Why do we devote so many resources to LDV? What do we get for these expenditures? Perhaps, the most important attributes that we get are freedom, access, and mobility. We get to go where we want when we want—subject to congestion, parking availability, vehicle costs, and other practical limitations. We can transport ourselves, our families, and our purchases and possessions.

But mobility explains only a small part of the expenditure. A basic transportation vehicle would provide mobility at a fraction of current expenditures. Most drivers insist on comfort, indeed, luxury. A new, high-end vehicle has leather seats, air conditioning, a sound system costing hundreds of thousands of dollars, and wireless communication capabilities. Our cars are status symbols and projections of how we see ourselves. For example, using a 7000-pound sports utility vehicle (SUV), with an engine so powerful that it will take the SUV from 0 to 60 mph in 7.9 s, to get one person to his office is going far beyond basic mobility.

The goal of this paper is to examine the range of fuels and propulsion systems that have the potential to power LDV over the next two to three decades with a focus on the US and Canada. We focus on fuels and propulsion systems that could have significant market penetration (more than 1%) during this period. This introduction makes it clear that motor vehicles are important to the economy and lifestyle of these countries. Importance goes well beyond the direct consumer expenditures and indirect (support) expenditures, such as roads, suburbs, oil wells, refineries, and service stations. They shape the way we live and how we see...
ourselves. Any attempt to change LDV and their use must overcome formidable barriers.

1.1. Key issues

Technology developments have created several challengers to the gasoline powered, internal combustion engine (ICE) vehicle. Which of these are attractive? Which are more attractive than the gasoline powered ICE?

The current LDV has evolved over a century in response to consumer demands, social regulations, and changing technology. Short of some wonderful new technology emerging, the evolving gasoline fueled ICE will continue to be the choice of consumers and automakers. Even with regulatory pressure, it is doubtful that any technology would displace the gasoline fueled ICE—at least not by 2020 or 2030. Perhaps, the only market signal that would make a new technology more attractive would be a large increase in gasoline prices. For example, $3 per gallon gasoline would encourage people to buy diesel or ethanol powered vehicles, perhaps in conjunction with a hybrid-electric technology. At $1.50 per gallon, these alternatives have a tiny market share.

The search for new technologies and fuels is driven by regulators, not the marketplace. Regulators are mandating increasingly stringent standards for emissions of air pollutants, the ability to use alternative fuels, and there is a warning of more stringent fuel economy standards. In addition to the concern for improving local air quality, regulators are concerned about lowering GHG emissions, dependence on imported petroleum, and switching from petroleum to a more sustainable fuel.

Regulators can penalize, or even prevent automakers from selling undesirable vehicles or fuel suppliers from selling undesirable fuels, but it is difficult to force consumers to buy what regulators consider to be desirable vehicles and fuels. Consumer appeal could lead to new propulsion systems or fuels, but consumers are generally satisfied with what they have now. For consumers to view new engines and fuels as more desirable, technology would have to produce superior performance and economy in these alternatives, or the current fuels would have to be seen as less desirable due, for example, to high greenhouse gas emissions. The greatest force for change is the action taken by government, from providing roads to regulating the ‘spillover’ effects of each alternative. Social goals influence what products are allowed on the market and how they are regulated. In the extreme, if highways are so crowded that vehicles are useless, vehicle sales will decline.

Some of the choices that motorists make have adverse effects on the health and well being of others. For example, the emissions from a vehicle pollute the air that others breathe. If the vehicle is unsafe or driven unsafely, the lives of other drivers, pedestrians, and others are put at risk. If a consumer chooses a vehicle that is a profligate user of raw materials and fuel, the consumer may be using resources that otherwise would be available to enhance the well-being of future generations.

The statistics quoted in the introduction indicate that automobiles pose major risks to our health and well being, from death and injury in crashes to air pollution. Thus, in addition to being the most important consumer product and offering consumers mobility and access, LDV impose large costs on society, costs that could grow to the point of negating their value. These safety and environmental ‘externalities’ are not handled by the marketplace. Regulations are required to correct the incentives. Government actions are also required to enable this technology by, for example, building roads or banning tetraethyl lead in gasoline. However, both automakers and regulators need to recognize the delicate balance between producing a product that is desired by consumers and having that product satisfy social goals as well. We examine this balance in evaluating the range of alternative fuels and propulsion systems that could power LDV during the next 20–30 years.

Alternative fuels and propulsion systems have the potential to solve many of the current social problems and concerns, from air pollution and global warming to other environmental improvements and sustainability issues. The advanced technology could help consumers but not regulators (more powerful, ever larger vehicles), regulators but not consumers (tiny, ultra fuel-efficient cars), neither regulators nor consumers (battery-powered vehicles (BPV)), or both regulators and consumers (modern, high efficiency, low emissions gasoline powered ICE). There are tradeoffs. It is not a foregone conclusion that alternative fuels and propulsion systems will displace the gasoline fueled ICE within 30 years. We lay out the issues, review the current state of technology, and examine alternative propulsion systems and fuels to ascertain their potential for satisfying both consumers and social concerns. We address issues of consumer appeal, the local and global effects of emissions, energy use, sustainability, and energy security. We do not address issues related to congestion and land use (including highways and parking).

1.2. Inherent contradictions/tradeoffs in light-duty vehicles

When the US Congress passed laws intended to increase safety, decrease emissions, and increase fuel economy, they did not realize that these were contradictory. The easiest way to increase safety increases weight, which decreases fuel economy. With the increasing market share of light trucks, the average fuel economy of LDV sold in the US has declined and is now 24 mpg, the lowest since 1980 [7]. Growing weight disparity costs society due to the increase in deaths caused by the collision of vehicles of different weights [8]. Small, light vehicles have high fuel economy but are less safe in crashes.

By spending more money, most of the attributes can be improved without harming others. For example, spending more money can lighten the vehicle (as with an aluminum
frame with greater energy absorbing capacity), improving performance and safety. However, low price is an important attribute of a vehicle.

To resolve these contradictions, the US Congress and Canadian Parliament need to specify the desired tradeoffs among safety, emissions, fuel economy, and cost. They also need to designate single agencies in each country to oversee the tradeoffs among their attributes and those desired by consumers. Currently, in the US, the Environmental Protection Agency (EPA) oversees pollution emissions and fuel economy, while the National Highway Transportation Safety Administration (NHTSA) oversees auto safety. Previous work outlining inherent tradeoffs in LDV includes Refs. [9–11].

Comparing fuels and propulsion systems requires a comprehensive, quantitative, life cycle (LC) based environmental/economic analysis with attention to vehicle comparability. Since it is nearly impossible to find two vehicles that are identical, we use the criterion of whether consumers (and regulators) would consider them to be comparable (Section 3.8). Focusing on a component of the LC invites mistaken conclusions. The analysis must be quantitative because each fuel and propulsion system has its comparative advantages; comparing systems requires knowing how much better or worse each alternative is with respect to the various dimensions.

We have organized this review by contrasting social issues with the issues that directly affect automobile manufacturers and drivers. The important gaps between the goals of society and those of individual manufacturers and drivers have been a major justification for government regulation. After examining these social issues, we review the tools and methods that are required to analyze the issues. We then examine the fuels currently used to propel the light-duty fleet and that are likely to play an important role in propelling the fleet in the next two to three decades. We then turn our attention to the propulsion systems currently in use as well as the propulsion systems likely to be competitive over the next 20–30 years. Having examined the fuels and propulsion systems separately, we examine combinations of systems, since the performance of fuels and propulsion systems interact with each other. A large amount of attention has been given to analysis of the life cycles of the fuels, propulsion systems, and the combinations. We review these studies in some detail. Finally, we present the conclusions of our analysis. Appendix A reports fuel terminology and definitions.

2. Relevant attributes for evaluating alternative fuel/propulsion systems

Evaluating alternative fuel/propulsion system automobiles is a multiattribute decision problem. As noted in Section 1, the importance and ubiquity of light duty vehicles puts them outside the realm of individual decisions. For example, if an individual once annoys or injures others, that is an issue to be ignored as unfortunate or as an issue to be treated by the judicial system. In contrast, any activity that involves 1/7 of total economic activity, 1/6 of total energy use, and almost 1/2 of total air pollution emissions requires social decisions concerning what designs and uses are acceptable.

Owners and drivers care about the cost to them of the vehicle, its fuel, and other expenses. They also care about the safety of people who ride in their vehicle. In contrast, their vehicle contributes such a tiny proportion to total fuel and materials use and to environmental discharges, buyers are much less concerned about these issues. If energy use, environmental discharges, and some aspects of safety are important to society, society will have to take steps to achieve the desired goals. Social actions can take the form of (a) command and control regulation, such as refusing to allow vehicles that do not meet the emissions standards to be sold, (b) charges and taxes, such as the gas guzzler tax for vehicles that get less than 22.5 mpg, (c) programs that allow greater flexibility to polluters, such as trading NOx allowances, and (d) programs that get individuals to change their behavior voluntarily, such as the use of a designated driver for people going to a party. For additional details, see Refs. [12,13].

In this section we introduce and discuss the array of environmental, vehicle, economic and additional social concerns relevant for evaluating fuel/propulsion system alternatives. This array of evaluation attributes is the basis for Table 1, a matrix developed to compare the alternative fuel/propulsion technologies.

2.1. Environmental

Myriad environmental problems both near and long-term result from LDV. Perhaps, the most well known is that of air pollution resulting from the engine exhaust emissions. Besides this, however, environmental issues include large volumes of materials and energy used in manufacturing and servicing automobiles, energy and emissions resulting from the production of fossil fuels to power them, the fluids used to lubricate and cool them, as well as wash the windows, and the materials used at the end of the vehicle’s life. For example, for the end-of-life stage, approximately 10 million automobiles are scrapped, disassembled and shredded each year in the US [14]. Currently, about 75% by weight of an automobile is recycled, reused, or remanufactured [15]. The remainder of the automobile is generally sent to a landfill. This solid waste is referred to as automobile shredder residue and three to five million tons of it is generated in the US annually [14]. As aptly noted by Rubin [16], “The variety of materials used in an automobile and the many components it contains (a modern automobile has over 20 000 individual parts) mean that any engineering decision that influences materials choice, shape, or quantity can have significant environmental consequences.”
2.1.1. Near term: local air pollution

Local emissions are of concern directly in the area they are released and have the most impact on urban areas where they are concentrated. Six criteria and related pollutants are regulated in the US—carbon monoxide (CO), nitrogen oxides (NO\textsubscript{x}), volatile organic compounds (VOC), sulfur dioxide (SO\textsubscript{2}), particulate matter (PM), and lead. These emissions are harmful to health and damage ecosystems, materials, and buildings. Exhaust and evaporative emissions from automobiles are the primary sources of CO, NO\textsubscript{x}, and VOC (or hydrocarbons (HC)), which react in the atmosphere to form ozone, especially in summer. Rubin [16] provides a good textbook style discussion of ozone formation and issues. Regulated air pollutants that comprise a substantial portion of exhaust emissions are VOC or HC, NO\textsubscript{x}, CO and from diesel vehicles, PM. When leaded gasoline was used, lead emissions from automobiles were a significant concern, however, as shown in Fig. 1, lead emissions have declined significantly since it was banned. These pollutants may have acute toxic effects as well as chronic effects. Numerous studies have linked increases in PM (small particles are inhaled and trapped in the lungs) with decreases in lung function, increases in breathing problems, hospitalization and premature death. Although exhaust emissions are the primary concern for air pollutants, these same pollutants and others are also released during other stages of the life cycle, such as during the production of materials necessary for the automobile itself.

The ozone forming potential of the fuels’ emissions are important, not just the quantity of emissions. The potential reactivity of the exhaust HC mixture toward ozone formation can be calculated from speciated non-methane organic gas (NMOG) data and maximum incremental reactivity factors. The maximum incremental reactivity is the predicted impact of the compound on ozone formation in certain urban atmospheres. California emissions requirements assign a maximum incremental reactivity value to individual compounds emitted in exhaust. The reactivity can be expressed as either (mass-normalized) specific reactivity (gram ozone/gram NMOG), or as ozone forming potential (grams ozone/mile).

Recent models of light-duty gasoline vehicles contribute less to ozone formation than older vehicles. This is as a result of these vehicles being ‘cleaner’, having lower
tailpipe emissions. In addition, some of the alternative fuels have lower ozone forming potential than gasoline. For example, the lower specific reactivity of compressed natural gas (CNG) exhaust is explained by its composition (primarily light HCs, either unburned fuel components or reaction products of methane (CH₄) (which have a lower ozone forming potential than typical HC in gasoline exhaust)). Gasoline consists of the full range of gasoline HCs and their combustion products, including more reactive olefins and aromatics [17].

As shown in Fig. 1, (reproduced from Ref. [18]), there have been significant reductions in emissions from transportation in the last 20 years, even though vehicle miles traveled (VMT) has increased substantially. This downward trend has resulted from the increase in the number of cleaner, new vehicles satisfying more stringent emission standards, the retirement of older, higher polluting vehicles, smog checks, etc.

2.1.2. Toxic air pollutants
Toxic air pollutants (also known as hazardous air pollutants) are those pollutants that are known or suspected to cause cancer or other serious health effects, such as reproductive or neurological problems. Motor vehicles emit several pollutants that EPA has classified as toxic air pollutants. These are emitted from all aspects of the vehicle life cycle; however, the primary focus is on exhaust emissions from the vehicles themselves. EPA estimates that mobile sources (e.g. cars, trucks, and buses) are responsible for releases of air toxics that account for as much as 50% of all cancers attributed to outdoor sources of air toxics [19]. For gasoline and diesel LDV, the toxics of importance are benzene, a known carcinogen, as well as formaldehyde, acetaldehyde, 1,3-butaadiene, and diesel PM, all of which are classified as probable human carcinogens. Benzene is a component of gasoline, some of which is emitted in the exhaust. The other toxics are not present in the fuel but are produced in the engine or catalyst. The 1990 Clean Air Act requires EPA to regulate air toxics from motor vehicles in the form of both standards for fuels, vehicles or both. Since cleaner fuels generally result in lower emissions of toxics, programs to control air toxics pollution have focused around changing fuel composition as well as improvements in vehicle technology and performance. Some of the alternative fuels are inherently cleaner than gasoline and diesel, and therefore their use has the potential to result in reductions of toxics. However, there may be tradeoffs, with increases of certain toxics (e.g. aldehydes from alcohol fuels).

2.1.3. Environmental: long term, climate change/global warming
As recently as a decade ago, climate change was a relatively obscure concept. It is now a key environmental policy issue. The 1997 Kyoto Protocol, where international leaders of major industrialized countries agreed to reduce their overall emissions of greenhouse gases (GHG) to an average of 5.2% below 1990 levels by the period 2008–2012 brought attention to the climate change issue. However, the Kyoto Protocol has never been ratified, and therefore countries have only implemented changes where they have desired to do so. The more recent, 2001 Marrakech climate change talks resulted in a reduced target of approximately 5% below 1990 levels by 2012. Climate change is global in scope with potential large-scale environmental and economic impacts; the potential restrictions threaten to impact human behavior and choices. A significant focus is the potential large-scale shift away from fossil fuel use.

Gases such as water vapor, CO₂, methane (CH₄), nitrous oxide (N₂O), and ozone (O₃) occur naturally in the earth’s atmosphere. These gases, along with others including, halocarbons, and perhalocarbons, are also released into the atmosphere by human activities. They are called ‘heat trapping’ or GHG. These GHG create a negative effect when they trap too much sunlight and block outward radiation. This is a long-term effect. These GHG have long atmospheric lifetimes, some remaining for tens or hundreds of years in the atmosphere and their accumulation over time is of concern, in that increases in levels of GHG are linked to increased temperatures [20]. Potential climate risks have been associated with the increases in GHG. These include more severe weather patterns, ecosystem change (e.g. loss of biodiversity), droughts and floods, sea level rise, and increases in incidence of infectious diseases [20]. In addition, there may be potential benefits such as longer growing seasons for agriculture and forestry. GHG generally do not have short-term effects on human health or ecology, one exception being ozone which is a main component of anthropogenic photochemical ‘smog’.

Since road transportation is almost entirely dependent on fossil fuels, large amounts of GHG are released from LDV. Carbon dioxide is the substance emitted in the largest quantity. The transportation sector worldwide is responsible
for about 25–35% of anthropogenic CO₂ emissions, most produced by the combustion of petroleum-based fossil fuels. For each kg of gasoline used in a car, about 3 kg of CO₂ are released into the atmosphere; therefore, per 100 km, this is about 20 kg of CO₂ being released. The US transportation sector accounts for about 5% of the CO₂ emitted by human activities worldwide [21]. No other energy use sector in the US or in another country accounts for a significantly larger portion of these emissions.

Methane results from activities currently associated with the automobile LC and potentially would play a more significant part in an alternative fuel automobile life cycle, such as CNG production and coal mining, and decomposing landfill wastes. Nitrous oxide emissions are associated primarily with the use of nitrogen fertilizers and land use change, significant sources associated with the production of ethanol from corn or biomass feedstocks. Car air conditioners used to be a significant source of chlorofluorocarbons (CFC) which are halocarbons. CFCs are being phased out internationally.

Although, the largest quantity of GHG emissions may be CO₂, this does not necessarily indicate that these emissions have the largest impact on the environment. Since the different GHG have different atmospheric lifetimes and all contribute to radiative forcing, the term global warming potential (GWP) has been devised to weight the various gases’ contribution to global warming. The term takes into account the radiative forcing of a gas and its atmospheric lifetime through using a weighting factor. The GWP of a gas is defined for a unit mass of the gas relative to a unit mass of CO₂. Carbon dioxide is assigned a weight of one. This allows analysts to compare combinations of GHG in terms of an equivalent mass of CO₂. For example, the 100-year GWP based on IPCC values [22] for CH₄ is 21 and N₂O is 310, indicating that the emission of 1 kg of CH₄ contributes to global warming the same amount as 21 kg of CO₂.

Since the light-duty fleet is almost entirely fueled with fossil-based fuels, its impact on global warming is of significant concern. Almost all of the carbon in the fuel is converted to CO₂. The important aspects for fossil fueled vehicles are the carbon content of the fuel and the fuel economy. Although diesel has a higher carbon content than gasoline, the higher efficiency of the diesel engine results in lower vehicle fuel use and therefore lower CO₂ emissions than a ‘comparable’ gasoline engine. Vehicles fueled with renewable fuels produced sustainably without fossil fuel use would have no net CO₂ emissions. However, there still remain emissions of non-CO₂ GHG. Since CH₄ and N₂O have higher GWPs than CO₂, these GHG cannot be ignored in LC studies.

Separating the carbon in fossil fuels and then sequestering it has been proposed as a means of retaining the use of fossil fuels while ceasing to emit CO₂ [23]. This technology could reduce or eliminate emissions from stationary sources but would not be feasible for motor vehicles burning fossil fuels. However, fossil fuels could be transformed into hydrogen as a motor vehicle fuel, with the carbon sequestered.

2.2. Sustainability

The Brundtland Commission defined sustainability as “meeting the needs of the present without compromising the ability of future generations to meet their needs” [24]. The underlying notion is that current activities should not impair the future.

In the most simple-minded way, sustainability might be taken to mean that the current generation should not use any non-renewable resources or rich ores since burning a gallon of gasoline today means that gasoline will be unavailable to future generations. Similarly, mining a rich ore body today means that future generations will be able to mine only leaner ore bodies. Similarly, anything done to deplete the soil, such as erosion is unsustainable.

Not only is this simple notion of sustainability unappealing, it is also too narrow. If, for example, the current generation develops a technology for mining poor ore bodies by using no more resources than are required today for rich ore bodies, the future generations will not be disadvantaged. Similarly, if the current generation develops alternative energy sources that are as inexpensive and non-polluting as extracting and burning petroleum, future generations will not be disadvantaged by current petroleum use.

Thus, the more general notion of sustainability asks what opportunities will exist for future generations and whether their options will be less than those of the current generation. If the answer is that they will have at least as wide a range of options, then current activities would be described as sustainable. However, note that the range of opportunities includes environmental quality and recreational opportunities—which are as likely to be affected by the growth of population as the depletion of natural resources.

We do not address sustainability comprehensively in our evaluation of vehicle options. However, as one component of sustainability, we consider fossil fuel depletion. In addition, although we address global warming as a separate issue in this work due to the current focus on this subject, it is also a component of sustainability.

2.3. Vehicle attributes

Alternative vehicles, which have the potential to make progress toward achieving social goals, cannot do so in practice unless consumers choose to purchase them instead of conventional automobiles. To displace conventional vehicles, alternative vehicles must be viewed by consumers as at least equally attractive or ‘comparable’ to these conventional vehicles. These important attributes are likely

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2 Throughout the review we refer to alternative vehicles as any vehicle options other than gasoline or diesel ICE vehicles.
to include vehicle price, size class, performance, range, comfort, lifetime, and safety standards. Additionally, it is necessary that the vehicles be produced in significant volumes so that supporting infrastructure is available for refueling and servicing the vehicles. Several of these issues are included in Table 1 categories other than ‘vehicle attributes’ (e.g., costs, safety). In our evaluation, for this section, we concentrate on comparability of vehicle range and performance, two attributes that vary greatly among vehicle options and are of significant concern to customers. The most important aspect of performance (other than starting) is acceleration, both from a stop and at highway speeds in order to pass. The time required to accelerate from 0 to 60 mph is a good overall measure of performance. These performance measures are related to having convenience comparable to that of conventional cars.

Today’s alternative vehicles emphasize a particular attribute, such as being run by batteries, having improved fuel economy, utilizing flexible fueling, or being powered by an alternative fuel. They score well on that dimension, but tend to be expensive and sacrifice other important dimensions, such as range, power, or convenience in fueling. As such, these vehicles are clearly intermediate steps, and thus are of limited commercial attractiveness. In some cases, the technology will progress to make the next generation attractive, as occurred with the direct injection diesel. In other cases, the technology advances will not be sufficient to deliver the needed innovations and the technology will drop from sight, as has occurred with the battery powered vehicles. The success of the direct injection diesel puts both automakers and the public on notice that advanced technology does have attractive contributions to make. However, there is insufficient data to tell which of the advanced concepts, if any, will be able to displace the evolving gasoline powered ICE.

2.4. Costs

The costs of owning and driving a car over its lifetime include the payments for the car, its fuel, maintenance, repair, licensing, insurance, and end of life. When a consumer buys a LDV, the price includes, indirectly, the cost of extracting the raw materials, transforming them into materials that go into the vehicle (including fuel and maintenance items) and the associated transportation and other manufacturing and distribution costs. Since most vehicles at the end of their life have a positive value, the original price of the car also covers the end of life costs. After purchasing a vehicle, the owner pays for fuel, maintenance, repair, insurance, and other costs of running the vehicle. These expenditures cover the costs of extracting, refining, and retailing petroleum products and other indirect expenses. However, these private costs do not include most of the costs associated with air and other pollution, noise, crash related and other injuries, and congestion. The costs associated with these ‘externalities’ are social costs.

It is important to distinguish between private and social costs. Automobile manufacturers are motivated to minimize their private costs in producing a vehicle of a special size and quality in order to increase their profit. Ordinarily, they give little or no attention to the social costs. Similarly, vehicle owners are motivated to minimize their ownership costs. Regulation is intended to deal with the social costs, making sure that they are not neglected in the push to minimize private costs. One approach is to order manufacturers to use specified pollution control technology or to meet discharge standards. Other approaches involve using market incentives, such as a congestion fee or pollution emissions fee to internalize the external costs and thus include them in a company’s efforts to minimize costs [13].

The relatively low costs of current vehicles and fuels (gasoline/diesel) over their lifetime make it difficult for alternative fuels and advanced vehicles to compete. In addition, presently, only gasoline and diesel have the infrastructure required for fuelling the 1/4 billion North American vehicles. Fueling a large proportion of LDV with a different fuel would necessitate significant investment. In Table 1 we deal with private costs in the ‘costs’ section.

2.5. Other social issues

2.5.1. Energy independence

The 1973 OPEC oil embargo was a shock to the USA and other oil importing nations. Not only was there a dollar price to oil, there was a political price as well. Furthermore, OPEC showed that it could manipulate the dollar price, leaving importing nations vulnerable to large price increases and the economic havoc that they could cause.

The USA embarked on an ambitious plan to become energy self-sufficient. This goal is clearly feasible, since domestic coal reserves are sufficient to supply enough energy, although not in the desired liquid form. The program showed that the USA could become self-sufficient through the use of oil shale, heavy oil, and conversion of coal to liquids. However, the economic and environmental cost of energy independence was high enough to prevent implementation of the new technologies. The USA continued to import petroleum and now imports much more than it did before the embargo. Energy independence remains a national goal, especially after the Persian Gulf War and the political instability of many of the OPEC nations. Energy independence could be pursued through a number of policies: one is drilling in the Arctic National Wildlife Reserve, although the USA cannot produce sufficient petroleum to make up for imports. A second policy is increasing the fuel economy of new cars; while the fuel economy almost doubled since 1974, it has been falling in recent years due to the increasing market share of light trucks. A third policy is substituting a renewable fuel, such
as ethanol from biomass, for gasoline. We discuss the second and third policies below.

2.5.2. Safety

The manufacture and use of light duty vehicles is important to the economy. It is also important in terms of safety and environment. Tens of thousands of people die in highway crashes each year in the USA and Canada. Billions of tons of pollutants are released into the air. Gasoline is a dangerous liquid in a crash, since it can explode or ignite. Producing, refining, and transporting gasoline leads to large environmental discharge of pollutants. The alternative fuels have implications for both safety and environment. Some aspects are better and some are worse, depending on the fuel. We explore some of these implications.

2.6. Additional issues

Many other social issues are associated with vehicle choice and use. For example, four-wheel drive vehicles are used to travel into desert and wilderness areas, sometimes causing erosion and other damage, disturbing the ecology, and the enjoyment of hikers and campers. The availability of low priced, low operating cost vehicles encourages the dispersion of residences into suburban and rural areas, leading to highway congestion and the demand for more highways and parking places. The availability of vehicles encourages the building of vacation homes and certainly increases the amount of travel.

We recognize that there are myriad other social issues. Our failure to discuss them in detail does not indicate that we view them as unrelated to the central issues in the paper or as unimportant. Rather, space limitations preclude an encyclopedic treatment.

Table 1 summarizes the array of environmental, vehicle attribute, economic, and social concerns for LDV alternatives. The table will be used later in the paper (Section 7) to summarize the issues for the various fuel/propulsion system combinations compared to the current gasoline fuel SIPI engine vehicle.

The above sections introduce the general categories in Table 1. In the remaining paper, we will introduce and discuss the issues associated with evaluating each of the alternative fuel/propulsion options with respect to the categories. It is not necessary to know much about LDV to know that there are inherent tradeoffs in any of the options. For example, fuel economic, lightweight vehicles benefit global warming and fossil fuel depletion but score low on safety in the event of a crash. A slightly less apparent example is that lean burn, direct injection engines are more fuel-efficient, however, they produce more NOx. How does society tradeoff safety or tropospheric ozone (related to the emissions of CO, VOC, and NOx) against using less petroleum? Society has to choose the dimensions that are most important.

In some cases, the tradeoffs can be improved by spending more money on the fuel or propulsion system. For example, sulfur in the fuel poisons the catalyst. By spending more to remove sulfur, environmental performance can be improved. Similarly, turbo charging increases engine power, allowing a smaller, more fuel economic engine. However, having low priced fuel and a low priced vehicle are important. The debates on the level of sulfur in fuel have been heated. For vehicle fuel economy, automakers work hard to achieve the fuel economy goal with a vehicle that is attractive in terms of performance at least cost.

The following example shows the nature of the tradeoffs as well as the fact that each actor is focusing on his individual costs. The federal fuel economy legislation gives a 1.2 mpg fuel economy credit for flexible fuel vehicles (FFV) (those able to use gasoline or a gasoline-alcohol blend up to 85% alcohol (E85)). Automakers determined that an FFV should be optimized for gasoline, not the alternative fuel, since it is nearly always fueled by gasoline. However, adding the components that allow flexible fueling increases manufacturing cost. Consumers are willing to pay little for an FFV and so manufacturers cannot recoup their costs. However, regulators provide an incentive for FFVs: for large SUVs and some other light trucks, automakers have found that making the vehicle an FFV is the cheapest way of achieving the CAFE standards. Thus, automakers make enough FFV to get their maximum FFV credit. Since the price of ethanol is higher than the price of gasoline (and it is only available in very limited supply), drivers find it unattractive to buy the alternative fuel. Gasohol with 10% ethanol has the largest tax subsidy per gallon of ethanol: it is the only level of ethanol that is attractive financially at present [25,26]. Thus, Congress gave automakers sufficient incentive to produce FFV but did not give consumers sufficient incentive to buy the E85 fuel. As a result, almost none of the flexible fuel is purchased, negating the purpose of the FFV incentives and the social value of the extra components.

Regulatory agencies have had, and generally continue to have, narrow goals. The California Air Resources Board has been concerned primarily with emissions of air pollutants in California. Greenhouse gas emissions, fuel economy, and other social issues were not important in their decision to require a low emissions gasoline and zero emissions or near zero emissions vehicles. When California groundwater became contaminated with the gasoline oxygenate methyl tertiary butyl ether (MTBE), it was the California legislature, not CARB, that ordered the removal of MTBE from gasoline [27]. Recent legislation in California limiting CO2 emissions will broaden CARBs goals.

Narrow goals are also evidenced in the US government-industry Partnership for a New Generation of Vehicles [28]. Fuel economy was the primary goal and so they initially settled on a diesel hybrid, which was more costly to manufacture and had emissions that could not meet the requisite standards. Generally, Congress gives each regulatory agency a narrow agenda, apparently not realizing that
the agencies’ goals contradict each other [11]. Greater safety results in a larger, heavier vehicle that gets fewer miles per gallon. Lower emissions generally result in additional vehicle cost. Congress and in Canada, the Canadian Parliament need to resolve these contradictions.

3. Policy analysis methods

In order to get meaningful comparisons among the vehicle options, a range of tools can be applied. The underlying issue in each case is the efficiency-advantage of each technology. For example, how much will reducing the weight of a car by 10 kg increase fuel economy? How much could lowering engine power, as measured by an increase in the 0–60 mph acceleration time, increase fuel economy? How much more efficient is a direct injection engine compared to a port injection engine? In Section 4, we address these technical issues, drawing together the scientific literature and the judgment of a range of experts where data are not available.

3.1. Predicting and influencing market reactions

In a market economy, incentives are important. Drivers want to pay less to fuel their vehicles. Since, ethanol from corn is more expensive to produce than gasoline, few drivers would be expected to buy ethanol. However, ethanol producers receive a federal tax reduction of $0.53 per gallon and up to $0.40 per gallon in state taxes in some states. These tax breaks provide a sufficient incentive to produce large quantities of ethanol from corn, despite its higher cost of production.

Another example concerns the mix of vehicles produced and their pricing. The Corporate Average Fuel Economy (CAFE) standards require automakers to sell small, light vehicles with small engines in order to sell large, heavy vehicles with large engines. For example, to achieve a CAFE of 27.5 mpg, an automaker could sell one vehicle getting 44 mpg in order to balance a 20 mpg full size car. Consumers want the latter and are willing to pay high prices to get them. Some Americans want small, fuel efficient cars, but CAFE requires automakers to sell more of these cars than Americans would desire if the price-cost markup were the same as for large powerful vehicles. As a consequence, CAFE gives a strong incentive to automakers to boost the price of large vehicles in order to subsidize the price of small vehicles so that the average new car sold will attain the CAFE standard.

Consumer demands, legislation, regulations, and tax incentives provide a vast network of incentives that influence the production and sale of LDV. In our analysis, we try to identify and control for these incentives. Regulations are perhaps the strongest incentive. For example, a vehicle model that does not pass the emissions certification requirements cannot be sold. Automakers have no choice except to meet these emissions standards. In contrast, the fuel economy standard offers considerably greater flexibility. First, the fuel economy of all new vehicles from a manufacturer is averaged. This averaging allows some vehicles to have poor fuel economy, as long as they are balanced by fuel-efficient models. Second, the legislation even allows manufacturers to accumulate CAFE credits and carry them forward to future years. Finally, if all else fails, a manufacturer can pay a fine that is proportional to the fuel economy shortfall.

3.2. Technology assessment

Evaluating vehicles that have not yet been built is inherently difficult. Evaluating current vehicles is far easier. Despite the difficulties, there is no alternative to finding methods to project the attributes, useful lifetimes, and manufacturing costs of advanced vehicles. For example, the spark ignition port injection (SIPI) ICE has been evolving for more than a century. Although engineers continue to improve its longevity, power, fuel economy, and emissions, the improvements are evolutionary. In contrast a direct injection engine is new and improvements are likely to be more rapid. The same is true for a hybrid electric vehicle (HEV) and a fuel cell vehicle (FCV). It makes no sense to rule out these new technologies because they are not competitive today. However, a judgment is required as to how rapidly and to what point these technologies are likely to advance. Many new technologies, even technologies of promise, are unable to overtake existing technologies.

Deciding how stringent a regulation should be is complicated by the fact that the average automobile is expected to last almost 15 years. Stringent regulations that make new vehicles more expensive or less attractive to drive would lengthen the life of existing vehicles, since consumers would be reluctant to trade them in for more expensive or less desirable vehicles. This actually occurred during the 1970s when air pollution standards made new vehicles less desirable and led consumers to keep old, highly polluting vehicles [29].

Technology forcing is a type of regulation designed to force automakers to find and perfect new technology [30, 31]. In the post-World War II period, automakers focused on power and size, giving relatively little attention to lower emissions levels, greater fuel economy, or greater safety. If regulators had simply required automakers to incorporate the best available emissions control, safety, and fuel economy technology, little would have been gained. Instead, regulators promulgated ‘technology forcing’ standards designed to get automakers to develop new technology to meet the regulations. Unfortunately, some of the time the technology forcing results in expensive vehicles which consumers do not find attractive. Bresnahan and Yao estimate that forcing technology for emissions control in the early 1970s in the US resulted in social losses of tens of
CO2 would be greater than those of the best comparable recycling the batteries. Lave found that if these smelting heavy metals, making the metals into batteries, and to recharge the batteries or the effects of mining and limited view failed to take account of the electricity needed environmental problems caused by LDV. However, this vehicle itself has no emissions, CARB, General Motors, and desirability of a new technology. For example, because the comprehensive look, analysts can be deceived about the product, its use, and its end-of-life. Without this framework requires a vast amount

In assessing a technology, there are two questions: (1) Compared to what? (2) Is this technology, on net, desirable? A technology might be expensive, unreliable, and polluting. However, if it is better than the current technology, and is better than other alternatives, it might be substituted for the current technology. For example, the LDV produced from 1975 to the present have polluted the environment and used large quantities of fuel. However, each generation of emissions control has been better than the previous generation, leading to less undesirable emissions. Unfortunately, there is always the question as to whether, on net, this technology is desirable. In the late 1970s, most Americans (and most people in developed nations) decided that nuclear power was not a net benefit to society. Methyl tertiary butyl ether (MTBE) is a desirable additive to gasoline, resulting in lower emissions from some vehicles. However, gasoline spills have resulted in MTBE contaminated groundwater, which led California to ban its use [27, 34]. They decided the use of MTBE did not result in a net benefit.

3.3. Benefit–cost analysis: valuing the environment and human and ecological health

Public decisions such as setting emissions or ambient air quality standards have enormous implications for both the economy and the environment. Making informed public policy decisions requires a systematic analysis of their implications. A number of decision frameworks are used to assess whether a proposed regulatory action is in the public interest [11]. The most comprehensive framework is benefit–cost analysis. This framework has been used by the Army Corps of Engineers to assess waterway projects since 1930s. Benefit–cost analysis enumerates the desirable and undesirable effects of a policy, relates the effects quantitatively to the degree of control, translates each effect into dollars, brings each dollar value to current dollars, and then compares the benefits and costs. For example, the direct benefits of automobile emissions control include lower ambient air concentrations of ozone, CO, NOx, and small suspended particles. The downstream benefits include reductions in morbidity and mortality and a reduction in acid precipitation. The direct costs include the cost of the emissions control devices while the downstream costs include reductions in power and fuel economy for a given engine. All these desirable and undesirable effects must be translated into dollars, the effects over the life of each vehicle must be discounted to the present, and the benefits and costs compared. The framework requires a vast amount

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of quantitative data as well as difficult judgments such as the dollar value of improvements in environmental quality (for example, see EPAs retrospective study of the benefits and costs of the Clean Air Act, 1970–1990 [35].

When people hear about benefit–cost analysis, they usually think that putting a dollar value on the effects and finding the right discount rate, are the most difficult and complicated. In practice, economists conducting a benefit–cost analysis are hampered because the goals of the program are not carefully specified. Not carefully stating the goal of a program makes it difficult to find the preferred actions, to run the program efficiently, or to evaluate afterward whether it accomplished the purpose. A benefit–cost analysis requires quantification of the effect of each intervention, e.g. the number of lives that would be saved by putting air bags in LDV. Generally, the information on the quantitative relationships is not available or is unreliable.

For goods valued in the marketplace, price provides a good metric, as long as the market is competitive and the price is not skewed by a temporary disequilibrium. For some products, there are important externalities (non-market effects) associated with the product. For example, prior to the 1970s, buying a gallon of gasoline included a range of environmental discharges during drilling, production, transportation, refining, and storage (leaky underground storage tanks). In the past, the dollar price of gasoline significantly understated the social costs of that product. As regulations have lowered these discharges by changing drilling and production practices, requiring doubled-hulled tankers, reducing environmental discharges from refineries, and eliminating leaky underground storage tanks, the price of gasoline has risen to cover these costs and now comes much closer to representing the social-environmental costs of the product.

Goods and services not traded in the marketplace are more difficult to value. For example, what is the value of preserving a wilderness area or of non-polluted air? A large literature comments on the good and bad aspects of proposals to value these non-market goods [36–38,174, 177]. Values can be estimated by taking the amount that people spend on travel to see an event, by finding private goods that are relatively similar to the public good, or by statistical analyses that disentangle the amount that people are willing to pay for a house that has a good view, is located near a lake or other amenity, or is in an area with low air pollution. While the measures are imperfect, they are clearly better than ignoring these aspects, since that assumes that the value of these goods is zero.

Matthews and Lave [39] examined values that four state public utility commissions along with a number of researchers have estimated for the social cost of emitting air pollutants. California, Nevada, New York, and Massachusetts put somewhat different values on CO, CO2, total suspended particles (TSP), sulfur dioxide (SO2), and NOx, however, the values fall within a plausible range and are related to the estimates of these values that come from the literature on the damage that results from polluted air. Matthews and Lave [39] analyze the variation-uncertainty explicitly by considering the full range of values and find that an explicit analysis of uncertainty is needed when translating the physical effects into dollar terms. The dollar values depend on where the air pollutants are emitted (population in the surrounding area), uncertainty concerning the health effects of the pollutants, the inherent values associated with abating urban ozone and other pollution, and probably on the current ambient air quality. They certainly depend on the income and environmental attitudes of the people doing the evaluation. Reflecting these considerations, the dollar values in the four state studies and in the research literature differ by more than a factor of 10.

The US Environmental Protection Agency [35] has analyzed the retrospective and prospective benefits and costs of the 1970 Clean Air Act (and its subsequent amendments). EPA was faced with all of these issues in estimating both the benefits and costs from 1970 to 1990 and from 1990 to 2010. EPA found the greatest scientific support for health effects of small particles suspended in the air (PM10) and so almost the entire calculated benefits stem from these estimated health effects. The economics literature justifies a high dollar value for the benefit of preventing premature death ($4.8 million, according to EPA) and so preventing premature death contributed almost 90% of the benefit of abating air pollution. The benefits of abating NOx, CO, and VOC were ignored, except in so far as they led to PM less than 10 μm (PM10).

The EPA analysis all but ignores other categories of benefits, such as ecology, damages to materials and visibility and more general benefits of abating air pollution. EPA was mindful of these categories of benefits, but the scientific literature provides little basis for estimating the benefits of abatement. EPA also estimated little or no benefit from abating hazardous air pollutants because the scientific literature does not provide an adequate basis for estimation. See also Ref. [40].

3.4. Market-based tools for achieving social goals

A competitive market is marvelous for producing cheaply the goods and services that consumers desire. The pressures to innovate and reduce costs pushes aside attaining other social goals, goals not explicitly sought by consumers in the marketplace, such as lowering environmental discharges. If your competitor lowers production costs by not worrying about environmental discharges, you will be at a competitive disadvantage, unless your customers are willing to pay more for your environmentally benign product.

These problems were recognized in the 1960s and 1970s; environmental legislation was passed that created federal and state regulatory agencies that could set and enforce discharge and ambient quality standards. Initially, the standards were explicit and detailed in terms of the specific
abatement technology or the amounts of discharges that would be allowed from individual point sources. However, the extent to which pollution can be abated and the cost of abatement differs across each source. Federal and state regulatory agencies do not have the data, expertise, or personnel to set and enforce these detailed standards.

With US Congressional encouragement, EPA tried a different approach to regulating environmental discharges [13]. For example, as lead was being phased out of gasoline, it became evident that refineries had different capabilities of producing gasoline with the required octane when they could not boost octane with tetraethyl lead. Rather than compel all refineries to follow the same phase out schedule, EPA gave ‘allowances’ to refineries that phased out lead more quickly than was required. These refineries could sell the allowances to refineries that were not able to meet the standards. This more flexible approach gave an incentive to refineries to clean up more rapidly, stopped the inevitable complaints from those that could not, and yet met the phase out schedule. Evaluators concluded that granting this flexibility helped the program to succeed by having fewer challenges in the courts and political process and allowing refineries to adhere to the phase out schedule.

Granting allowances and flexibility for individual polluters was tried on a much larger scale in the 1990 Clean Air Act [41,42]. Congress instructed EPA to use an allowance approach to cut SO2 emissions in half from coal burning electricity generators. The cost of lowering SO2 is estimated to have decreased by at least 2/3 due to using allowances to give individual plants flexibility. Allowances are also being used in abating NOx and VOC.

As noted above, Congress used a flexible approach to regulate fuel economy, since it allowed automakers to offset gas-guzzlers with gas-sippers, as long as the average new car sold by a manufacturer met the fuel economy standard [8].

Policy analysts and Congress have concluded that allowing greater flexibility is beneficial, as long as there is stringent pressure to keep polluters focused on attaining the goal. The flexibility is especially valuable when it is combined with market incentives, such as tradable allowances. However, introducing flexibility and market incentives requires polluters and regulators to collect more data and engage in more record keeping. For example, if plant X wants to sell 10 000 SO2 allowances, the regulators have to make sure that they have earned the allowances. If plant Y buys the allowances, the regulators have to make sure that the levels of emissions are not greater than the total number of allowances that they have. This was feasible for SO2 since the emitters were large and could afford continuous emissions monitoring. The monitoring cost would be too large for smaller sources, although other approaches might prove feasible. In particular, it is hard to see how allowance trading could be applied to individual automobiles. Continuous monitoring is too expensive and some drivers might tamper with their engine and control system after inspection to increase the power of the vehicle. Additional discussion of regulatory methods can be found in Refs. [13, 42–45].

3.5. Treating and managing uncertainty

Policy analysis and most technology and business decisions are complicated by the fact that some of the most important parameters are unknown, or at least uncertain. Waiting until the uncertainty is resolved means waiting until many opportunities have passed. While regulators who act before all the information is collected and analyzed might regulate the wrong pollutant or set a standard that is too lenient or too stringent, regulators have to tradeoff the cost of delaying action against the cost of setting the wrong standard by acting prematurely. For example, there has been more than 30 years of controversy as to the relative importance of the health effects of SO2, CO, NOx, ozone (O3), and suspended particles. The US EPA feels reasonably confident that it can quantify the major health effects of air pollution, using TSP or PM10 as a surrogate. However, there is considerable uncertainty about the health effects of each of these individual pollutants.

One way of dealing with uncertainty is to ignore it. When EPA initially set the national ambient air quality standards, there was so little data that EPA tended to ignore uncertainty. One consequence was that when the ozone standard was revisited in 1977, EPA relaxed the standard from 80 to 120 ppb.

A second way of treating uncertainty is to conduct a sensitivity analysis. Often the analyst takes the plausible range and conducts an analysis to see the implications of using values from the middle and extremes of this range [39]. Alternatively, the analyst can try to find ‘critical’ values that make an important difference to the analysis.

Usually implicit in a sensitivity analysis is the assumption that the analyst has no idea of the likelihood that each outcome is likely to be correct [46]. For example, is the lowest value extremely unlikely or somewhat unlikely? If the analysis can put a subjective probability estimate over the distribution of values, a Monte Carlo analysis can be conducted. In this analysis the probability density function of the parameter values can be translated into a probability density function of outcome values. For example, if there were a distribution of the effects of PM10 on mortality in New York City, a Monte Carlo analysis would give the probability density of the number of deaths on a given day as a function of the concentration of PM10 and the number of people exposed to the air pollution. This outcome distribution gives more information than the sensitivity analysis. Unfortunately, the distribution is no better than the analyst’s judgment on the initial probability density function.

A final way of analyzing uncertainty is to construct a ‘scenario’ or conditional probability analysis [47]. The scenario assumes that uncertainty is resolved in a particular
way and then examines the implications. The scenario analysis can be regarded as an exercise in science fiction or as a rigorous application of conditional probability analysis that is related to sensitivity analysis and Monte Carlo simulation.

Even when the best of these analysis tools are applied, the uncertainty is still likely to be important. One way of managing the uncertainty is to find strategies that are robust in the face of the uncertainty. For example, there might be a regulation that, while not optimal for any value of the effect of PM$_{10}$ on mortality, tends to be good across a wide range of values. Thus, the analyst needs to search for regulations that are good across the range of likely uncertain values, rather than for regulations that have the greatest net benefits for a particular value. Sources providing details about uncertainty issues include Lave (1994) and Morgan [46].

3.6. Life cycle assessment

Researchers in the US and Europe have developed LCA methods most extensively. LCA is a systematic tool to provide information on the environmental impacts of alternative materials, products, processes and services. LCA attempts to trace out the major stages and processes involved over the entire life cycle of a product. In the US, the Society of Environmental Toxicology and Chemistry (SETAC) [48] and the US EPA [49–51] led the way in method development, publishing guidelines for LCA. Keoleian [52] presents a good overview of the life cycle design framework developed by USEPA. In Europe, similar guidelines have been issued by the Nordic Council of Ministers [53]. These methods utilize process models to trace the chain of material and energy flows all the way back to primary extraction.

The International Organization for Standardization (ISO) has recently published LCA guidelines that fall within their ISO 14000 series for implementing an environmental management system. They classify the LCA standards with other ‘product oriented’ standards, including environmental labeling. The LCA standards are ISO 14040: Environmental Management, LCA, Principles and Framework; 14041: Life Cycle Inventory Analysis; 14042: Life Cycle Impact Assessment; 14043: Interpretation. These four standards address the four components of LCA.

Goal definition and scooping. This first component of the LCA requires defining the purpose and the scope of the study including boundary definition, establishing the functional unit to be considered (e.g. an automobile with a lifetime of 150 000 miles), documenting assumptions, study limitations, and procedures for quality assurance of the results. Many of the controversies associated with LCA result from the assumptions made at this stage.

Inventory analysis. This LCA stage is an accounting of the energy and raw materials use and discharges to all media over the entire life cycle of the product, material, process, etc. Information in a life cycle inventory (LCI) includes, for example, for an automobile, the number of kg of CO$_2$ emissions from the use life cycle stage (the driving of the vehicle throughout its lifetime).

Impact analysis. ‘Impact analysis in LCA is a systematic process to identify, characterize, and value, potential eco-system, human health, and natural resource impacts associated with the inputs and outputs of a product or process system’ [50]. To date, this life cycle stage has not been implemented comprehensively. Sometimes the results of the inventory analysis have been aggregated into impact categories such as global warming and ozone depletion [54,55]. However, most studies have stopped short of actually characterizing and valuing impacts on health.

Improvement analysis. This final LCA component is a systematic evaluation of the needs and opportunities to reduce the environmental burden associated with the life cycle of the product. Both quantitative and qualitative options should be proposed.

LCA of automobiles have focused on inventory analyses. Several studies have taken steps to present impact measures, e.g. GWP, weighted toxics, etc. but none have resulted in a complete impact analysis. Newell [56] presents a LC method that makes progress in moving beyond inventory information by calculating social costs through estimating damage functions. We treat LCA for automobiles more extensively in Section 6.

Unfortunately, the ‘conventional’ LCA method and the results of studies utilizing this method have generated much controversy. Critics have charged that LCA cannot accomplish what is desired [54,57,58], Field [180]. Controversies over boundary selection, the difficulty that each industry is dependent directly or indirectly on most others for inputs resulting in the chain of inputs into a product expanding exponentially and the presence of circularities have been some of the difficulties. Analysts have struggled to obtain detailed and accurate, up to date data for all of the processes required. As a result, often they have had to draw narrow boundaries. Differences in the results of analyses of even simple products such as paper versus polystyrene foam (plastic) cups [54,59–61] indicate some of these shortcomings. Joshi [62] provides a thorough discussion of conventional LCA shortcomings.

In 1995, researchers from the Green Design Initiative at Carnegie Mellon University, Pittsburgh, PA proposed using economic input–output analysis techniques for overcoming the boundary problem in conventional LCA [54,62,63]. The method, called economic input–output life cycle analysis (EIO-LCA), has evolved into a comprehensive LCI tool with publicly available data. The model is available free of charge on the internet [64]. The current version utilizes the 1997 485 sector by 485 sector matrix of the US economy augmented with an environmental matrix.
3.7. Information needed to evaluate alternative fuel/vehicle life cycle inventory studies

LCA has long emerged from its exploration phase. Unfortunately, many analysts continue to act as if they are the first to face these issues and do not bother to compare their results to previously published work. Rather, analysts in the alternative vehicles area need to recognize that the LCA studies have the same overall goal: evaluate the attractiveness of alternative fuel/vehicle propulsion systems for the next 20–30 years. However, it is difficult to determine overall results from even one study and even more difficult to compare studies. The majority of studies do not present sufficient detail to analyze the method and results thoroughly. In most cases, little economic data are included and there is little discussion about the differing levels of development of the technologies and required infrastructures and how these impact the results that are reported. To provide valuable information to decision makers and facilitate study comparison, in our judgment, all studies should present the following core set of information.

(i) All options should be clearly specified and time frame and geographic location of analysis noted. Quantitative results for fuel cycle and vehicle operation should be presented clearly. For other life cycle stages (manufacture, service, end-of-life), at least qualitative information should be presented, detailing the most important differences in a particular option from today’s conventional vehicles and fuels.

(ii) A baseline conventional SIPI gasoline fueled vehicle should be included as a benchmark. Each vehicle being analyzed should be characterized by its style, size class, range, vehicle lifetime, thermodynamic efficiency and fuel economy (city/highway).

(iii) All alternative vehicle options should be modeled taking into account comparability from the point of view of the consumer and regulator (Section 3.8). This should include at a minimum; performance (acceleration, etc.), range, size class, style, vehicle lifetime, power to weight ratio, and emissions levels. Where it is not possible for an option to achieve equivalent attributes, this should be noted. Thermodynamic efficiencies and fuel economies (city/highway) of all vehicles should be reported, along with the level of development and a quantitative estimate of uncertainties.

(iv) The studies should include a standard set of GWPs for weighting the greenhouse gases, a standard lifetime (200 000 km) and a standard driving cycle for fuel economy and emissions. Since vehicles are used in different ways, the study can go on to present a driving cycle and lifetime that is most relevant for that model. However, it is important to present a standard scenario in order to compare the results with other studies.

(v) Each study should present current reformulated gasoline (RFG) or diesel as a standard test fuel for comparison. This standard will provide an anchor point for comparison with other studies and other fuels. If the focus is on the well-to-tank (WTT)—fuel cycle stage, the studies need to define a standard for reporting that is comparable to the Delucchi or Wang (GREET) frameworks [65,66]. Additional details about these frameworks are presented in Section 6.9. For biofuels, the studies need to specify the yield of volume of fuel/land area required to produce that fuel (e.g. gallons/acre) based on the near term situation as well as assumptions regarding sustainable production (assumptions regarding little use of fossil fuels throughout fuel cycle). For all fuels, the study should present estimates of emissions of regulated pollutants and toxics, GHG as above from raw materials extraction, transportation, and carbon sequestration where applicable.

(vi) Almost all studies have been conducted as if vehicle prices are irrelevant. Price is certainly not irrelevant to consumers. Thus, a good study should include estimates of the cost per vehicle mile (including initial purchase price, fuel, vehicle service, and fixed costs). The studies to date suggest that the costs of conventional ICE options are likely to be similar, even for those with direct injection engines or fueled with CNG or cellulosic ethanol. However, the costs may be greater for electric vehicles. For new fuels or vehicles, the study should contain a description of the infrastructure changes that are required and estimated costs.

(vii) When assumptions are being made about future improvements in technology, such as efficiency of the ICE or costs of cellulosic ethanol, the study should be explicit about the nature of the assumptions and, if possible, their justification.

(viii) Finally, results and associated uncertainties should be clearly presented.

3.8. Importance of ‘vehicle comparability’ in comparative analyses of alternative fuel/vehicle systems

Comparability of vehicles can mean that the vehicles have identical power, size, range, etc. Alternatively, it can mean that customers (and regulators) find the bundle of attributes of a vehicle at least equally attractive compared to the bundle of attributes of alternative vehicles. The latter criterion for comparability is most useful when it is all but impossible for the alternative car to deliver the same attributes as a current gasoline powered car. For example, if certain drivers do not regard a decrease in range as important, then the design could be shifted to compromise...
the unimportant attributes in order to score well on the desired attributes.

For vehicles that consumers do not regard as comparable, making analytical adjustments to render them comparable is difficult, but ignoring differences among vehicles is perilous. The fuel and vehicle system must be treated as a system when looking at comparability; the comparability of individual components is not relevant. A straightforward, but difficult, method of making vehicles comparable is to adjust fuel economy for differences in power, range, and weight. For example, EPAs Hellman [67] developed a formula for gasoline fueled vehicles to adjust fuel economy for differences in power. Adjusting for comparability does not end the difficulty. Some fuel/propulsion system combinations are better for some performance goals. For example, batteries are good only for short range, CNG for low emissions, diesel for high fuel economy. Battery-powered vehicles (BPV) have an advantage for operating in enclosed spaces or other areas that are difficult to ventilate.

Current sales of conventional vehicles show that consumers desire a wide range of designs. Some consumers desire small sports cars with quick acceleration. Others buy sport utility vehicles, the larger the better. No vehicle can meet the requirements of all consumers. However, to be ‘commercial,’ a vehicle has to appeal to enough consumers so that it meets at least the minimum scale economies in manufacturing, about 100 000 vehicles per year. To provide convenient servicing, a vehicle must command at least 1% of new vehicle sales. Thus, the 100 000 units per year could be sold in 10 countries to account for manufacturing scale economics, but the vehicle would not find convenient servicing.

Up to this point, we have focused primarily on vehicle comparability. There are related fuel comparability issues that must be considered. Primary issues include the potential for large-scale production/availability of the fuel at reasonable economies of scale. For example, ethanol from biomass is available at a relatively low cost when the feedstock is bagasse or other biomass residues. When this supply is used up and the feedstock costs $45/ton, the costs rise sharply.

Each fuel must satisfy the baseline availability, technology development (proven versus requiring technology breakthroughs), safety, suitable storage and vehicle use, and meet fuel regulations. Special attention must be paid to the attributes of the fuels not currently in large-scale production and their associated issues. For example, the vast majority of energy required to produce gasoline is from fossil fuels, whereas, renewable biofuels have the potential to be produced without using any fossil fuels and so would have no net CO2 emissions. Failing to differentiate between these two sources of energy use would be misleading.

Gasoline and diesel are taxed heavily in Europe and Japan and taxed moderately in many nations. While the tax motivates drivers to purchase vehicles with greater fuel economy and to drive less, it also serves to raise large revenues for government. Any fuel that assumes a large share of the market will have to pay its share of taxes. Thus, the comparison among fuels should be on the basis of refinery gate cost or of retail price, where each fuel has the same tax burden. It is misleading to compare the untaxed price of one fuel to the taxed price of another.

Comparability has proven to be the most difficult task for analysts. No one has managed a fully satisfactory method for adjustment, although some have gotten further than others. The principal reason why absurd comparisons have not been made, such as comparing the fuel economy of a tiny Metro to that of an Expedition SUV, is the good sense of analysts. However, we cannot depend on the good sense of all future analysts. We review, briefly, the way in which analysts have adjusted for vehicle comparability in their analyses.

Analysts have made varying levels of progress in accounting for equivalency in examining automobile alternatives. Recently, LCA studies comparing alternative fuel/vehicle options have devoted more attention to comparability of the vehicles and fuels they analyze [10, 68–70]. We examine several studies, including these recent examples as well as earlier works, noting the steps taken into account for comparability and their impact on the study results. These studies were completed with a focus on product planning, sustainability, and environmental impacts.

Since alternative fuels and advanced vehicles on the road today and in development are not optimized for performance, comparisons of these vehicles with the best conventional gasoline ICE vehicles are misleading. The latter have been refined over a century. To level the playing field somewhat, many researchers have estimated the potential efficiencies of various alternative-fueled automobiles [9, 71–74] compared to a baseline gasoline automobile. These estimates have been generally based on the thermal efficiency of the alternative fueled vehicle propulsion system compared to that of a gasoline vehicle for combined city/highway driving, taking into account the fuel and engine properties. This is a first step. However, not taking into account the comparability of the remainder of the vehicle (e.g. whether diesel vehicles can achieve the stated efficiency and meet the same emission standard as the conventional gasoline vehicle or if the CNG vehicle has a range only half that of the conventional vehicle, or comparing a 2-seater with a luxury sedan) will lead to misleading results. The fuel/engine combination must be placed within the social context of being comparable from both consumer and regulatory perspectives.

Of all alternative fueled vehicle studies, Delucchi [65,71] and Wang [66] modeled the most extensive sets of alternative-fueled passenger cars with production of fuels from various pathways. The analysts used previous studies and expert judgment to model the vehicles, primarily through adjustment of their fuel economies based on estimated
efficiencies compared to a baseline conventional automobile. Vehicle emissions were based on emissions standards, vehicle test results, and modeling. In lieu of making an assumption about vehicle lifetimes, the model results were presented on a per mile basis. The model results did not state whether the vehicles were of equivalent size, range, or were comparable in other performance parameters. The fuels and corresponding fuel cycles were modeled based on production data and engineering judgments.

Kreucher [75] is another early study reporting LCA results for various conventional and alternative fueled vehicles. He addressed comparability by modeling the vehicle options from a Ford Escort, assuming 100% penetration of the particular fuel option and constant vehicle lifetime. In addition, cost differentials from the baseline Escort were calculated.

Sullivan [76] held powertrain performance constant in examining an ICE gasoline engine Taurus and three diesel (compression ignition ICE) ‘functionally equivalent’ vehicles. Sullivan mentioned the increase in emissions for the diesel options and the issue of meeting regulatory standards but did not appear to adjust the vehicle efficiency to account for emissions treatment required to meet the standard or to account for the additional costs associated with reducing the weight of some of the vehicle options.

Brekken [77] developed a method for comparing the efficiency of competing propulsion technologies and fuels. To compare vehicles, the authors start with a baseline Ford Taurus and calculate the total energy required to move a vehicle from point A to point B, starting with the original source of the energy. All of the vehicles are also required to do the same amount of useful work. They also considered comparability of power to weight ratio and range.

MacLean [68] and Lave [10] accounted for several of the aspects of comparability that, in their judgment, are highly valued by consumers and regulators, modeling the vehicles from a baseline popular conventional gasoline ICE vehicle, the 1998 Ford Taurus LE sedan. Their studies utilize the Taurus conventional sedan fueled with unleaded gasoline as the baseline vehicle. In modeling alternative fuel ICE vehicle options, the authors held constant, vehicle style and size class, driving range, lifetime, emissions level (California Ultra Low Emission Level (ULEV)), and comfort. In addition, the vehicles were modeled assuming large-scale penetration of the vehicle/fuel options into the market, and in estimating efficiency differences from the baseline vehicle it was assumed that all of the combinations were optimized for their fuel and met the ULEV emissions standard. However, the performance of the options has not been proven, and comparable vehicle attributes, e.g., acceleration, interior and trunk space, etc. were not held at the same level as the baseline vehicle. The authors show the significant impact on vehicle weight (and therefore, performance) of not holding vehicle range constant (Fig. 2). The impact is most significant for fuels that have low energy densities, such as CNG, and, to a lesser extent, ethanol.

MIT [69] noted that they ‘evaluate in a consistent way major new vehicle and fuel technologies which have the potential to reduce significantly the emissions of GHGs’. The study examined technical characteristics of new technologies, GHG and other emissions, energy efficiencies, costs, consumer perceived performance, convenience, safety, and reliability. The study selected a baseline average-size (US) passenger car, gasoline fueled with an ICE and with the evolutionary improvements expected by the year 2020; the vehicle is assumed not to incur extra costs other than those necessary to keep up with the market. As in the GM/Argonne study, the MIT study looked at options that could be produced and used at a volume great enough to capture most of the economies of scale. The study assumed that all vehicles will meet US Federal Tier 2 national requirements for emissions and accounted for estimated costs of the emission control system required.

The MIT study reported that ideally, each vehicle alternative should provide the same acceleration, drivability, driving range, refueling ease, interior driver and passenger space, trunk space and meet applicable safety and pollutant emission standards. The analysts took steps to deal with these issues, but remark that only some of them could be dealt with quantitatively in the study. The attributes that they held constant among the vehicle options were that all propulsion system and vehicle combinations were adjusted to provide the same ratio of maximum power to total vehicle mass (75 W/kg), driving range of 600 km (except the BPV), vehicle size was kept relatively constant, they assumed that the California Low Emission Vehicle (LEV) II and EPA Tier II emissions standards for 2004–2008 could be met by improved exhaust gas treatment technology for the ICE engines and were within reason for fuel cell systems (noting that the least confidence was placed on the diesels meeting these standards), and some consideration of cost differences. Vehicle options were modeled using computer simulations and assuming the vehicles go through specified driving cycles. The vehicles utilized advanced technologies in the propulsion systems and lightweight materials and reduction of other driving resistances, aerodynamic drag and rolling resistance. The BPV were not comparable in range.

A study by General Motors and Argonne National Laboratory [70] considered comparability with respect to a number of important issues. First, the authors reported that the study is limited to fuel/vehicle options having the potential for large volume penetration in the LDV market from 2005 to 2010. The mass, and aerodynamic and rolling resistance coefficients of the vehicles in the study were based on a conventional gasoline fueled GM Silverado full size pickup truck. The focus of the study was on the potential for improving fuel economy (efficiency), while maintaining the vehicle performance demanded by North American consumers. The study specified performance
targets for all of the alternatives developed in the work. These targets were vehicle acceleration (0–60 mph time and 0–30 mph), vehicle acceleration in top gear, maximum vehicle acceleration, time to maximum acceleration, vehicle gradeability at 55 mph for 20 min, top vehicle speed, and vehicle ZEV range. These performance targets drove the powertrain sizing process. Vehicle mass was determined on the basis of component sizes and the powertrain operation was optimized on the driving cycles by implementing energy management and control strategies to achieve the maximum fuel economy for each vehicle option. However, additional constraints were placed on component operation (e.g. engine, accessories, motors, batteries) to take into account vehicle drivability and comfort requirements. In addition, the study assumed that vehicles would meet certain Federal Tier II emissions standards. The vehicle portions are modeled using proprietary GM software. The authors note that factors such as packaging, cold start, transient response and cost were not considered within the scope of the work.

Although the GM/Argonne [70] study has made progress toward consideration of comparability in the development of the vehicles, it is important to note that significant technological developments will have to be achieved for the advanced vehicles to be viewed by consumers as equivalent to the baseline pickup truck, of particular importance are cost and overall performance issues with the FCVs which are as yet unproven.

Hackney and de Neufville [78] described “a life cycle model for performing level-playing field comparisons of the emissions, costs, and energy efficiency trade-offs of alternative fuel vehicles through the fuel production chain and over a vehicle lifetime”. Hackney’s vehicles had a lifetime of 12 years and the ‘level playing field’ approach was related to the removal of taxes and subsidies to evaluate how each combination would compete in the absence of regulations that favor certain alternatives. In addition, the authors mentioned that the vehicle models share a common ‘gliding’ vehicle chassis that is used as a base and then modified to accommodate the various vehicle power plant and fuel options. Efficiencies of each vehicle’s drive train were represented by a normalization factor relative to the efficiency of a conventional gasoline vehicle. They included some uncertainty in efficiency values. All of the vehicles were assumed to be fuel-efficient subcompact passenger cars of 40 Horsepower (Hp), driven the national average annual vehicle miles traveled. There is not sufficient detail in the paper to examine vehicle weights, ranges and performance issues.

Pembina [79] evaluated FCV options and focused on defining a ‘functional unit’ in order to provide an ‘apples to apples’ comparison. Their functional unit was defined as having all of the vehicle options able to provide the service required for the vehicle for 1000 km of traveled. They assumed a pattern of 55% city driving and 45% highway driving in an A-Class Mercedes Benz. Each vehicle was designed to have a 600 km driving range on a tank of fuel.

Lave [80,81] proposed a simple tool for predicting the consumer appeal of an alternative vehicle. Assuming that performance was comparable (or that the differences were not important), they calculated the differences in the...
costs of owning a conventional (Toyota Corolla) and alternative (Toyota Prius HEV) vehicle over their lifetimes. The cost differences included initial purchase price, fuel, and any differences in service and maintenance. Since the Prius has better fuel economy and lower emissions of pollutants and GHG, they calculated the ‘breakeven’ price of gasoline ($3.55/gallon), pollution emissions (11 times the assumed median values from Ref. [39]), and GHG emissions ($130/ton CO₂) that would equate the lifetime ownership costs of the two vehicles (assuming the current price premium of $3495 for the Prius over the Corolla). Alternatively, they calculated the price premium for the HEV that would equate the lifetime ownership costs and asked whether it would be possible to manufacture an HEV for this cost premium. Finally, they asked what characteristics an advanced vehicle whose size and performance were comparable to a Corolla would have to have in order to be attractive to consumers. Suppose an advanced vehicle used no fuel and had no pollutant or GHG emissions. How much more than the Corolla could this vehicle sell for and still have the same lifetime ownership costs? The authors came up with the value of $5540 (assuming a discount rate of 6%). These calculations illustrate how difficult it is for advanced vehicles to displace the modern SIPI engine vehicle. Although, HEV are likely to improve significantly from the initial models in terms of performance and cost, it appears that, unless the hybrids offers performance features worth more to the consumer than those of the conventional vehicle, they are unlikely to gain a large market share.

More generally, this analysis framework allows an automaker to evaluate any prospective alternative vehicle against a conventional vehicle with respect to lifetime costs. Adjusting for other differences between vehicles is more difficult. For example, the Toyota Prius is similar to the Corolla, allowing for relatively straightforward adjustments to make them reasonably comparable. The Honda Insight (another HEV) is much smaller and not directly comparable to other models sold in the USA, making adjustment difficult. Less costly examples include CNG vehicles and E85 used in flexibly fueled vehicles. This tool can be used to calculate the value of an improvement in fuel economy or lowering of pollution or GHG emissions. While each fuel/vehicle combination has some advantages and disadvantages compared to conventional gasoline vehicles, the costs and improvements of alternative vehicles are hard to justify in competition with the best current vehicles. For new fuels, infrastructure and convenience of fuel supply are major issues as well.

Predicting the performance of technologies not in large-scale production and comparing these with those that are is exceedingly difficult. Even though some of the above noted studies consider vehicle and fuel comparability to a reasonable extent, there remains much work to be done in this area.

4. Attributes of fuel and propulsion system options: technical issues

This section discusses fuel and propulsion system options with the potential for large-scale use in the next two to three decades. We begin by describing the fuel and propulsion system options individually. This discussion is necessarily general since specific vehicle attributes (e.g., efficiency, fuel economy, and performance) depend on the fuel/propulsion system pair. Thus, following this initial discussion we focus on specific fuel/propulsion system combinations. Since there is a broad literature in the area of characteristics of alternative fuels and propulsion systems, we provide some introductory material and focus on primary aspects that differentiate the options but refer readers to additional sources for more detailed information.

4.1. Fuels

Nearly all motor vehicles today are powered by either gasoline or diesel. Both fuels are derived from petroleum, a non-renewable resource. The gasoline and diesel sold today is not the same as that sold in the 1960s, since regulations have forced the reformulation of these fuels to improve environmental performance. These reformulated fuels have lower sulfur and fewer aromatics; tetra-ethyl lead is banned throughout the USA and Canada.

In 2000 in the US, 67% of petroleum consumption was for transportation and the transport sector is 97% dependent on petroleum [3]. Gasoline and diesel have an enormous infrastructure that supplies the fuel each year to the US and Canadian light-duty fleets. These fuels are attractive for LDV because of their price, availability, ease of use, and high energy density. However, production, refining, transport and use of these fuels cause local and global environmental problems. If a substantial portion of the fleet were to run on an alternative fuel, a large infrastructure would have to be constructed at enormous cost and protest [72].

We discuss the characteristics of conventional and alternative fuels under consideration in the near term for light-duty transportation, focusing on those most relevant for assessing their potential for large-scale use. Guibet [82], Poulton [72], DOE [83], Owen [84], NREL [85], and Argonne National Laboratory website and publications [14] are good sources for information about alternative fuels, their properties, advantages and disadvantages of their use for personal transportation. Selected properties of the fuels are shown in Table 2 and described in the following sections. Fuel property definitions are in Appendix A.

The efficiency of production of a fuel from raw materials (well-to-tank) is an important attribute. Where little processing is required, the efficiency is high, e.g. gasoline from crude oil. Where a great deal of processing is required, the efficiency is low, e.g. Fischer–Tropsch fuels from coal or natural gas. For renewable fuels, efficiency of production
is not well defined. It could be defined as the ratio of the energy in the fuel to the energy in the sunlight that struck the relevant portion of ground. It seems most useful to estimate the number of square meters of ground required to propel a standard vehicle a specified distance.

However, large investments are required to transform sunlight or biomass into fuel. A LCA is required to calculate the total materials and energy required for the process. For example, with a photovoltaic cell, a smaller area of ground is needed to propel a vehicle a mile than would be needed to grow the amount of biomass required to produce the ethanol necessary to propel that vehicle a mile. However, a great deal more materials, labor, and energy are required to make the photovoltaic cell than is required to produce the ethanol. Thus, a full LCA is required to determine which is better.

4.1.1. Motor gasolines

Gasoline is a blend of hydrocarbons with some contaminants, including sulfur, nitrogen, oxygen and certain metals. The four major constituent groups of gasoline are olefins, aromatics, paraffins, and naphthenes. These groups vary in their octane level and reactivity. Petroleum varies in density, chemical composition, boiling range, etc. For example, petroleum from the Persian Gulf tends to be high in aromatics, while oil from the North Sea is usually high in alkanes. To meet product specifications, gasoline blending is often required. The important characteristics of gasoline basestocks are density, vapor pressure, distillation range, octane, and chemical composition.

To be attractive, a motor gasoline must have (a) desirable volatility, (b) anti-knock resistance (related to octane rating), (c) good fuel economy, (d) minimal deposition on engine component surfaces, and (e) complete combustion and low pollutant emissions [86]. The most difficult requirements to meet from a technical and economic perspective are volatility and octane rating (Research Octane Number (RON) and Motor Octane Number (MON)) [82]. If gasoline volatility is too high or too low, it can deteriorate vehicle performance for cold starting and warm-up time at both hot and cold temperatures, idle stability, acceleration performance and operation at cruising speeds [82]. The octane rating of the fuel is influenced by the chemical structure; for example, octane number decreases with increasing chain length, with decreasing number of side chains for the same number of carbon atoms, and with decreasing number of ring structures (cycloalkanes and aromatics) [87]. Typical RONs of gasoline vary from 90 to 100, while the MONs vary from 81 to 90. In the US, the three grades of gasoline (Regular, Midgrade, and Premium) have Anti-Knock Index (AKI) ratings of 87, 89, and 91, respectively. The AKI is calculated by averaging the RON and MON of the fuel.

The flash point of gasoline is about $-40^\circ C$; while the fuel is reasonably safe to store, it is less safe than diesel fuel, which has a much higher flash point. A disadvantage of gasoline (and diesel) is that it biodegrades very slowly; spilled fuel may penetrate the ground and pollute soil and water.

The refining industry has been undergoing a transition due to changes in product demand and the quality of the gasoline and diesel blend components required. These changes result from more stringent emissions standards, fuel economy regulations, and fuel regulations, as well as petroleum price increases. If refineries could purchase any petroleum they wanted and produce any product mix, then a

<table>
<thead>
<tr>
<th>Property</th>
<th>Gasoline</th>
<th>No. 2 diesel fuel</th>
<th>Methanol</th>
<th>Ethanol</th>
<th>Propane</th>
<th>Compressed natural gas</th>
<th>Hydrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical formula</td>
<td>H, C₂ to C₁₂</td>
<td>H, C₃ to C₂₅</td>
<td>CH₃OH</td>
<td>C₂H₅OH</td>
<td>C₃H₈</td>
<td>CH₄</td>
<td>H₂</td>
</tr>
<tr>
<td>Composition, weight %C</td>
<td>85–88</td>
<td>84–87</td>
<td>37.5</td>
<td>52.2</td>
<td>82</td>
<td>75</td>
<td>0</td>
</tr>
<tr>
<td>Density, lb/gal at 60°F</td>
<td>6.0–6.5</td>
<td>6.7–7.4</td>
<td>6.63</td>
<td>6.61</td>
<td>4.22</td>
<td>1.07⁺</td>
<td>–</td>
</tr>
<tr>
<td>Reid vapor pressure, psi</td>
<td>8–15</td>
<td>0.2</td>
<td>4.6</td>
<td>2.3</td>
<td>208</td>
<td>2400</td>
<td>–</td>
</tr>
<tr>
<td>Research octane no.</td>
<td>90–100</td>
<td>–</td>
<td>107</td>
<td>108</td>
<td>112</td>
<td>–</td>
<td>130 +</td>
</tr>
<tr>
<td>Motor octane no.</td>
<td>81–90</td>
<td>–</td>
<td>92</td>
<td>92</td>
<td>97</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>(R + M)/2</td>
<td>86–94</td>
<td>–</td>
<td>100</td>
<td>100</td>
<td>104</td>
<td>120 +</td>
<td>–</td>
</tr>
<tr>
<td>Cetane no.</td>
<td>5–20</td>
<td>40–55</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Flammability limits, vol%, lower, higher</td>
<td>1.4, 7.6</td>
<td>1.6</td>
<td>7.3, 36</td>
<td>4.3, 19</td>
<td>2.2, 9.5</td>
<td>5.3, 15</td>
<td>4.1, 74</td>
</tr>
<tr>
<td>Lower heating value, Btu/gal at 60°F</td>
<td>115 000</td>
<td>128 400</td>
<td>56 800</td>
<td>76 000</td>
<td>84 500</td>
<td>19 800⁺</td>
<td>–</td>
</tr>
<tr>
<td>Stoichiometric air/fuel, weight</td>
<td>14.7</td>
<td>14.7</td>
<td>6.45</td>
<td>9</td>
<td>15.7</td>
<td>17.2</td>
<td>34.3</td>
</tr>
</tbody>
</table>

Adapted from alternative fuels data center, www.afdc.nrel.gov/pdfs/fuel/table.pdf

⁺ For compressed gas at 2400 psi.

² Octane values are for pure components.
relatively simple refinery would be suitable. However, with strict product requirements, and the necessity of accommodating varying crude oils, complex refineries are the norm. Many reference books provide useful background information about the refining industry and refinery processes [84, 88].

The major steps in the gasoline (and diesel) fuel cycles are shown in Fig. 3. Wang [66] outlines these in a straightforward manner as petroleum recovery, crude oil transportation and storage, crude oil refining, production of oxygenates (if required), transportation, storage and distribution of petroleum product. Additionally, Wang [66] and Delucchi [65, 71, 89] discuss the major energy and environmental burdens associated with each of the stages of the fuel cycle.

4.1.2. Reformulated gasolines

Reformulated gasoline (RFG, referred to as ‘clean gasoline’ in other nations) is designed to reduce both exhaust and evaporative emissions from vehicles. ARCO first introduced RFG in 1989 in Southern California. RFG meeting increasingly stringent fuel specifications are mandated in North America and other countries. In the US, the Clean Air Act Amendments of 1990 require the sale of RFG in areas of the US where ambient air quality fails the National Ambient Air Quality Standard (NAAQS). California has the most stringent gasoline regulations in the world. Bowman [90], Guibet [82], Owen [84], and Gary [88] discuss these concepts.

Reformulation of gasoline has focused on the reduction of vehicle exhaust emissions (VOC, NOx, and air toxics) and evaporative emissions of VOC and benzene, through lowering fuel volatility, concentrations of aromatics (especially benzene, due to its carcinogenicity) and volatile olefins. Several studies have investigated alternative formulations with respect to their effect on air quality [91–94], finding significant reductions in regulated pollutants and toxics with RFG compared to conventional gasoline. The lower energy density of RFG carries a small fuel economy penalty [94].

All RFG have specified requirements for performance and chemical composition. For example, in addition to required octane levels and vapor pressure, these requirements include T90 temperature, maximum sulfur content, maximum olefin content, and at this time in the US, an oxygenate is required (2.0–2.7% by mass).

Empirical models are used to determine whether using RFG will result in the levels of pollution reduction outlined by the standards. Poulton [72] summarizes RFG research programs up until that time. AQIRP [91, 92], CARB [95], and EPA [35] report more recent RFG information. Additional information on Federal RFG can be found in Ref. [35] and on California RFG in Ref. [95]. Guibet [82] and Poulton [72] summarize the basic regulations, fuel properties, and air pollutant reductions.

The US EPA documents the deleterious effect of sulfur in gasoline [96]. The sulfur poisons catalysts. Sulfur and sulfur oxides inhibit the reaction of HC, CO, and NOx on the catalytic surface. EPA [96] also found that sulfur interferes with the management of oxygen on the catalyst surface. This must be precisely controlled to maximize NOx emission reductions. Sulfur will likely have a larger impact with more stringent emissions standards, however, there are ways to make the vehicles less sensitive to sulfur (e.g. increased use of rhodium in catalyst and maintenance of high temperatures during catalyst operation). Sulfur is an even larger problem for DI and FCVs. These vehicles require almost sulfur free fuels. Therefore, gasoline sulfur removal is not only important to maintain the emissions control potential of current vehicles, but is required as an enabler of future technologies.

Oxygenates. Oxygen is not a natural component of gasoline. Since 1979, it has been added in the US in the form of MTBE and ethanol. Initially, these oxygenates were used as octane enhancers to replace lead in limited areas of the country. During the 1980s, oxygenates were utilized on a larger scale as some areas implemented oxygenated gasoline programs to control emissions of CO in cold weather. Use of high percentages of oxygenates in gasoline increased again with the 1990 Clean Air Act Amendments which requires...
that they be added either seasonally (15% MTBE by volume) or year round (11% MTBE by volume) in parts of the US where CO levels in the winter or ozone concentrations in the summer exceed the National Ambient Air Quality Standards.

Oxygenates have high molecular oxygen content and are either alcohols or ethers. The purpose of oxygenates in gasolines has been to assist with fuel combustion, leading to lower emissions of CO and HC's through the presence of additional oxygen. They also have higher octane ratings than gasoline and are blended with low octane gasoline basestocks to meet octane requirements. Bowman [90] provides a good discussion on the effects of oxygenated gasoline components.

The effects of oxygenates in gasoline on vehicle emissions have been studied by several researchers. Kirchstetter [93] provides a summary of studies up to that time. Kirchstetter [93] found no change in NOx emissions and decreases in CO and VOC for the oxygenated gasoline. Keller [97] reports that oxygenates were found to have no significant effect on exhaust emissions from advanced technology vehicles when comparing oxygenated and non-oxygenated gasolines that met all other CaRFG2 standards. The emissions reduction benefit of oxygenated gasolines is highest for older vehicles with open loop control. Newer vehicles with computerized closed-loop control get a lesser benefit, and there is only a small benefit for advanced technology vehicles. These vehicles have a feedback ECS that takes away the majority of the effect of the oxygenate. Generally, the oxygenate requirement remains for the following reasons; it is an octane booster, it is helpful to older vehicles, and it is domestically produced, displacing imported petroleum [181].

The most commonly used oxygenate in the US has been MTBE, due to its compatible blending properties, high octane, low vapor pressure, availability and low cost. However, as noted earlier, this oxygenate is being phased out due to its detection at low levels in groundwater and possible toxicity. The majority of detections have been below public health concern levels. However, research on the health risks of MTBE provides inconclusive results [97] (Erdal, 2000). The very low odor and taste thresholds of MTBE have caused the majority of problems. People complain about water that smells or tastes bad and the costs associated with remediating contaminated water can be very high. Erdal [182] provides a thorough assessment of the environmental health impacts and policy implications of MTBE in gasoline.

A number of studies have looked at alternatives to MTBE [98,99]. Ethanol is the only approved replacement at this time. However, there are cost and supply issues if a large amount of ethanol is required [98,99]. In addition, ethanol raises the vapor pressure of the ethanol–gasoline mixture, resulting in increased evaporative emissions.

From a life cycle perspective, there are fuel cycle/vehicle tradeoffs. Additional processing of RFG requires additional energy use and results in additional emissions compared to refining of conventional gasoline. These upstream ‘costs’ must be compared to reductions in vehicle emissions.

4.1.3. Diesel fuels

Diesel oil (Number 2) comes from the middle distillate fraction of a crude oil distillation column. It is a more complex and variable (density, volatility, and general composition) fuel than gasoline. Diesel fuel’s two major benefits over gasoline are its higher energy density (its volumetric heat value is 10% greater and therefore the fuel consumption at the same efficiency would be 10% lower) and its suitability for use in the automotive power plant with the current highest thermal efficiency (compression ignition direct injection (CIDI) ICE). These two aspects result in fuel economy benefits compared to other alternative fuels in ICE.

Important characteristics of a diesel fuel are ignition quality (cetane), density, heat of combustion, volatility, cleanliness, and non-corrosiveness. The cetane number indicates how readily the fuel self-ignites. If a fuel has too low a cetane number for the engine, the fuel may not ignite or may ignite poorly, especially on cold days when starting a cold engine.

Viscosity is another important property for fuel injection, starting and engine performance. The flashpoint of diesel fuel is at least 55 °C, and therefore it is safer to store than gasoline. The high sulfur content of diesel fuel is of concern due to fouling of emission control systems, as well as acids formed in the atmosphere after emission, leading to deposition as small suspended particles. Functioning of diesel oxidation catalysts is severely compromised unless the fuel is essentially free of sulfur [82]. Removing sulfur from diesel fuel is more difficult (requiring more energy and cost) than removing it from gasoline due to the fuel’s molecular structure.

Diesel fuels, like RFG, can be reformulated to lower vehicle emissions. This is primarily accomplished through lowering sulfur content. Legislation in the many countries is addressing this issue. In the US, sulfur content was reduced to 0.05% (500 ppm) by mass in 1993, and Europe adopted this level in 1996. Low sulfur diesel fuels have lower lubricity, lower electrical conductivity and reduced stability, but these can be corrected with additives.

The major fuel cycle stages for diesel are similar to those for gasoline as shown in Fig. 3.

Biodiesel. Biodiesel is a renewable diesel fuel substitute. The term originally referred to any diesel fuel that is derived from biomass or animal fat. Most recently, the term has referred to methyl or ethyl esters that are produced from vegetable oils or animal fats (in North America biodiesel is most commonly produced from soybean oil and in Europe, from rapeseed oil). Potential advantages of biodiesel are that

-- Diesel fuel has been historically high in sulfur, but currently, 1000 ppm sulfur is allowed in federal gasoline and only 500 ppm sulfur in onroad diesel.

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it is a renewable fuel, its use would reduce dependence on foreign petroleum and would leverage limited supplies of fossil fuels, mitigate GHG emissions, reduce air pollution and related public health risks and produce local jobs [100]. See Refs. [85,100] for detailed information on biodiesel.

Sheehan [100] reviews literature to investigate the claim that biodiesel is a petroleum diesel substitute and finds that overall, the ester form of biodiesel is compatible with current engines but reports that it exhibits cold weather problems (related to higher viscosity) and some storage instability problems. Biodiesel has a lower energy density than conventional diesel (117 000 compared to 131 300 Btu/gal of No. 2 diesel). Benefits of biodiesel include zero aromatic content, higher cetane numbers, zero sulfur content and low flashpoint.

As with other fuels, the production process for biodiesel is important. Of particular importance for renewable fuels are the feedstock sources (and therefore, potential land requirements for feedstock production), infrastructure cost, and the issue of coproducts. With conventional fuels, the energy balance is calculated based on the heating value of the products obtained and the total energy required for production. With renewable fuels, usually two energy balances are established, one that includes and one that excludes the renewable energy. Co-products usually accompany biofuel production. If the co-product market becomes saturated, prices fall and the entire production cost must be earned by the sale of the biofuels.

As an example of a biodiesel fuel cycle, soybean biodiesel starts with soybean farming, soybean transportation to soy oil plants, soy oil production, transesterification of soy oil to biodiesel, transportation of biodiesel to build terminals, and distribution of the biodiesel to refuel stations [66]. See Refs. [66,85,100] for additional information on biodiesel production.

**Fischer–Tropsch Diesel.** Fischer–Tropsch (F–T) is a production process that produces a diesel fuel from syngas (H2/CO), which is produced from NG or coal via autothermal reforming. The F–T diesel fuel has no sulfur, almost no aromatics and high cetane. These properties make the fuel attractive for use in a diesel engine. F–T synthesis was used during World War II for fuel supply.

The F–T process is very energy intense (overall energy yield of 60–65% is much less than the standard refining processes [82]) and the capital investment is large, on the order of $1B to $1.5 B for a plant producing 50 000 barrels per day of F–T diesel. Building a F–T plant would be attractive only if crude oil prices were expected to remain at more than $20 per barrel and there were a large supply of natural gas at a location, but too small a supply to justify liquefaction for export and so the gas was available at a very low price.

4.1.4. Compressed natural gas

Natural gas (NG) is a naturally occurring form of fossil energy and therefore non-renewable. However, NG has some advantages compared to gasoline and diesel from an environmental perspective. Natural gas is composed primarily of methane (CH4) but has other HC compounds in small amounts (e.g. propane, butanes and pentanes). It is a cleaner burning fuel than either gasoline or diesel (they are more complex mixes of HC and other compounds). However, NG also contains active compounds, such as sulfur, and inert compounds such as nitrogen and CO2. Some portions of these other compounds in the NG are removed in processing the gas for shipment. NG has a high octane (RON = 110–130) and therefore potential for use in a high compression engine.

Methane has a very high autoignition resistance. The minimum spark energy required for methane ignition is much higher than that required for other HCs. It also has a wider flammability range than HC, allowing an engine to operate lean. However, engine performance is reduced with CH4 because the volume of the gas reduces the air breathing capacity of the engine. Natural gas’ low flame temperature helps to limit the formation of NOx and since it contains only 75% carbon by mass versus 86–88% for gasoline or diesel, NG produces less CO2 per unit of energy released. Other benefits are that NG is neither toxic, carcinogenic, nor caustic. CNG is likely to be safer than gasoline or diesel, since its low density, high ignition temperature (540 °C) and high flammability limits give the gas a high dispersal rate and make it less likely to ignite [72]. The low energy density of CNG also causes storage problems onboard vehicles, along with the issue of heavy pressurized storage cylinders necessary to store the gaseous fuel. Issues associated with high pressure storage offset some of the combustion safety benefits mentioned earlier.

The natural gas fuel cycle is made up of four basic stages: natural gas production, processing, transportation and storage, and distribution [66]. In the production stage, NG is recovered and collected in NG and oil fields, then transported by pipeline to NG processing plants. The processing stage separates high-value liquids (e.g. propane, butane) from NG and removes impurities (e.g. sulfur and CO2) resulting in pipeline quality NG. The transportation of NG is through pipelines from the processing plant to local distribution companies. The distribution of the NG to refueling stations consists of high-pressure NG from a transmission pipeline being depressurized and delivered.

4.1.5. Alcohols

**Ethanol.** Ethanol (C2H5OH) has a higher octane number (RON = 108), broader flammability limits, higher flame speeds and higher heats of vaporization than gasoline. These properties allow for a higher compression ratio, shorter burn time and leaner burn engine, which leads to theoretical efficiency advantages over gasoline in an ICE. Disadvantages of ethanol include its lower energy density than gasoline (but about 35% higher than that of methanol), its corrosiveness, low flame luminosity, lower vapor pressure (making cold starts difficult), miscibility with water, and toxicity to
methanol. However, mixing ethanol with even a small amount of gasoline greatly increases the volatility of the fuel (increases RVP), improving engine cold starting but resulting in an increase in evaporative emissions. At present, ethanol produced from biomass is about twice the price of gasoline without any taxes, after accounting for the energy densities.

In the US, ethanol is used as a gasoline extender, octane booster, as an oxygenate in the winter oxygenated fuels programs, and in reformulated gasoline. For the first option, usually one part of ethanol is blended with nine parts of gasoline (often referred to as gasohol or E10). This fuel has been in use since 1973. In the oxygenated fuels program, usually 10% ethanol or 7.7% ethanol is used. For RFG, usually 5.7% ethanol is used to provide 2.0% by weight oxygen. IEA [101] reports that the US ethanol market is 22% oxygenated gasoline, 42% RFG, and 36% octave enhancer and volume extender. The other LDV motor fuel application option is the sale of higher level blends (up to E85) for the small number of flexible fuel SIPI ICE vehicles that are designed to be run on gasoline or blends up to E85. Currently only 0.25% of the ethanol sold in the US is in high-level blends [101].

Current annual ethanol consumption in the US and Canada is over five billion liters [101], representing about 1% of the motor vehicle fuel market. Ethanol can be produced through three general methods; from petroleum and NG by hydration of ethylene (C₂H₄), from biomass via the fermentation of sugar derived from grain starches or sugar crops or from biomass via the utilization of the non-sugar lignocellulosic fractions of crops or wastes. Ethanol produced from corn is the most common motor fuel option in the US. However, large-scale production from corn would not be desirable from either social or environmental viewpoints [25,26]. Ethanol produced from lignocellulosic feedstocks (woody and herbaceous biomass) could provide a renewable transportation fuel.

**Methanol.** Methanol (CH₃OH) has a higher octane number (RON = 107), flammability limit, flame speed and vaporization advantages over gasoline. These properties lead to the potential for higher engine thermal efficiency when operating on methanol. Methanol’s wide flammability limits allow ICE using the fuel to operate lean.

Methanol is less likely than gasoline to ignite in open air after a spill. However, neat fuel vapor can burn in a closed tank if enough ignition energy is supplied (due to reduced volatility and the higher upper flammability limit compared to gasoline [72]. Methanol has some serious limitations as a motor fuel; it is corrosive, highly toxic, colorless, odorless, and tasteless. In addition, its flame is almost invisible in daylight. Its energy density is lower than that of gasoline due to the high atomic weight of the oxygen it contains. On a mass basis, gasoline provides over twice the heating energy of methanol. neat methanol has the same problem with cold starting as neat ethanol due to its low volatility (RVP = 4.6). Methanol–gasoline blends solve this issue. Methanol has a lower carbon to hydrogen ratio than gasoline or diesel, and therefore produces less CO₂ when burned.

Virtually all methanol is produced from NG, although it can be produced from wood, coal, or any carbonaceous material that can be converted to synthesis gas (carbon monoxide and hydrogen). If inexpensive NG is available, the steam methane reforming technology is an economical way to produce methanol. Methanol is currently distributed primarily as an industrial chemical.

### 4.1.6. Hydrogen

The potential and promise of a hydrogen economy have been on the energy agenda for decades. Hydrogen is an odorless and invisible gas (an odorant can be added to aid detection). Like electricity, hydrogen is an energy carrier not an energy source. A primary advantage of hydrogen over other fuels is that its only major oxidation product is water vapor; its use produces no CO₂. Combustion of hydrogen in air can result in the formation of NO₂, but it may be reduced to low levels by proper design. Hydrogen has a higher octane number (RON = 130+) and wider flammability limits than gasoline. In the event of a fuel leak, hydrogen will disperse more quickly than gasoline. Hydrogen is non-toxic and not carcinogenic. There are some safety concerns. Its flames are very hot, but do not radiate much heat, making fires difficult to locate.

Hydrogen’s usefulness as an energy carrier is reduced by its low energy content on a volume basis, limiting onboard storage. It can be stored as a gas, a cryogenic liquid, or, in addition, solid-state storage is also possible. A particular problem with liquid hydrogen is boil off. As the liquid warms, boil off gas is released which must be vented from the storage tank. In confined spaces there is a risk of fire or explosion if contacted by a flame. Contact with liquid hydrogen destroys living tissue due to the very low temperature of −253 °C, so serious burning could arise from contact with hydrogen escaping from pressurized fuel systems [72]. Cannon [102] and Poulton [72] provide an overview of hydrogen issues related to its use as a LDV fuel.

There are three general strategies for the hydrogen fuel cycle [79]. The first is production at large centralized facilities and then distribution via pipelines or trucks to refueling stations. Second is the option of producing hydrogen at a large number of decentralized facilities, such as service stations, where it would be delivered to vehicles. Finally, the hydrogen could be produced by reforming a hydrocarbon fuel (e.g. gasoline, methanol, natural gas) onboard a vehicle.

Hydrogen can be produced through a number of pathways; the two most common are reforming of NG and electrolysis of water using electricity. Steam reforming of NG converts NG to synthesis gas, from which CO₂ and CO are removed. Electrolysis consists of passing an electric current through an electrolyte to split water into its constituents. The method of electricity generation (whether from renewable resources, coal, etc.) significantly impacts
the LC results for the fuel cycle portion of hydrogen production [103]. Any method of hydrogen production that requires the production of an interim energy carrier (e.g. electricity) prior to production of the hydrogen will have significant efficiency disadvantages due to the energy required for each of the two conversions. MIT reports the conclusion of several studies [104–107,183] that decentralized gas reforming stations can provide hydrogen at lower cost than any of the other options within the 2020 time frame.

4.1.7. Liquid petroleum gas

Liquid petroleum gas (LPG) is derived from the lighter HC fractions produced during petroleum refining of crude oil, and from the heavier components of NG, which are removed before the gas is distributed. Utilizing NG liquids lessens US dependence on foreign energy supplies, but the supply is small.

There is considerable experience with LPG as an alternative motor vehicle fuel in North America. It has been in use as a commercial motor vehicle fuel worldwide for over 60 years [72]. LPG sold in the US is primarily propane. However, it can consist of butane or mixtures of the two. It has good fuel properties, higher octane rating (RON = 112) and wider flammability limits than gasoline. It also does not need enrichment at startup. Vehicles powered by LPG should be able to meet NOx emission standards more easily than those using CNG, due to the faster flame speed and lower octane rating of LPG. The limited supply of LPG means that it could not be other than a niche fuel in North America.

4.1.8. Liquefied natural gas

Natural gas is condensed by a combination of refrigeration and compression, which consumes approximately 10% of the energy content of the NG [9]. In addition to the energy required, liquefaction and storage require expensive equipment. LNG has been considered as an option for fueling automobiles, since liquefaction reduces the volume compared to CNG by a factor of 600, making transport by tanker economically feasible. Vehicles issues, however, deter the use of LNG with potential problems including vapor boil-off from small storage tanks and heat transfer. Due to these constraints, this fuel is not considered an option for fueling LDV, save possibly fleet vehicles that return to a central facility each day.

4.1.9. Electricity

Battery-powered vehicles (BPV) have been marketed as ‘Zero Emissions Vehicles’ or ZEV since they lack any vehicle emissions. However, the source of electricity generation used to charge their batteries is important. Electricity can be generated without air pollution by nuclear, hydro or wind power, or its generation can result in significant upstream emissions through the use of wood or coal. The attractiveness of the electricity from an environmental and energy perspective depends on which energy sources are utilized [103]. In 1998, in the US, 57% of the electricity was produced from combustion of coal, 20% from nuclear, 10% from natural gas, 10% from hydropower and 3% petroleum [22]. The mix of energy sources for electricity is likely to change over the next 20 years. Infrastructure investments are significant and power plants have long lives but for electricity to be a ‘clean fuel’, the national electricity mixes of the US and Canada would have to be altered.

Current batteries have low energy density and so a large battery mass is required to give the vehicle a desirable range. Since almost all battery materials are toxic heavy metals, there are environmental discharges and thus undesirable effects from mining and smelting the metal, making the batteries, and then recycling the batteries [33,108].

4.2. Fuel attributes

As the above discussion suggests, there are a number of desirable attributes for fuels for LDV. These can be grouped into four broad categories:

- **economic issues**: low delivered price,
- **performance issues**: octane, cetane numbers, high energy density, easy and safe storage, other safety issues,
- **environmental issues**: carbon content, volatility, and impurities (sulfur and hazardous air pollutants), and
- **sustainability issues**: will the fuel be available indefinitely or is it exhaustible?

Important considerations for the production of the fuels include the efficiency of their production (considering both total and fossil only energy balances), emissions of criteria air pollutants, air toxics, and GHG from the fuel cycles, and other environmental burdens. In addition, co-product issues are of importance for biomass fuels.

Efficiency estimates of the fuel cycle alone (commonly referred to as ‘well-to-tank’ (WTT)) tell only half the story. The other half is the efficiency of the propulsion system (‘tank to wheels’ (TTW)). Evaluating the combination is required for assessing the overall ‘well to wheels’ (WTW) efficiency for a comparison of vehicle options. Note that the vehicle manufacture, maintenance and end-of-life components of the vehicle life cycle are not included in traditional WTW studies.

The fuels being considered for the light-duty fleet are diverse with respect to the above attributes. This diversity is reflected in performance, economic, environmental, and sustainability differences among the fuel/vehicle systems under evaluation. The fuel properties impact fuel cycle and vehicle design and optimal performance of the fuel/vehicle system. Differences may require minor modifications or complete new designs of fuel production, distribution, storage, and refueling systems and vehicles. The fuel properties mentioned in Section 4.1 and shown in Table 2 characterize the elements of primary importance for
determining their attractiveness for motor vehicle use. ICE may be different than electric vehicles.

4.3. Propulsion systems

The propulsion system consists of components for fuel storage, those for getting the fuel to the power plant, and the power to the wheels, as well as the environmental system designed to prevent or lower pollutant emissions. For conventional ICE vehicles, the propulsion system consists of a tank to store the gasoline or diesel fuel, a fuel pump, activated carbon canister to absorb fuel vapors, an ICE that is spark ignited for gasoline and compression ignited for diesel, a transmission, and an exhaust treatment system. Sources providing detailed information on the characteristics of propulsion systems include Refs. [82, 83, 86, 109–111]. We limit our discussion to a few introductory remarks as well as the primary issues related to comparing the propulsion systems and their performance with alternative fuels. In this section when discussing efficiency, we focus on the efficiency of the propulsion system itself.

4.3.1. Spark ignition port injection engines

Spark ignition (SI) port injection (SIPI) engines power nearly all North American LDV. ICE generate power by converting chemical energy (burning fuel) into heat and then into mechanical work. In an SIPI port injection engine, a mixture of air and fuel is ignited inside a cylinder by a spark. The SI cycle is called the Otto Cycle after Dr N.A. Otto who in 1876 patented a stationary gas engine using approximately the same cycle. The efficiency of a modern SIPI engine is limited by a number of factors, including losses by cooling and friction. Generally, the efficiency of these engines is determined by the compression ratio (the ratio between the minimum and maximum volumes of the combustion chamber). Typical efficiencies for these engines are on the order of 20%. Characteristics and operation of ICE are described in many sources, including those listed in the previous section.

Development of these engines to date has focused on their use with gasoline as the fuel, however, other fuels with suitably high octane numbers, volatility, and other appropriate properties (e.g. ethanol and methanol/gasoline blends, CNG, LPG) have been utilized in these engines when modified (e.g. materials, engine design and control) for the particular fuels.

4.3.2. Spark ignition direct injection engines

Spark ignition direct injection (SIDI) engines may bring a major improvement in SI engines because of their potential reduction in fuel consumption. However, for compliance with stringent emissions standards while performing at high efficiency levels, this engine requires further development, including advanced exhaust treatment and low sulfur fuel compatible with its operating characteristics. Zhao [112] provides a thorough review of these engines.

Direct injection engines compress air in the cylinder and then fuel is injected into the compressed air, allowing more precise control over the air–fuel mixture and the placement of fuel in the cylinder compared to port injection. Direct injection can be used to achieve a rich air–fuel mixture near the spark plug at the time of ignition (charge stratification). Therefore, these engines can operate lean at partial load, resulting in reduced fuel consumption during this period. Other improvements to thermal efficiency for these engines result from the exhaust gases having a composition much closer to that of air and a lower temperature (which reduces heat loss) and the induction of excess air reduces pumping losses. These features have the potential to improve fuel consumption compared to that of a SIPI engine, however, the efficiency improvement in practice is highly dependent on the emissions standards required to be met by the vehicle. Harms [113] reports that Bosch’s first generation gasoline DI engines with all-guided injection resulted in fuel consumption reductions of 10–15% compared to a SIPI ICE. He also reports that they expect savings of up to 20% with future spray-guided injection processes; however, no note is made regarding emissions.

In principle, the SIDI engine can use the same fuels as a port injection engine, although modifications may be required to enable advanced emissions control systems (i.e. low sulfur fuels).

4.3.3. Compression ignition engines

In 1892 Rudolf Diesel patented the compression ignition (CI) ‘diesel’ engine. Unlike the SI engines, ignition of the fuel in CI engines is due to a rise in temperature and pressure of the fuel during compression. The energy required for ignition results form the high temperature of air compressed in the cylinder that causes self-ignition of the fuel when it is injected near the end of the compression stroke. These engines operate lean in order to achieve complete combustion. This results in higher efficiency and torque but less horsepower than an SI engine of comparable size. A supercharger or turbocharger can be used to produce additional horsepower by putting more fuel and air into the cylinder.

There are two main classes of CI engines, those with direct injection (DI) into the combustion chamber, and those with indirect injection into a pre-chamber. Indirect injection engines have lesser fuel injection requirements and lower injection pressures are satisfactory. The pre-chamber produces good mixing of the fuel and air, however, the division of the combustion chamber results in a pressure drop and a greater heat transfer, and therefore these engines are only 85–95% as efficient as DI engines.

Compression ignition DI engines using diesel fuel are about 24% efficient compared to about 20% efficiency of SIDI injection engines using gasoline. The higher maximum efficiency is due primarily to three reasons: the higher compression ratio; during the initial part of compression, only air is present; and the air/fuel mixture is always lean. It
should be noted that the higher compression ratio and rapid heat change of the CI engine require a sturdier, heavier engine than is necessary for a SI engine.

Diesel oil from petroleum sources is the primary fuel used in CI engines due to its fuel properties, particularly its high cetane number. Biodiesel and Fischer–Tropsch diesel are also considered as potential fuels in this work.

4.3.4. Electric motor with battery power

Battery-powered vehicles (BPV) have an electric motor that drives the wheels without needing a transmission and use electrical energy that is stored in chemical form in batteries for power. Electric motors convert electrical energy from the energy storage device (battery) into mechanical energy that drives the wheels of the vehicle. Since almost all of the energy in electricity is converted into useful work in an electric motor (only about 10% of the energy is lost to heat), this is a more efficient system than an ICE. (Another advantage of electric motors over ICE is that they provide full torque at low speeds, increasing acceleration, compared to the necessity of ICE to ‘ramp up’.)

A battery is an energy storage device. Lead acid batteries were the first to be used in BPV due to their low cost, high reliability, and established recycling infrastructure [83]. However, batteries are much less efficient in storing electricity than is a fuel tank in storing gasoline or diesel oil. Batteries have low energy density, which results in a battery weighing many times more than a fuel tank containing the same amount of energy in gasoline. The lead-acid batteries onboard General Motors’ EV-1 weighed about 1100 lb and gave the car a range of about 70 miles. If a similar car had been built with a gasoline powered ICE, less than 2 gallons of gasoline would be required to drive 70 miles. Thus, together the gasoline and fuel tank would weigh about 27 lb (2 gallons of gasoline at 6 lb/gal and a fuel tank weighing about 15 lb), or 1/50 the weight of the battery. A nickel metal hydride battery would reduce the ratio to about 1/30.

Batteries do not operate well at cold temperatures and the total number of cycles (discharge and recharge) is limited. Finally, a battery is many times more expensive than gasoline/diesel and a fuel tank that stores the same amount of energy. Battery technology development is progressing and alternative batteries are being developed. The US Advanced Battery Consortium, a cost shared effort between the three North American automakers and the US Department of Energy, is at the forefront of this development in the US. Advanced batteries offer improvements in energy storage, power and number of cycles, but are generally more expensive than lead-acid batteries. Not even large-scale production is expected to lower the costs of advanced batteries to the level of lead-acid batteries. Nickel metal hydride batteries are being used in the second generations of BPV and there is discussion of using lithium batteries in the next generation. However, no current battery technology has the required power, efficiency, and life cycle with reasonable economics [83].

4.3.5. Hybrid electric vehicles

HEVs combine an energy transformation system with one or more energy storage systems. The most common option is an ICE (gasoline) and a battery, however an ICE running on any fuel, a fuel cell, or a gas turbine could be substituted for the gasoline ICE and an ultracapacitor or flywheel for the battery. In the 1970s and 1980s, HEV developers focused on improving the range of BPV. More recently, the focus has been on fuel economy and lower emissions.

A HEV can take a range of forms:

A vehicle that has a conventional ICE with a 42 V electrical system and a slightly larger battery than a conventional ICE vehicle;
A conventional HEV with much more electricity storage onboard and an ICE that either charges the battery (series hybrid) or both charges the battery and provides direct power to the wheels (parallel hybrid); or
A vehicle whose batteries are charged from the electrical grid with an ICE onboard to provide ancillary power to help recharge the batteries.

These are the three points on a spectrum from a slight modification of a current ICE vehicle to a vehicle that is almost strictly battery-powered.

4.3.6. Fuel cells

FCVs are considered by many to be the most promising alternative technology for personal transportation vehicles. They have the potential of zero vehicle emissions and high efficiency when fueled with hydrogen. Fuel cells convert energy stored in a fuel directly into electricity without combustion. Unlike a battery where the supply of chemicals is limited by the size of the battery, fuel cells can be fed continuously with fuel to produce electricity indefinitely. A fuel cell consists of an anode, a cathode and an electrolyte. Fuel cells are characterized first by the kind of electrolyte that they use and then subcategorized by the type of fuel they use. The two broad categories of fuel cells are acid and alkaline (referring to the chemical nature of the electrolyte). The fundamental fuel required for fuel cells is hydrogen; in the future the use of other fuels may be possible.

In a typical fuel cell, hydrogen is introduced at the anode and splits into hydrogen ions and free electrons. The hydrogen ions flow through the electrolyte to the cathode, where oxygen is introduced. At the cathode, the oxygen binds with the hydrogen ions to form water. To complete the process, the free electrons released at the anode must join with the hydrogen and oxygen at the cathode. The movement of electrons from anode to cathode creates a current that can be used to power an electric device.

Several types of fuel cells are being developed both for mobile and stationary sources; proton exchange
membrane, solid oxide, molten carbonate, phosphoric acid, alkaline, etc. Each of the options varies in size, weight, energy output (electrical and heat), cost and other parameters. Fuel cells for transportation must meet more stringent requirements in terms of size and weight limits than those for stationary applications. The leading fuel cell technology for the automotive sector is the proton exchange membrane (PEM) fuel cell. According to the National Fuel Cell Research Center, PEM have greater than 55% efficiency (fuel cell only) when running on hydrogen.

According to Peppley [114], PEM have the following attributes that make them suited to automotive use:

- They operate at relatively low temperatures (less than 90 °C);
- Have a high power density and fast response;
- Have safe and easy handling during manufacture and operation;
- Quick startup and shutdown; and
- Maintenance is not expected to be significant.

However, there are challenges to commercialization that include the cost of catalyst, membrane and fabrication, materials (bipolar plates, membrane, poison tolerant catalyst system is very sensitive to impurities in the fuel), supply of the pure hydrogen fuel that is required, and lack of fueling infrastructure.

4.4. Fuel/propulsion system combinations

In the last two decades, technology development of conventional gasoline-fueled SIPI vehicles and CIDI diesel engines has progressed rapidly. Attention to improving vehicle efficiencies and resulting higher fuel economy while further reducing vehicle emissions has necessitated improvements in all engine components and subsystems with enhanced coordinated control of engine management, clutch and transmission-shift control, braking systems, electrical on-board power supply, and thermal systems [113]. For example, the amount of fuel required to move 1000 lb 100 miles for the average gasoline automobile dropped by 36% from 1968 to 1993; and some gasoline vehicles have been certified to the super ultra low emission vehicle (SULEV) standard. These improvements have significantly raised the baseline to which alternatives have to be compared.

Heywood [109] outlines important criteria that should be considered when evaluating propulsion system and fuel combinations. These include performance over the system’s operating range (usually related to maximum power or torque available at each speed within the useful operating range as well as the range of speed and power over which the engine operates satisfactorily), fuel consumption and cost of required fuel (function of driving cycle), noise and air pollutant emissions (function of driving cycle), initial cost, and reliability and durability, maintenance requirements and how these affect system availability and operating costs. We build on this list in the following sections.

5. Attributes of fuel and propulsion systems: social issues

To be attractive, a fuel-engine combination has to be successful along many dimensions, from cost to safety to performance. We explore some of the performance and technical issues later in this section but to begin, we remind the reader of a few other important dimensions; costs, fuel safety, infrastructure and supply.

American consumers have gotten used to paying about $1.50 per gallon for gasoline and Canadians slight more. A fuel that was significantly cheaper (as NG used to be) or significantly more expensive (as hydrogen might be) would be an important attraction or liability. The important dimension is not the cost per gallon, but the cost per mile. For example, diesel has about 10% more energy per gallon than gasoline and methanol has about half as much. Thus, the price per gallon has to be corrected for the distance the gallon of fuel will take the vehicle.

Similarly, a diesel engine is more expensive to manufacture, particularly a CIDI, but gives better fuel economy. The additional manufacturing cost of a CIDI or HEV needs to be noted, although the analysis should focus on the lifetime costs of the propulsion system, not its first cost. The lifetime cost will also be affected by fuel economy, lifetime miles driven, and need for maintenance. For example, a vehicle that travels a long distance each year, like a New York City taxicab, would gain more from the fuel economy of a CIDI than would a vehicle driven only a few thousand miles over its lifetime.

Safety is an important dimension. Motor vehicles in the USA and Canada are driven and refueled by people with a wide range of competencies. Collisions can rupture the fuel tank, fuel can vaporize and escape in a garage, and fuel is spilled during refueling. The 42 000 highway deaths and almost 4 million injuries attest to the many mistakes made by drivers [2]. Murphy’s law is certain to apply to both refueling vehicles and driving them. The current system of using gasoline is accepted by society even though it poses major hazards, particularly in collisions, Thus, gasoline provides a benchmark to compare other systems.

An extensive infrastructure has been built to manufacture current engines and produce and distribute gasoline. Even a relatively small shift, such as switching to CIDI engines would require a large investment. A radical shift, as to a fuel cell, would require massive investment and worker retraining. However, the investment in propulsion systems is small compared to the investment in producing fuel. The infrastructure for exploration and production of petroleum, bringing crude oil to the refinery, and then shipping the gasoline to service stations and selling it costs hundreds of
billions of dollars. Producing an equivalent amount of energy in the form of other fuels would require a similar investment. For example, generating enough electricity to run the fleet would require an investment in electricity generation, transmission, and distribution of $300–600 billion. In view of public attitudes toward environmental quality and our unwillingness to locate dangerous or unsightly facilities nearby, building a new fuel infrastructure would be difficult. Although there have been doomsayers since the early 19th century warning that we are running out of petroleum, the resource base has turned out to be much larger than they expected. The amount of energy required to power the light duty fleet is immense for the US, about 15% of total country’s fuel use. Finding a substitute energy source would not be easy. To be sure, the resource base for coal is even larger than that for petroleum, but there are large environmental problems associated with mining, transporting, and burning the coal. The potential resource base for nuclear reactors is large, but public opposition and high cost have prevented the ordering any new reactors in the USA for two decades. Growing enough energy crops to produce ethanol to replace gasoline would require using perhaps 1/6 to 1/3 to the total land area of the USA. A proposal to devote so much land to energy crops would certainly be subject to intense public scrutiny, even if it were ultimately successful [25].

In summary, alternative fuels and propulsion systems face an immense difficulty because of the success of gasoline and ICE and the immense investment in the infrastructures for producing these engines and fuels bringing the fuels to market.

5.1. Modeling alternative fuel vehicles

Except for gasoline SIPI and diesel CI engines, none of the other options have been produced in large scale with systems optimized for the particular fuel/engine combination. Therefore, alternative vehicle options must be modeled based on production and prototype conventional and alternative vehicles and other data using engineering principles and expert judgments. Of central importance are estimates of fuel/engine combination thermal efficiencies. Many researchers have developed estimates of the efficiencies of alternative fuel vehicle options compared to that of a baseline gasoline SIPI ICE (Section 3.8). These estimates are based on R&D and expert judgment. However, the lack of real world experience with the alternatives limits the credibility of the estimates.

MacLean [68] presented two matrices that compare the potential thermal efficiencies of various fuel/ICE combinations with that 1998 Ford Taurus sedan. They defined efficiency as in Ref. [109], as fuel conversion or thermal efficiency (Well-To Tank efficiencies are not included in the values). Thermal efficiency is the inverse of the product of the specific fuel consumption (sfc) and the lower heating value of the fuel (QHV), as shown in Eq. (1). Specific fuel consumption is the fuel flow rate per unit power output in milligram/Joule (mg/J) and measures how efficiently an engine is using fuel supplied to produce work. QHV is determined in a standardized test procedure and is in Megajoule/kilogram (MJ/kg).

\[
\text{Thermal efficiency} = \frac{1}{(sfc \times QHV)}
\]  

MacLean [68] only considered ICE vehicles. The baseline Taurus has a SIPI engine fueled with conventional US federal gasoline. An initial matrix was developed without an emissions constraint for the combinations, since literature up to that time did not specify that level of detail. The matrix estimates are from literature and expert judgment. However, the importance of meeting strict emissions standards led MacLean to elicit judgment from automobile industry experts of the efficiencies with the constraint of meeting the California ULEV standard. The matrix estimates assumed that the quality of the fuel required for each option to meet the standard was available. This matrix is presented in Table 3. The table indicates, for example, that neat ethanol (E100) used in a SIDI engine would be 13–28% more efficient per MJ of fuel than the baseline fuel/engine combination. However, since E100 has a lower energy density, this car would require more fuel to travel a fixed distance. There is more uncertainty in the estimates for DI engines due to the lack of experience with this engine design, the lean operation required for high efficiency, and the current state of catalyst development for these vehicles.

More recently, several LCA studies of alternative vehicles have reported estimates of efficiencies for ICE and advanced vehicle options. GM/Argonne [70] and MIT [69] estimates for the alternative fuel options are generally less optimistic than those of MacLean and other previous researchers, while Harms [113] is more optimistic. However, due to the varying assumptions in the studies, it is difficult to compare their result.

5.2. Vehicle emissions control

Reducing vehicle exhaust and evaporative emissions from LDV continues to be a priority. The majority of LDV sold worldwide must meet stringent emissions standards. Emissions standards were first implemented by the state of California in 1968, followed shortly thereafter by US Federal standards in the Clean Air Act of 1970. The standards in the State of California are the most stringent in the world, followed with a lag of a few years, by the Federal US standards. Both sets of standards regulate the same pollutants (HC, CO, NO\textsubscript{x}, PM), they apply to new vehicles,
and the standards are expressed in grams pollutant released per vehicle-mile.

Emissions test procedures vary from country to country but generally the objective of the test procedure is to establish the mass of each exhaust component emitted during an emissions test cycle. The concentration of each pollutant in a known gas volume is measured when the vehicle is operated on a chassis dynamometer (essentially a treadmill for vehicles) according to a certain standard driving cycle. The driving cycle is designed to simulate driving conditions in urban or other highly congested traffic. Variations between countries include substantial differences in the driving cycle (speed and distance), vehicle pre-conditioning, and analytical equipment [84].

We briefly discuss vehicle emissions control, however, we refer the reader to the large body of literature in this area (e.g. Society of Automotive Engineers books and papers [115]) for details. Our discussion emphasizes the necessity of vehicle options having to meet increasingly strict emissions standards and focuses on primary differences in emissions control required for the various alternative fuel/propulsion system options. There are three general approaches to emissions control. These are to clean the fuel (prior to its use in the propulsion system), reduce the formation of pollutants during combustion, and finally, to clean the exhaust gases.

Vehicle emissions control is related to engine-design measures and exhaust-gas treatment. Engine design measures include fuel metering, mixture formation, uniform distribution, exhaust gas recirculation, valve timing, compression ratio, combustion chamber design, ignition system, crankcase ventilation. Exhaust gas after treatment is primarily related to catalyst design and loading (as well as the air management system) [110].

The exhaust system reduces the pollutants in the exhaust gas generated by combustion in the engine. A conventional automobile exhaust system consists of three main components [110], a catalytic converter, muffler, and exhaust pipe. The catalytic converter was introduced in 1975 as a result of the requirements of the US Clean Air Act.

For HC fuels, the major proportion of the exhaust gas is composed of the three components: nitrogen, CO₂ and water vapor. These are non-toxic. The exhaust gas also contains pollutants; CO, NOₓ, HC and PM and air toxics such as benzene, 1,3-butadiene, aldehydes, etc.

For SI vehicles, the three-way or selective catalytic converter with lambda closed-loop control is the most effective option for exhaust gas after treatment. The CO and HC are oxidized either by utilizing the excess air supplied by lean engine mixtures or by relying on secondary air injection. Nitrogen oxides are reduced through a deficiency of air. The catalytic converter provides the reductions of all three pollutants but requires that the engine is operated with a stoichiometric mixture \( \lambda = 1 \). The system has a very tight ‘window’ for treatment and significantly higher emissions will result if the mixture moves from close to stoichiometry. Today’s catalytic converters are able to reduce emissions of HC, CO, and NOₓ by over 90%. They are employed globally on over 300 million vehicles. Low sulfur fuels are essential for achieving strict emissions standards, as the sulfur poisons the catalyst.

For DI engines (which operate lean), conventional three-way catalytic converters are not suitable. The success of the DI option, particularly in North America, will depend to a

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<table>
<thead>
<tr>
<th>Fuel/engine technology</th>
<th>Spark ignition, indirect injection (SIII)</th>
<th>Spark ignition, direct injection (SIDI)</th>
<th>Compression ignition, direct injection (CIDI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasolinea</td>
<td>Baseline</td>
<td>8–18, 5–15, 10–15</td>
<td>–</td>
</tr>
<tr>
<td>Reformulated gasoline (CaRFG2b)</td>
<td>6º, 0º</td>
<td>15–25, 13–28</td>
<td>20–25, 20–23</td>
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<tr>
<td>EC dieself</td>
<td>–</td>
<td>5º, 13–28</td>
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<tr>
<td>Ethanol 100h</td>
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<tr>
<td>Compressed natural gasi</td>
<td>–10º, 10º, 10º</td>
<td>5º, 13–28</td>
<td>–</td>
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</tbody>
</table>

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Table 3
Estimated fuel/engine efficiencies for internal combustion engine vehicles meeting California ultra-low-emission vehicle standards (% change in efficiency from baseline)

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- Conventional federal unleaded (non-reformulated, non-oxygenated) gasoline. Lower heating value (LHV) is 115 000 Btu/gal at 60F, wt% carbon is 85.
- California Phase 2 Reformulated Gasoline. LHV is 111 600 Btu/gal at 60F, wt% carbon is 84.
- Ref. [170] (two different groups, therefore double entries for some combinations).
- Ref. [171].
- Ref. [172].
- ARCO Emission Control (EC) diesel, currently in a demonstration project in California. LHV is 126 763 Btu/gal, wt% carbon is 87.
- Combination is unattractive.
- Neat ethanol (E100). LHV is 76 000 Btu/gal, wt% carbon is 52.2.
- Compressed natural gas. We analyze CNG at 3000 psi, LHV is 24 720 Btu/gal at 60F, wt% carbon is 75.
significant extent on whether suitable lean NOx catalysts are developed along with complex engine control systems. In addition, almost no sulfur can be tolerated in the fuels for these vehicles if emissions requirements are to be met. These engines must be developed taking into account the entire vehicle system.

5.2.1. Control issues for alternative fuels

**Gasoline.** There have been significant improvements in last decade for these vehicles, including vehicles certified to SULEV standards. These vehicles require very ‘clean’, low sulfur fuels. The EPA-designated toxics emitted as conventional automobile exhaust and evaporative emissions are benzene, 1,3-butadiene, formaldehyde, acetaldehyde and polycyclic organic matter. With lowered benzene content in RFG, benzene has become less of a problem than in the past. DI engines tradeoff efficiency (lean operation) against higher engine-out emissions.

**Diesel.** The primary constraint to the future use of diesel-fueled automobiles in the US and Canada is their exhaust emissions, particularly of NOx and PM. There have been recent advances in emissions control from diesels that have been assisted by the upcoming regulations for clean fuel, sulfur of 15 ppm, but major issues still require resolution. One important issue is that there will be a loss in fuel efficiency due to the energy required to power the emission control systems necessary to meet PM and NOx emissions standards.

There are two issues associated with PM from diesels that are of concern, the amount of the emissions from the vehicles (diesel engines inherently produce more PM than do gasoline engines), and the concern over whether diesel exhaust particles are more toxic than gasoline exhaust particles of the same size. Diesel PM was classified as a carcinogen by CARB in 1998 [116,117]. In 2000, the National Institute of Environmental Health Sciences classified diesel PM as ‘reasonably anticipated to be a human carcinogen’ [118].

MacLean [68] reports that ethanol-fueled (E85 and E100) automobiles are expected to be able to meet near term emissions standards. They will require engine and emissions control similar to those for gasoline vehicles. The lack of sulfur in the ethanol is an additional benefit, reducing catalyst fouling. A vehicle fueled by neat ethanol would be expected to have total exhaust HC lower than those from gasoline, and emissions levels of NOx and CO approximately the same [72]. There are expected to be lower evaporative losses due to the lower vapor pressure of ethanol. Ethanol fueled engines produce higher emissions of aldehydes than do gasoline-fueled vehicles.

CNG is a ‘cleaner burning’ fuel than gasoline. CNG vehicles have lower CO and NMHC emissions, although total HC may be higher due to unburned methane. The emissions of HC that cause air pollution problems are lower with CNG vehicles. A gas-fueled engine does not require cold-start enrichment and therefore, emissions from ‘cold’ engine operation are lower than with liquid fuels. Gas systems are designed to be ‘airtight’ and so should have almost no evaporative emissions. The low sulfur content of CNG leads to lower catalyst poisoning.

Advanced electric vehicles generally have lower vehicle emissions and require less advanced emissions control. Battery-powered electric vehicles do not have a tailpipe or vehicles emissions and therefore do not require a vehicle exhaust system. HEV with ICE should result in lower tailpipe emissions than conventional vehicles with the same type of ICE due to their use of batteries for some of the more emissions intensive driving stages. However, the vehicle still requires an emissions control system. FCVs run on pure hydrogen would not require vehicle emissions control, since they produce only water vapor. However, if an onboard fuel reformer were used to transform some fuel into hydrogen, some emissions treatment would be required.

Improvements in emissions control can result from modifications to propulsion systems, after treatment systems, or the fuels themselves. The improvements in all of these facets in conventional gasoline vehicles during the last decade have been significant. It is arguable whether alternative fuels in ICE have the potential for significant reduction (both related to magnitude and toxicity) in emissions of regulated air pollutants and toxics over those from RFG-fueled vehicles. Experts expect that Tier 2 Bin 5 US Federal standards can be met by all of the ICE vehicle options while still retaining a reasonable efficiency (perhaps with the exception of diesel and gasoline DI) [70]. If so, then the focus on externalities shifts away from these emissions, except that there is still a concern whether ‘real world’ emissions, the actual emissions of the vehicles over their lifetime, are much higher than those that would be estimated based on the vehicle certification level.

Past studies have documented that real world emissions levels have been substantially greater than emission certification measurements [119–124]. The discrepancy between emissions standards and actual vehicle emissions should diminish with time due to improved onboard diagnostic and catalytic control systems, improved durability of catalysts, longer standards lifetime (120 000 miles in the US), test cycles more representative of real world driving, and cleaner fuels (less likely to foul emission control systems). Additional research is needed to investigate the durability and performance of advanced systems. Although the majority of the vehicle technology improvements are targeted at conventional vehicles, experts expect that these technologies will apply with minor modification to all ICE.

5.2.2. Emissions estimates in life cycle inventory studies

An LCI requires information on the lifetime emissions of a vehicle. These data would be difficult to collect and so a variety of surrogates are used. Some studies assume that the emissions measured in the EPA certified tests will approximate emissions in practice, perhaps with an adjustment for
increasing emissions as the vehicle ages. Emissions tests of consumer owned vehicles show that most vehicles have emissions greater than what would be predicted from the certification testing and some vehicles, the ‘super emitters,’ have many times the test levels. Thus, an LCA should be based on actual, not test emissions. However, recent model year vehicles have not been in use long enough for their actual lifetime emissions to be measured. Emissions from vehicles that have not yet been produced are even more difficult to estimate. Rapid technological change vitiates the usefulness of either test or real world emissions data. For example, the SULEV certified vehicles should have much lower lifetime emissions than current vehicles. Due to the difficulty of estimating emissions and the judgment that real world emissions will be much closer to certification based estimates in the future, some recent LCA studies have assumed that all options will meet upcoming US federal or California emissions standards. However, they acknowledge the difficulty of diesel and other DI vehicles meeting the standards. The more comprehensive studies include vehicle efficiency penalties for meeting emissions standards based on estimates of the amounts of energy required for powering emissions control systems for each of the options to meet the standards [10,68–70].

A limited number of studies have made efforts to account for real world emissions through including estimates of emissions resulting from off-cycle (non-Federal Test Procedure) driving, malfunctioning and deterioration of emissions control systems over the vehicle lifetime [5].

### 6. Automobile life cycle assessment

This section summarizes the application of LCI to automobile issues generally, aside from those focused on conventional and alternative fueled vehicle options. The Society of Automotive Engineers has published much of the automobile related work on LCA and associated, Design for the Environment (DFE). The studies include those that deal with method and application issues, such as the use of LCA to improve the ‘greenness’ of an auto, method issues such as data quality, boundary specification, uncertainty, examining a particular component or material, methods for examining a particular life cycle stage of the auto, various options for a particular LC stage, LC issues associated with a particular environmental burden (e.g. energy use), and LC cost issues.

Research on the development and use of LCA for automotive applications has been done by several automobile companies, consultants, and university researchers. Keoleian [125] and Graedel [126] are good overview texts that characterize the main environmental burdens associated with the automobile life cycle, identifying opportunities for improvement through technology and design, policy and regulation, and changes in usage patterns.

### 6.1. Abbreviated LCA methods

The complexity of the automobile has resulted in a focus on the design of the product including the development of more cost-effective application methods for LCA for these products. Rebitzer and Fleischer [127] described the development of a software-based method for setting appropriate system boundaries and simplifying the LCA due to the much cited, time and cost burdens of conventional LCA. The method focuses on algorithms that check the significance of going ‘one step further’ in including further process flows in analyzing product options. The method is used in conjunction with Ford for a case study of two material options for a front subframe system of a car. Sullivan [76] detailed an abbreviated LCA method called Modified Life cycle Analysis (MLCA) that Ford developed to reduce, in a ‘technically sound manner,’ a large amount of information on environmental burdens of a product to a few metrics representing its contributions to a set of environmentally relevant categories. Sullivan applied the method to compare SI and CI automobiles.

Life cycle energy analysis is another method that is a subset of the complete LCA method, focusing only on energy requirements over the lifetime of the product. Sullivan [128] and Stodolsky [129] provide examples of this work. Sullivan completed a LC energy analysis of passenger cars, while Stodolsky looked at potential energy savings over the life cycles of vehicles that are aluminum intensive.

### 6.2. Design for environment and LCA

The use of LCA and DFE for designing automobiles with a lower impact on the environment is considered in Refs. [76,130–132]. These authors focused on the need for, and development of, methods and powerful and efficient tools for evaluating environmental impacts. They also stressed that these methods need to be incorporated into the company’s design framework. Finkbeiner detailed the development of life cycle engineering as a tool for design for the environment within Daimler Chrysler with the emphasis on implementing the methods within the product development process.

### 6.3. LCA methods

Field (1994), Hentges [133], Saur [134] and Newell [56] considered specific method issues associated with LCA with an emphasis on automobiles. Field pointed out that while LCA is a promising approach and has been heralded as an ‘environmental panacea, capable of providing engineers, designers, and managers with everything that they need to make environmentally correct decisions’, in practice this is far from the case. Field focused on the difficulty of dealing with conflicting objectives and values within the group of decision makers. Hentges [133] documented some of the key method details of the US Automotive Materials
Partnership (USAMP) LCI analysis of a generic automobile and examines some of the challenges inherent in conducting an LCI of an extremely complex product such as an automobile; data collection and quality, and allocation issues. Saur [134] discussed uncertainties and assumptions in interpreting LCA results and includes a case study of different design options for a body in white considering uncertainty in data quality, error estimates for data quality and sensitivity analysis.

6.4. LCA of vehicle components

Examples of LCA of particular vehicle components include those by Steele and Allen [135] who completed an abridged LCA of BPV batteries. The study compared potential health and environmental impacts of four battery technologies (lead-acid, nickel cadmium, nickel metal hydride, and sodium-sulfur) and focused on the recycling and waste disposal life stages. The study is not a complete LCA as it does not include material extraction or battery manufacturing. Steele concluded that NiMH batteries are the most environmentally benign but that a recycling infrastructure does not exist for these batteries. Other LCI-based studies on vehicle batteries include Refs. [33,108,136,137].

Another example of a LCA focused on a particular auto component is Saur [138] that studied five different fender designs (materials include steel, aluminum, and three injection molded polymer blends) for an average compact class automobile in Germany. Saur evaluated the choices with respect to resource consumption, global climate change considerations, and economics as well as technical performance.

Gibson [139] is an example of a LCI study comparing automotive parts made from various materials to investigate the substitution of lighter alternative materials for conventional materials. Keoleian [140] and Joshi [62,184] considered alternative materials for automotive fuel tanks. Young [141] discussed a framework to apply LCA to materials, to measure the extrinsic environmental properties of the materials.

6.5. Life cycle stage

Studies that focus on a specific vehicle LC stage primarily consider the use stage as it is the most complex for automobiles and it is well documented that it is responsible for the majority of environmental impact. Kirkpatrick [142] found only minor differences in environmental impact for several proposed end of life options.

6.6. Incorporation of cost issues in LCA

If the full social costs were embodied in the price of each good or service, there would be no need for LCA. For example, if the price of coal and steel reflected the environmental and health costs of producing them, producers could choose among materials and fuels on the basis of their price and the desire to lower production costs. In this world, the price of a LDV and the price of fuel would embody social costs and consumers could choose among vehicles and fuel on the basis of price. It is the failure of materials and energy prices to reflect their full social costs that gives rise to the need for LCA. Thus, LCA is an attempt to probe beyond the current prices of materials and fuels to account for their full social costs.

A small number of studies examine the life cycle costs (LCC) of automobiles or their specific components. Lazzarri [143] discussed the inclusion of environmental costs in traditional LCC studies. He considered conventional and environmental costs of thin sheet steel automotive components. Gaines [185] considered LCC of lithium-ion vehicle batteries. The study included material, processing, operating and recycling costs and revenues but did not assess environmental costs. The study found that the most significant contribution to LCC was the battery materials.

The diversity of the above categories and the studies give an indication of the emphasis, time and money spent on life cycle related studies of automobiles, as well as the diversity of the study objectives.

6.7. Life cycle assessment of light-duty vehicle options

This section focuses on LC studies for conventional and alternative fuel/propulsion system options that include the entire vehicle life cycle. The goal of LC studies of LDV options should be to consider all LC stages (Fig. 4) and to provide information on the impacts on human and environmental health of all important burdens resulting from the LC so as to provide complete information for making informed decisions. Practice is far from meeting this goal. Due to the complexity of the fuel/vehicle system and many systems not being produced commercially, variation in fuel and vehicle production, and data availability, even estimating a subset of the material and energy inputs and environmental discharges of each stage of the life cycle is difficult, uncertain, and time consuming. However, despite this pessimistic picture, much progress in LDV LCI has been made in the last decade with the publication of studies of both conventional and alternative vehicle options. These studies provide information about the relative contributions of the various LC stages, importance of particular environmental burdens, attractiveness of alternative fuel or propulsion system options, and provide insights allowing analysts to focus future studies and to improve their cost-effectiveness. Although, it is beyond the scope of this work to evaluate all of these studies, we examine a large set of published studies, discuss their features, results, and overall insights.

We classify published LDV LCI studies into two broad categories for simplification. The first category comprises LCI of conventional vehicle options (gasoline SIPI and
The second category consists of studies that consider alternative fuel/propulsion system options. These may include alternative fueled ICE options or electric vehicles. Data for the former class of studies exists, as these are commercially produced vehicles and fuels, whereas for many of the options in the latter class of studies, technology assumptions have to be made as vehicles are not fully developed or produced commercially. Essentially all of the studies are limited to LCI analysis, impact is only included as far as some studies reporting proxy indicators for impact such as weighting of toxics, GWP or ozone depletion potential. Life cycle impact analysis is hindered by lack of knowledge about physical effects and methods to evaluate these effects. We do not know the impact of climate change or dose–response relationships for many discharges.

LC studies should include the automobile LC stages shown in the simplified diagram, Fig. 4. The major components that comprise the automobile LC are manufacture, use (broken down into fuel cycle, vehicle operation, vehicle service, and fixed costs) and end of life. A brief summary of these stages follows. Usually capital equipment and infrastructure required for production of products are not included in LCA.

Vehicle manufacture consists of acquisition and processing of raw materials that serve as inputs for materials and the energy sources required for the vehicle. A vehicle consists of approximately 20 000 parts and therefore, tabulating the inputs and outputs of just this LC stage is significant. In addition vehicle assembly is included in this life cycle stage. Some analysts separate manufacture into materials production and product manufacture.

The primary environmental concerns associated with the Manufacture LC stage include energy use necessary to produce large amounts of steel, aluminum, plastic and glass for the vehicle. Pollutant emissions arise from the processes and transportation of materials and parts. Painting operations have been the source of large amounts of emissions and transfers. However, with improvements in processes and less toxic alternatives, this impact has been lowered.

Fuel cycle (or well-to-tank (WTT)) includes the components of the fuel LC from recovery or production of the feedstock for each fuel (e.g. crude oil in the case of gasoline or potentially switchgrass in the case of ethanol), transportation of the feedstock, through conversion of the feedstock to the final fuel (e.g. reformulated gasoline or ethanol) and subsequent storage, distribution and delivery of...
the fuel to the vehicle fuel tank (or sometimes to the vehicle refueling station).

Of primary importance for comparing alternative fuel vehicles are energy use and emissions throughout the fuel cycle, including the proportion of the energy coming from fossil fuel sources. Assumptions about feedstock and fuel transportation methods and distances impact results.

Vehicle operation (or tank-to-wheel (TTW)) consists of the energy required to drive the vehicle (calculated based on the lifetime distance traveled, energy in the fuel required, and the efficiency of the vehicle) over its lifetime as well as any exhaust or evaporative emissions (e.g. pollutant emissions, air toxics, GHG) from the vehicle. Vehicle energy use accounts for approximately 80% of total primary energy consumption of the conventional automobile [5]. GHG and criteria pollutant emissions are primary concerns during this LC stage.

Vehicle service comprises maintenance, repair, and collision repair and displays great variability in parts and fluids replaced and replacement prices. Included are resources and energy required to produce replacement parts and fluids, resulting wastes, etc. Variability depends on technical differences among vehicles, owner behavior patterns, environmental aspects, and regional requirements. Additional data-related problems include confidentiality and aggregated data (broken down into only a few service categories). Moreover, published automobile operating costs are usually based on data from a vehicle’s first few years of life, which are usually much less variable than later years. Often this category is not included comprehensively in LCA, although automotive service operations and their suppliers compose a significant portion of the US economy (about $50 billion in 1993). Automotive repair operations generate significant waste. Their suppliers, primarily parts and fluids manufacturers generate major environmental discharges.

No data exists on service for electric vehicles since they are not in large-scale use. There are no published studies on the lifetime of various battery types in BPV or HEV.

Fixed costs include insurance, license fee, depreciation and finance charges. The economic impact of these costs over the vehicle lifetime is much greater than that of the initial vehicle purchase, fuel, or service [5]. However, the impact on the environment of these costs has not usually been included in LCA studies. MacLean [5] and [10], however, do include environmental impact of the insurance required over the vehicle lifetime as a proxy for environmental impact of fixed costs.

End-of-life can be broken down into four functions: transportation of the vehicle to a dismantling facility, dismantling, shredding, and disposal of the shredder residue [76]. Environmental impacts during the end-of-life stage consist of waste generated and energy use during the different processes. The impact depends on materials composition, recycling requirements and the infrastructure in place.

6.8. LCI of conventional automobiles

Initial LCI of automobile studies focused on then-current model year conventional ICE (SIPI) gasoline fueled passenger cars in North America and Europe. The most comprehensive automobile LCI study is the US Automotive Materials Partnership (USAMP) study [144]. This study of a midsize sedan was a 5-year, $2.7 million project of the three North American automobile manufacturers, and the US steel, plastics and aluminum industries [145]. The objective of the study was to develop a set of metrics to benchmark the environmental performance of a generic vehicle, a 1994 Intrepid/Lumina/Taurus. The benchmark would then serve as a basis for comparison for environmental performance estimates of new and future vehicles.

Sullivan [128] and Schweimer [146] were two of the early LCI studies of conventional automobiles; Sullivan focused on energy use while Schweimer reported a broader LCI for a Volkswagen Golf. MacLean [5] was the first LCI of a conventional automobile utilizing the EIO-LCA model [64], examining the economy-wide economic and environmental implications of the life cycle with the exception of end-of-life. A prior study by Lave utilized the EIO-LCA model to examine the automobile manufacture life cycle stage [54]. MacLean [5] examined a 1990 Ford Taurus sedan. Model sectors corresponding to vehicle manufacture (Motor Vehicle and Passenger Car Bodies), the fuel cycle (Petroleum Refining), vehicle use (Automotive Service, Insurance Carriers) were utilized. MacLean [5] compared the results of their analysis of energy consumption with those of Sullivan [128] and Schweimer [146], generally finding that the EIO-LCA method included additional activities compared to the studies based on the SETAC method, therefore resulting in increased energy consumption. All of the studies noted came to the broad conclusion that the use life cycle stage of the automobile has by far the most impact on the environment for energy use, GHG and pollutant emissions, followed by manufacture, then end-of-life. Most studies do not include economic impact, however, MacLean [5] found the same trend for economic impacts.

Few LCI analysts provide comparisons of their results with other studies, and we are aware of only one publication that compares a broad set of LCI primarily of conventional vehicles. Sullivan [147] evaluated and compared eight published LCI, primarily those that consider conventional SI gasoline vehicles, but as well a small number of CI diesel and BPV options. Sullivan confirmed that the vehicle operational stage is dominant for energy use and associated emissions (accounting for 60–80% of total LC energy use) and that materials production is dominant with respect to solid waste generation. Sullivan [147] noted the difficulty of comparing LC studies due to differing boundaries, data quality, and study assumptions. Fig. 5 is reproduced from Sullivan [147] as this figure confirms general knowledge that almost all conventional automobiles designed today have comparable 0–60 mph time (and other performance
parameters) and therefore their fuel economy reported in the figure as variable energy per mile driven (and resulting CO₂ emissions) is proportional to vehicle weight. This does not hold for alternative options such as electric vehicles. Sullivan’s insights for conventional ICE vehicles that vehicle operation, not manufacture, service or end of life from the point of view of energy use and emissions has the most impact, supports the focus of alternative fuel/vehicle studies on the fuel cycle and vehicle use. Another important point that Sullivan makes is that weight dependence on fuel consumption (and related CO₂ emissions) increases as powertrain efficiency decreases. Therefore, a kg of weight saved on a vehicle yields more life cycle energy and CO₂ emissions reduction for an inefficient vehicle than an efficient one. In addition, Lave [10] and MacLean [68] found that for alternative fueled ICE options, vehicle manufacture is not significantly different and has much smaller impact on differences among alternative vehicle options than the operation or the fuel cycle. However, for electric vehicles, large vehicle manufacture (including cost) differences exist from conventional ICE. LCI studies including these vehicles should not ignore these manufacture issues.

6.9. LCI of alternative vehicle options

The choice of fuel and propulsion system for the light-duty fleet is the subject of much debate. Analysts have offered answers based on analyses of the economics of fuel production, emissions of greenhouse gases or criteria pollutants, energy use and efficiency, fuel availability, historical perspectives, vehicle emissions, etc. LCI of alternative fuel/vehicle options have made progress in integrating some of the environmental and sustainability aspects associated with the production and use of alternative options and in providing insights on the promise of options for lessening burdens on the environment. However, as noted above, it is not feasible to complete an entirely comprehensive LCI even for conventional vehicles, so when vehicles or fuels are not yet produced commercially, as with fuel cell cars and biomass ethanol, constructing the life-cycle is even more difficult. In addition, a LCI by itself, does not consider the full range of important issues for alternative vehicle options such as impact on human and ecosystem health, cost, consumer acceptance, safety, fuel supply, infrastructure, and scale issues. These aspects have to be considered in conjunction with the insights of the LCI.

Among LCI studies of alternative fueled vehicles, there is a distinction in the level of detail employed in analyzing the vehicle portions. The primary focus of a larger class of studies has been the fuel cycles (WTT), with vehicle life cycle issues (TTW, manufacture, use, and end-of-life) receiving less attention. More recently, studies have included vehicle issues more comprehensively, paying more attention to vehicle comparability of options considered, potential efficiency and emissions improvements compared to a baseline, etc. along with the fuel portions, therefore providing more balanced LCA of the fuel/vehicle systems (see previous discussion of vehicle comparability in Section 3.8). Primary attention has been focused on vehicle operation/use with few of the alternative fuel LCI including other LC stages in a comprehensive manner.

Aspects of the fuel cycles that analysts have examined in most detail are energy efficiency, total energy consumption, fossil energy consumption, and GHG emitted (CO₂, sometimes including CH₄ and N₂O). We define efficiency (%) as: [(energy in the fuel delivered to consumers/energy inputs to produce and deliver the fuel) \times 100], e.g., 100 MJ of energy input results in 80–87 MJ of gasoline delivered to the consumer, and an associated efficiency of the fuel cycle of 80–87%. Results are most often reported on a per distance of vehicle driving basis (e.g. MJ/km for energy use or kg CO₂/km) or on a fuel energy content basis (e.g. MJ/MJ of fuel produced or kg CO₂/MJ of fuel produced). A few studies include other environmental burdens such as air pollutant emissions, land requirements (for biofuels), solid waste, and some economic data. Infrastructure issues are not generally included.
The aspects of the vehicles receiving most attention are vehicle fuel economy (efficiency), GHG emissions, operational energy use, and vehicle exhaust emissions of regulated pollutants. A number of recent studies assume that all vehicle options are able to meet near term US or European emissions standards (since this is required if they are to be sold), rather than estimating emissions from the various vehicle options.

Some of the earliest LCI models for alternative fuel/propulsion system options were developed by Mark Delucchi at University of California at Davis during the period 1987–1993. Delucchi has continued to update his work [65,148]. Michael Wang of Argonne National Laboratory has produced another LCI model [66]. Both Delucchi and Wang’s models are spreadsheet—based life cycle models that consider a large number of fossil and biofuel/vehicle combinations for LDV [65,66,71,149,175]. Delucchi’s spreadsheet model predicts emissions of GHG and criteria pollutants from a large number of alternative fuel/vehicle options. The model is comprehensive in scope (including fuel cycles, vehicle operation, manufacture, service, etc.) and requires significant input of details such as energy usage for fuel production, emissions factors, etc. Default values are also included. The updating of the work has consisted primarily of improving fuel cycle energy and fuel cycle and vehicle emissions estimates and adding new fuel and vehicle options. Delucchi [150] is the most recent work reporting air pollutant and GHG emissions results of the model for highway vehicles, forklift trucks and household heating in the US. Delucchi’s model has been adapted for Canada as a project for Natural Resources Canada [151] followed by additional adaptation by Levelton Consulting of Vancouver, B.C. [152].

Michael Wang’s work dates back to 1995 and has been updated with additional information, parametric assumptions, fuel, and vehicle options. GREET (Greenhouse gases, Regulated Emissions and Energy Use in Transportation), as Wang’s model is called, estimates energy use (total, fossil, petroleum) and emissions (GHG and criteria pollutants) resulting from the LC of alternative transportation fuels and vehicles but like Delucchi, primarily focuses on the fuel cycle (WTT) aspects. These models have been utilized or are the basis (with some modifications) for many of the other LCI studies [68,70].

Wang [66] provides a good summary and qualitative comparison of a number of alternative fuel studies up to 1999 that focused on the fuel cycles. These include Refs. [65,71,100,149,153–162]. The studies focus on fuels and electricity for vehicle use and vary in their level of detail, number of options considered, geographical location, study assumptions and results. Wang reported that the Delucchi and Acurex studies are the most comprehensive in terms of fuels and technologies. Other studies consider smaller numbers of fuel and vehicle options but may be more comprehensive with respect to particular options than Delucchi and Acurex.

6.10. Evaluation of LCI alternative fuel/propulsion system option LCI studies

We evaluate and compare a number of recent alternatives fuel/vehicle LCI studies. Are methods and results similar? What overall insights regarding vehicles and fuels can be gained? What insights do we get with regard to LCI? We compare the studies qualitatively, and where possible, quantitatively. Due to the complexity of the studies, differences in fuels and vehicles considered, technology assumptions, lack of comparability of vehicles, differences in metrics reported, activities considered, and incomplete reporting of study methods, models and data, meaningful comparisons are difficult. The studies cannot be classified usefully by comparing a small number of metrics; results are dependent on a large number of assumptions regarding the fuel/vehicle systems. However, on a more positive note, important insights are gained from a comparison.

We select a broad set of recent LDV LCA studies that include reasonably comprehensive sets of conventional and alternative vehicle options and that utilize a reasonably balanced approach to treating the fuel/vehicle system. We consider the studies in chronological order as follows: Kreucher [75], IEA [163], Levelton [164], Lave [10] and MacLean [68], MIT [69], Hackney [78], GM/Argonne [70, 178], and Delucchi [150]. These studies focus on fuels and vehicles that have the potential to be commercialized in large volumes within the near term (10–20 years). With a few exceptions (e.g. LPG, BPV), fuels and propulsion systems that appear to be commercially viable only in niche markets were not considered. With the exception of Lave [10], who employed the EIO-LCA model for some aspects of the LCI, all other studies utilized the conventional LCA process model method. In addition to the LCI portion of the studies, Levelton [165], Lave [10] and MIT [69] included some consideration of vehicle affordability. Results for gasoline and diesel from Ref. [165] (Joshi, ADL and Hoehlein) are also presented in Figs. 6 and 7 for comparison purposes. We also include in the comparison, recent studies that examined smaller sets of alternative vehicle options. These studies include Refs. [77,79,104,166]. Hydrogen FCV offer the possibility of being highly efficient ‘zero emission vehicles’. Thus, analysts are eager to investigate this potential through LCI. The last three studies focus on options for FCV, comparing these to conventional vehicles. One of the primary difficulties is that that no FCV (not even those that use liquid HC fuels, reforming them to hydrogen) are being produced on a commercial scale (barely at a prototypical scale) and significant breakthroughs in both fuel and vehicle technology are required before they will be produced. There is very limited data publicly available for fuel cell technologies. LCA of products not yet fully developed for the market are the most difficult, and results of these studies must be analyzed carefully.

Table 4 shows the fuel/vehicle options and fuel feed-stocks considered in the various studies.
6.11. Evaluated LCI studies

The following are short summaries of each of the studies to supplement the entries of Table 5.

Kreucher [75] is a North American focused study (but resulted from a similar study of options for China by the Chinese government and Ford Motor Company [179]). The study is an LCI reporting energy efficiency and emissions of GHG and criteria pollutants. Kreucher also included economic estimates for the vehicles, operation, and fuels. Fuel cycle emission estimates were based on a spreadsheet model by A.D. Little, supplemented with estimates from publicly available information. Vehicle options were modeled with Ford software and based on a Ford Escort gasoline vehicle with 31.5 mpg.

IEA [163] reports the results of a study by the International Energy Agency that compared the alternative fuel systems with a world-wide focus for 1–5 and 15–25 years in the future. Primary emphasis was placed on the fuel cycles, although vehicle operation was included. Energy consumption, GHG and criteria pollutant emissions were reported based on an evaluation of published study results and assumptions about alternative vehicle efficiencies. The baseline vehicle was a gasoline SI car. Results are reported by setting the baseline vehicle equal to 100 and deviations from this baseline for the metrics are presented based on this scale. IEA notes that actual physical units are not directly comparable, therefore, it is not possible to include the quantitative results in our comparison.

Levelton [164] reports the results of a study commissioned by the Transportation Table of the National Climate Change Process for Canada. It investigated the role that alternative and future petroleum fuels could play in reducing GHG emissions from light and heavy-duty vehicles in Canada and the US for the time frames 2000, 2010, and 2020. Included were estimates of GHG and criteria pollutant emissions from fuel production, vehicle operation and manufacture, as well as fuel and vehicle costs. Cost-effectiveness measures for reduction of GHG emissions with the various options were based on the effects of differential prices in fuels and vehicles (excluding taxes). The baseline vehicle was a SI passenger car fueled with 300-ppm sulfur...
Lave [10] and MacLean [68] examined the LC economic and environmental implications of options expected to be available over the next two decades for powering a large proportion of the US light-duty fleet. Lave utilized the EIO-LCA model for vehicle options, supplemented with fuel cycle data from Ref. [66] with adjustments by the authors. Energy use (total and fossil), GHG, and criteria pollutant emissions were reported for the LC. The baseline vehicle was a 1998 Ford Taurus sedan fueled with conventional federal gasoline.

MIT [69] assessed likely technologies for US passenger cars for the year 2020 that could benefit from most economies of scale. The study included energy, GHG, and economic factors over the life cycles of the fuel/vehicle options. Impacts of the technologies on the 'main stakeholder groups'—fuel manufacturers and distributors, vehicle manufacturers and distributors, customers, and governments, were assessed. An important aspect of this study, differentiating it from the others, is the assumption of an 'evolved baseline' gasoline ICE vehicle for the year 2020. This baseline was modeled from a 1996 vehicle similar to a Toyota Camry but has substantial evolutionary improvements in fuel economy (43.2 mpg) and GHG emissions (about 1/3) and vehicle weight reduction (vehicle weight is 1236 kg) compared to the baseline, assumed at 5% additional cost. The efficiency improvements result from assumed advances in the efficiency of the engine and transmission, and in the areas of drag and rolling resistance, as well as the use of lightweight materials. The vehicle was fueled with low sulfur gasoline. The vehicle modeling was based on updated versions of Matlab Simulink programs originally developed at ETH, Zurich [167] and the fuel cycles based on published data. Fuel and vehicle economic issues were included in the study.

Hackney [78] developed and presented a LC spreadsheet model for comparing criteria pollutant, GHG emissions, energy use and cost of alternative fuel/vehicle options. The data sources for the spreadsheet included ADL [168], and extensions by Hackney [186] based on Delucchi [187] and Wang [159] along with others noted. The focus of the study was model development but reference values from published studies were given so the publication does include results and insights for the various options. The time frame was not specifically defined, but was characterized as 'near term'. The baseline vehicle was a gasoline SI subcompact passenger car with a fuel economy of 30 mpg. Results of the study are presented graphically and therefore cannot be translated into numerical values for quantitative comparison with the other studies.

GM/Argonne [70] combined the fuel cycle model of Argonne National Laboratory with modeling of vehicle options using proprietary GM software, therefore achieving a more balanced treatment of fuel and vehicle than most studies. The overall assessment of the vehicle options was based on their potential for improving fuel economy and lower GHG emissions while maintaining the vehicle performance demanded by North American consumers. The study time frame was 2005–2010 and the baseline vehicle a 2000 Chevrolet Silverado full size pickup truck using low sulfur gasoline, having a fuel economy of 20.2 mpg.

<table>
<thead>
<tr>
<th>Fuel feedstock</th>
<th>Gasoline</th>
<th>Diesel</th>
<th>LPG</th>
<th>CNG</th>
<th>Methanol</th>
<th>Ethanol</th>
<th>Electricity</th>
<th>GH2/LH2</th>
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</thead>
<tbody>
<tr>
<td>Petroleum</td>
<td>1SF, 2S, 3SH, 4SDFH, 5SHF, 7SFH, 8SF, 9S, 10SF, 11F, 12F, 13SF, 14SHF</td>
<td>1CF, 2C, 3CH, 4C, 5CH, 7CH, 8C</td>
<td>1S, 2S, 3S, 5SF, 7CH, 8S</td>
<td>8SF</td>
<td>1SF, 2SCF, 3SF, 5F, 7F, 8SF, 10F, 11F, 12F, 13F</td>
<td>8B</td>
<td>3F, 5F, 7F, 8SF, 9F, 10F, 11F, 12F, 13F</td>
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</tr>
<tr>
<td>Coal</td>
<td>5CH, 8C, 13F</td>
<td>8S</td>
<td>1S, 2S, 3S, 4SD, 5SH, 7S, 8S, 9S</td>
<td>8SF</td>
<td>1SF, 2SCF, 3SF, 5F, 7F, 8SF, 10F, 11F, 12F, 13F</td>
<td>8B</td>
<td>3F, 5F, 7F, 8SF, 9F, 10F, 11F, 12F, 13F</td>
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</tr>
<tr>
<td>NG</td>
<td>1SF, 2SF, 3SF, 5SF, 7SFH, 8SF</td>
<td>1SF, 2SCF</td>
<td>1S, 2SC, 3S, 8S</td>
<td>8SF</td>
<td>1SF, 2SCF, 3SF, 5F, 7F, 8SF, 10F, 11F, 12F, 13F</td>
<td>8B</td>
<td>3F, 5F, 7F, 8SF, 9F, 10F, 11F, 12F, 13F</td>
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<tr>
<td>Food crops</td>
<td>2C, 8C</td>
<td>2SCF</td>
<td>1S, 2SC, 3S, 4S, 7SFH, 8SF</td>
<td>8SF</td>
<td>1SF, 2SCF, 3SF, 5F, 7F, 8SF, 10F, 11F, 12F, 13F</td>
<td>8B</td>
<td>3F, 5F, 7F, 8SF, 9F, 10F, 11F, 12F, 13F</td>
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</tr>
</tbody>
</table>

Number indicates study number. 1: Ref. [150], 2: Ref. [70], 3: Ref. [78], 4: Ref. [163], 5: Ref. [75], 6: Ref. [10], 7: Ref. [152], 8: Ref. [69], 9: FEA (1999), 10: Ref. [173], 11: Ref. [166], 12: Ref. [104], 13: Ref. [79], 14: Ref. [77]. S: spark ignition port injection engine, D: spark ignition direct injection engine, C: compression ignition direct injection engine, H: hybrid electric (internal combustion engine and electric motor), F: fuel cell, B: battery-powered.
Table 5
Fuel/vehicle life cycle study summary table

<table>
<thead>
<tr>
<th>Reference</th>
<th>Location, time frame</th>
<th>Baseline vehicle</th>
<th>Vehicle modeling</th>
<th>Fuel cycle modeling</th>
<th>Life cycle stages included</th>
<th>Energy use/efficiency</th>
<th>GHG&lt;sup&gt;3&lt;/sup&gt;</th>
<th>Air pollutants&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Econ.&lt;sup&gt;2&lt;/sup&gt;</th>
<th>Uncert. sens.&lt;sup&gt;2&lt;/sup&gt;</th>
<th>Compare results&lt;sup&gt;1&lt;/sup&gt;</th>
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<td>[163] IEA countries</td>
<td>Current gasoline ICE car</td>
<td>Published data</td>
<td>Published data</td>
<td>F, O</td>
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<td></td>
<td></td>
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<td></td>
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<td>Not incl.</td>
</tr>
<tr>
<td>[77] US near term</td>
<td>1997 Taurus, gasoline ICE 23.2 mpg</td>
<td>Own model based on pub. studies</td>
<td>Own model based on own model</td>
<td>F, O</td>
<td>Incl.</td>
<td>Not incl.</td>
<td></td>
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</table>

Table includes life cycle studies of alternative fuel/propulsion system options. Fuels and vehicle types included in the studies are reported in Table 4.

- **Study designation/reference.**
- **Geographical area(s) and time frame(s) considered in study.**
- **Baseline vehicle and fuel with which fuel/vehicle options are compared, fuel economy also reported where available.** ICE: internal combustion engine, RFG: reformulated gasoline, S: sulfur.
- **Modeling/data source for vehicles.**
- **Modeling/data source for fuel cycles.**
- **Life cycle stages included; F: fuel cycle, O: vehicle operation/driving, M: vehicle manufacture, S: service, F: fixed costs, E: end-of-life.**
- **Whether energy use is reported in the study.**
- **Whether greenhouse gas emissions are reported in the study.**
- **Whether criteria and/or toxic pollutant emissions are reported in the study.**
- **Whether economic data are reported in the study.**
- **Whether the study includes any uncertainty or sensitivity analyses.**
- **Whether the study includes any comparisons of results with other studies.**
Delucchi [150] presented LCI results for the US for years 2000 and 2020 (with a focus on fuel cycle and vehicle operation) of GHG emissions and urban pollutants from a range of alternative fuel and feedstock combinations for LDV. The baseline vehicle was a current gasoline SI ICE passenger car with a fuel economy of 25 mpg. Delucchi utilized his own model for the work. Delucchi included a broader set of GHG than other studies, including not only CO₂, CH₄ and N₂O but also chlorofluorocarbons and hydrofluorocarbons. Delucchi does not include energy use in this work but provided these results from his model to the authors.

Brekken [77] compared the efficiency (GHG emissions are not included) of the fuel cycles and vehicle operation of a small set of near term light-duty options for the US. Fuel cycle efficiencies were taken from published literature and Brekken models the vehicles based on required power to weight ratio, vehicle range, and base weight. The baseline vehicle was a 1997 Ford Taurus SI with 23.2 mpg fuel economy running on conventional gasoline.

Ogden [104] focused on FCV and fuel infrastructure design. Fuel cell, PNGV type, midsize automobiles with reduced weight, rolling resistance and aerodynamic drag fueled with hydrogen, methanol, and gasoline were modeled and analyzed. In most cases the vehicles were fuel cell HEV. Ogden developed a computer simulation model for the vehicles (including onboard fuel processors) to calculate vehicle performance, fuel economy and cost for the various options. Unlike the majority of other studies, Ogden developed capital cost estimates for refueling infrastructure development for the fuel options. Although Ogden’s study is not a LCI, we include it since it has a comparable portion and the study offers insights into the attractiveness of FCV options.

Methanex [166] assessed emissions of GHG from FCVs for both Canada and the US, comparing them with those from a gasoline ICE vehicle. The study modeled ‘best technology expected to be commercially available’ in the year 2010 for both the fuel cell and conventional vehicle options. The SI ICE ran on 30 ppm sulfur gasoline. The vehicles are modeled based on Directed Technologies Inc. model [169] and fuel cycles are based on the Canadian version of the Delucchi model with refinement.

Pembina [79], a study by the Pembina Institute for Appropriate Development of Alberta, Canada, compared five ‘near term fuel supply opportunities’ for FCV systems with a Mercedes Benz A-Class ICE (7.3 l/100 km) using California Phase II RFG. Options included onboard RFG and methanol fuel processing, centralized and decentralized NG reforming, and decentralized electrolysis. Only GHG emissions were considered in the study, and unlike the other studies, the functional unit for this study was 1000 km traveled by the vehicle. The study used the LCI approach but does not include vehicle manufacture. Pembina used their own model, Pembina LCVA, to model the vehicles and ‘best available public domain data sets’ for the fuels.

Six of the studies included some cost estimates associated with vehicles and fuels (Hackney, Kreucher, Lave, Levelton, MIT, and Ogden) and four of the studies included limited uncertainty or sensitivity analysis (GM, Hackney, MIT, and Brekken).

6.12. Comparison of LCI studies

All of the above studies are most detailed in the information they provide on the WTW energy use/efficiency and GHG emissions. A number of the studies include vehicle manufacture and a small number include other aspects of the LC (e.g. service, end-of-life). Although the vast majority of energy use, GHG and criteria pollutant emissions result from vehicle operation, and secondarily from the WTT portion of the LC for ICE vehicles, this is not as clearly the case for electric vehicles. In addition, environmental burdens other than those cited above may be important for decision makers, e.g. solid waste generation, fossil fuel and other resource consumption. Therefore, although we focus our comparison on fuel cycle (WTT) and vehicle operation (TTW) aspects, we do not imply that the other LC components should be given less attention. However, at this time, little detail is available for the other LC stages for vehicles other than ICE.

For our quantitative portion of the comparison, due to data availability, we only consider the WTT and TTW components of the LCIs. Figs. 6–8 and Table 6 (Section 6.12.1) report the study results for the WTT portion for the various fuels. Figs. 19–24 and Table 7 (Section 6.12.2) report the study results for the well-to-wheel—WTW (the sum of the WTT and the TTW portions) portion for the fuel propulsion systems considered. We first consider the WTT portion and examine the results for the various studies.

6.12.1. Fuel cycles (well-to-tank—WTT)

Although analyzing the results of the various fuel cycles is more straightforward than analyzing the results of vehicle operation (due to the lack of comparability of vehicles and their complexity), comparability aspects complicate the fuels analyses as well. Insights gained from isolating any component of the LC must be evaluated only when taking into consideration the entire LC, systems approach. No single metric can adequately describe the WTT aspects of any fuel. For example, assumptions regarding production and level of sulfur in gasoline or diesel, feedstock source assumptions and percentage of fossil fuel assumed used to produce ethanol, hydrogen fuel production pathways, electricity generation mixes all significantly impact fuel cycle results. All of these issues make it necessary to carefully evaluate the WTT and a variety of metrics important to the decision maker before coming to conclusions about the attractiveness of a fuel. The aspect that makes comparing the fuels (WTT portion) more straightforward than the TTW portion, is that we know that 1 MJ of hydrogen produced by electrolysis is equivalent to 1 MJ of hydrogen produced from natural gas as far as propelling the vehicle a certain distance.
The majority of the studies only report quantitatively, efficiency (or energy use) and GHG emissions. This limits the scope of our quantitative comparisons to these two metrics. Where efficiency as a proportion is not reported, we calculate it from the number of MJ of fuel delivered to consumer divided by the number of MJ of process energy input. GHG are usually reported in the studies in grams CO\(_2\) equivalent/MJ or MMBtu of fuel with CO\(_2\), CH\(_4\), and N\(_2\)O considered and weighted by their GWP. However, there are a few exceptions where only CO\(_2\) is considered, where additional GHG are included, or where the GWP are slightly different than the usual 100-year International Panel on Climate Change (IPCC) values of 21 for CH\(_4\) and 310 for N\(_2\)O [150]. We have adjusted results where possible to provide a consistent comparison. Table 6 provides an overall summary of the ranges of the efficiencies and GHG emissions for the WTT portions for the fuels reported in the LC studies. The values in the table are taken from Figs. 6–18 discussed in this section.

Overall, a portion of the similarity in results for many of the fuels occurs because several of the studies take results from the models of Wang and Delucchi (e.g. Lave [10]/MacLean [68] and GM/Argonne [70] use Wang with some modifications, Levelton [164] uses Delucchi with modifications to make the analysis applicable to Canada).

For conventional petroleum-based fuels, fuel cycle pathways are reasonably straightforward, while fuels like hydrogen and ethanol have many alternative fuel cycle options (different feedstocks, processes, distributions, etc.), resulting in much less variation in results among options for the former fuels. We must keep in mind when interpreting the following fuel cycle results that a MJ of gasoline is not equivalent to a MJ of hydrogen for use in a vehicle due to the different efficiencies of the vehicle powerplants.

All of the studies use gasoline from petroleum feedstock as the baseline fuel. However, the fuel characteristics, whether it is low sulfur, reformulated, has an oxygenate, etc. differ among the studies examined. While the majority of studies are for the US, several are for other geographical areas which contributes to differences in the results. Even with all of these differentiating factors, the results for the gasoline fuel cycles efficiencies all range between 80 and 87% (mean = 83), with one exception at 94% [104] (Fig. 6).

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**Fig. 8.** CNG fuel cycle (well-to-tank) efficiencies reported in life cycle studies. GM NANG = North American natural gas [70], MIT = MIT [69], Kreucher = Kreucher [75], MacLean = MacLean [68], Brekken = Brekken [77], GM NNA NG = non North American natural gas [70], IEA = IEA [163], Delucchi = Delucchi [150].

**Fig. 9.** Methanol fuel cycle (well-to-tank) efficiencies reported in life cycle studies. GM NA, NG = source of methanol is North American natural gas [70], GN NNA NG = source is non North American natural gas [70], MIT NG = source is natural gas [69], Ogden = source not specified [104], Kreucher NG = source is natural gas [75], IEA NG = source is natural gas [163], Delucchi NG = source is natural gas [150], IEA cellulosic = source is cellulosic feedstocks [163].
Whether the efficiency is 80 or 87 does not impact the overall attractiveness of gasoline significantly. There is not sufficient detail in Ogden to provide a definitive answer regarding the source of the difference in Ogden’s estimate. However, Ogden assumes that the conversion of petroleum in the refinery to gasoline is 95% and that the truck delivery energy is 1% of total energy required as being inputs into the statement that ‘for 100 units of primary energy input, 94 units of gasoline energy are delivered to the vehicle’ [104, p. 152]. The higher value results in part from assuming a higher refining efficiency than the other studies. For example, MIT [69] assumes a value of 86.6% for refining efficiency. However, this value appears to be on the low side due to the MIT assumption of additional energy use for producing very low sulfur gasoline.

Results for GHG emissions for gasoline (Fig. 13) range from 15 g CO₂/MJ of fuel for Kreucher (only considering CO₂) to over 25 g CO₂ equiv/MJ for Methanex’s no sulfur gasoline. As expected, within a particular study an increase in GHG emissions is associated with a decrease in sulfur content of the fuel due to the additional energy required for removing sulfur. Sources of differences result from GHG emissions considered (whether just CO₂, or whether CH₄ or N₂O or others are considered) and geographical location. (Canadian emissions are generally slightly higher than those for the US.)

The efficiencies for the diesel fuel cycles shown in Fig. 7 range from 83 to 90 (mean = 88). The efficiency of diesel production is slightly higher than that of gasoline, and this is shown in the studies examined here. The variation in the

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Fig. 10. Hydrogen fuel cycle (well-to-tank) efficiencies reported in life cycle studies. GM Central GH2 NA NG = GM centralized gaseous hydrogen from North American natural gas; GM Station GH2 NA NG = station gaseous hydrogen from North American natural gas; GM Station GH2 NNA NG = station gaseous hydrogen from non North American natural gas; GM Station GH2 US Mix = station gaseous hydrogen from US electricity generation mix; GM Station GH2 NA NG CC = station gaseous hydrogen from North American natural gas combined cycle; GM Central LH2 NA NG = centralized liquid hydrogen from North American natural gas; GM Central LH2 NNA NG = centralized liquid hydrogen from non North American natural gas; GM Stn LH2 NA NG = station liquid hydrogen from North American natural gas; GM Stn LH2 NNA NG = station liquid hydrogen from non North American natural gas; GM Stn LH2 US Mix = station liquid hydrogen from US electricity generation mix; GM Stn LH2 NA NG CC = station liquid hydrogen from North American natural gas combined cycle; MIT CompH syn fr NG dec fuel = MIT compressed hydrogen synthesis from natural gas decentralized reforming [69]; Brekken = Brekken [77]; Ogden H, NG steam ref. = gaseous hydrogen from natural gas steam reforming [104]; IEA H, electrolysis = gaseous hydrogen from electrolysis [163]; Delucchi GH2 NG = gaseous hydrogen from natural gas [150].

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Fig. 11. Electricity generation (well-to-tank) efficiencies reported in life cycle studies. GM US mix = source is average US electricity generation mix [70], GM NA NG CC = North American natural gas combined cycle plants, MIT national grid = average US electricity generation mix [69], Kreucher US = average US electricity generation mix [75], Kreucher world = average world electricity generation mix, Kreucher W. Europe = average Western Europe electricity generation mix, Kreucher CA = California generation mix.
results is expected to result from differences in geographical conditions, specific fuel production pathways, fuel composition, etc. Differences in sulfur content are expected to be a primary differentiating factor, with the increase in process energy required to lower the fuel sulfur level. Diesel fuel WTT GHG emissions are shown in Fig. 14 and range from a low of 7 g CO₂/MJ for Kreucher to 18 g CO₂/MJ for MacLean [68] and GM future diesel. Both these studies assume very low sulfur fuel. Consuming many MJ of fuel with higher CO₂ emissions could have a significant impact.

Results for CNG are shown in Fig. 8. This is another fuel with a known pathway, with efficiencies ranging only from 83 to 91%, except for two outliers, GMs result for non-North American production at 77% and the IEA estimate of 96%. IEA provides large ranges of values for each of the fuel cycle stages (e.g. 30–90 MJ/GJ for fuel distribution). Although the median estimate is 96%, values reported in other studies fit within the ranges given. GHG emissions are reported in Fig. 15 and fall between 10 g CO₂/MJ for Kreucher and 27 g CO₂ equivalent for the GM non-North American option. Since
Kreucher has not included methane in the calculation and combustion of CNG releases substantial amounts of methane, this significantly impacts the results.

Fuel production efficiency estimates for F–T diesel were included in two studies, GM and MIT. GM’s estimate of 59% is somewhat more optimistic than MIT’s 52%. However, the much lower efficiency of these fuel cycles compared to those of conventional diesel should be noted.

Methanol was included in five studies, with natural gas as the feedstock. All results were in the range of 56–66% efficiency as shown in Fig. 9. IEA [163] also reports a result for cellulosic feedstock (58%).

The GM/Argonne study considers the largest range of options for production of both gaseous (six options) and liquid (six options) hydrogen. The options include those from NG both in North America and outside North America, from electrolysis, and central vs. station options. The efficiencies for the hydrogen fuel cycles are shown in Fig. 10. Overall, as expected, the efficiencies for the gaseous options are higher than those of the liquid options. The central and station North American NG options have the highest efficiencies, 57 and 56%, respectively.

However, these efficiencies are much lower than those of conventional petroleum-based fuels. The lowest efficiency option is the liquid hydrogen from electrolysis, US mix at 23%. This low efficiency results from compounding the low efficiency of electricity generation with the additional energy requirements of producing the hydrogen from the electricity as noted earlier. MIT analyzes gaseous hydrogen produced from NG decentralized refueling resulting in an estimate of 56%. Brekken assumes gaseous hydrogen through NG reforming in an industrial plant and is more optimistic at 65%; Ogden also assumes NG steam reforming with an estimate of 76%. Delucchi [150] reports hydrogen from natural gas at 44% efficiency. IEA assumes production by electrolysis with a 31% efficiency. GHG emissions from the hydrogen options vary greatly (Fig. 16). Hydrogen produced using electrolysis and the US mix have the highest emissions (265–332 g CO₂/MJ fuel produced) while the Canadian studies [164,166] and Delucchi options from NG have the lowest estimates at about 85 g CO₂/MJ fuel. Levelton [164] option of producing hydrogen using 100% hydroelectricity has lowest overall emissions as would be expected. As is
evident, the pathway assumed for the hydrogen has a significant impact on the results.

Electricity generation has a low efficiency compared to conventional petroleum fuels production; GM, MIT and Kreucher all estimate the efficiency of the US mix with results of 42, 32, and 29%, respectively (Fig. 11). The highest estimate is given by GM at 48% for North American NG combined cycle. Emissions of GHG from electricity generation are shown in Fig. 17. They are highly dependent on the feedstock assumed, with the majority of conventional grids resulting in considerable emissions (ranging from Kreucher’s estimate for Western Europe of 127 to MITs national US grid estimate of 198 g CO₂ equivalent/MJ of electricity).

![Greenhouse Gas Emissions - Hydrogen (Well-to-Tank)](image)

**Fig. 16.** Hydrogen fuel cycle (well-to-tank) greenhouse gas emissions reported in life cycle studies. GM Central GH2 NA NG-centralized gaseous hydrogen from North American natural gas [70]; GM Central GH2 NNA NG = centralized gaseous hydrogen from non North American natural gas; GM Station GH2 NA NG = station gaseous hydrogen from North American natural gas; GM Station GH2 US Mix = station gaseous hydrogen from US electricity generation mix; GM Station GH2 NA NG CC = station gaseous hydrogen from North American natural gas combined cycle; GM Central LH2 NA NG = centralized liquid hydrogen from North American natural gas; GM Central LH NNA NG = centralized liquid hydrogen from non North American natural gas; GM Sin LH2 NA NG = station liquid hydrogen from North American natural gas; GM Sin LH2 US Mix = station liquid hydrogen from US electricity generation mix; GM STN LH2 NA NG CC = station liquid hydrogen from North American natural gas combined cycle; MIT CompH syn fr NG de… = hydrogen synthesis from natural gas decentralized reforming [69]; Methanex CH2 NG = gaseous hydrogen from natural gas [166]; Methanex LH2 NG = liquid hydrogen from natural gas; Levelon CH2 NG = gaseous hydrogen from natural gas [164]; Levelon CH2 water = gaseous hydrogen from water; Delucchi 2000 CH2 NG = year 2000, gaseous hydrogen from natural gas; Delucchi 2020 CH2NG = year 2020, gaseous hydrogen from natural gas.

![Greenhouse Gas Emissions - Electricity (Well-to-Tank)](image)

**Fig. 17.** Electricity fuel cycle (well-to-tank) greenhouse gas emissions reported in life cycle studies. GM US mix = source is average US electricity generation mix [70], GM NANG CC = North American natural gas combined cycle plants, MIT nat’l grid = average US electricity generation mix [69], Kreucher US mix = average US electricity generation mix [75], Kreucher world = average world electricity generation mix, Kreucher W. Europe = average Western Europe electricity generation mix, Kreucher CA = California generation mix.
Ethanol results are highly dependent on the fuel pathway and assumptions employed (e.g. whether electricity credits given, use of lignin for heat in the process). Since only 2% of commercial production of ethanol in the US has been from biomass sources other than corn, assumptions and results for the other pathways are more uncertain. Fig. 12 shows the WTT efficiency taking into account total energy. We report, where possible, results for both total energy use efficiency and also efficiency only including fossil fuel use (Table 6). As expected, the attractiveness of lignocellulosic ethanol improves significantly from an efficiency point of view when just fossil fuel inputs are considered (due to the potential of using lignin for process energy). In contrast, corn results do not improve when only fossil fuels are considered since corn does not have the lignin energy source of the cellulosic feedstocks and the use of corn stover which could provide some process energy is not assumed in the studies. Ethanol has the potential to be produced ‘sustainably’ (defined here as no fossil fuel in the ethanol fuel cycle, e.g. ethanol to fuel tractors), however, today’s production does not follow this route. With total energy considered, the corn cycles are more efficient than the lignocellulosics (on the order of 65 vs. 40%) but the situation reverses with fossil energy only considered (65 vs. 90%).

Fig. 18. Ethanol fuel cycle (well-to-tank) greenhouse gas emissions reported in life cycle studies. GM corn = ethanol feedstock is corn [70]; GM woody = feedstock is woody biomass; GM herb = feedstock is herbaceous biomass; Lave Corn = feedstock is corn [10]; Lave Herb.credit = feedstock is herbaceous biomass, includes electricity credit; Lave herb no credit = feedstock is herbaceous biomass, does not include electricity credit; Lave woody credit = feedstock is woody biomass, includes electricity credit; Lave woody no credit = feedstock is woody biomass, does not include electricity credit; Kreucher corn = feedstock is corn [75]; Kreucher cell.biomass = feedstock is cellulosic biomass; Levelton 2010, agr res = year 2010, feedstock is agricultural residues [164]; Levelton 2010,corn = year 2010, feedstock is corn; Delucchi 2000 corn = year 2000, feedstock is corn [150]; Delucchi 2000 cell. = year 2000, feedstock is cellulosic biomass; Delucchi 2020 corn = year 2020, feedstock is corn; Delucchi 2020 cell. = year 2020, feedstock is cellulosic biomass.

Table 6
Comparison of life cycle inventory studies: well-to-tank efficiencies and greenhouse gas emissions

<table>
<thead>
<tr>
<th>Fuel/source (if applicable)</th>
<th>Efficiency (%), range</th>
<th>Greenhouse gas emissions (g CO₂ equiv./MJ fuel), range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>80–87</td>
<td>15–26</td>
</tr>
<tr>
<td>Diesel</td>
<td>83–90</td>
<td>12–18</td>
</tr>
<tr>
<td>FT-diesel</td>
<td>52–59</td>
<td></td>
</tr>
<tr>
<td>CNG</td>
<td>83–91</td>
<td>10–27</td>
</tr>
<tr>
<td>Methanol</td>
<td>57–66</td>
<td>22–41</td>
</tr>
<tr>
<td>Ethanol (corn): total energy</td>
<td>45–67</td>
<td>−19 to +90</td>
</tr>
<tr>
<td>Ethanol (corn): fossil energy</td>
<td>60–67</td>
<td></td>
</tr>
<tr>
<td>Ethanol (lignocell.): total energy</td>
<td>26–56</td>
<td>−85 to +14</td>
</tr>
<tr>
<td>Ethanol (lignocell.): fossil</td>
<td>83–96</td>
<td></td>
</tr>
<tr>
<td>Hydrogen (various sources)</td>
<td>23–76</td>
<td>76–332</td>
</tr>
<tr>
<td>Electricity (various sources)</td>
<td>29–48</td>
<td>127–198</td>
</tr>
</tbody>
</table>

Table does not include outliers. Efficiency (%) is defined as: ((energy in the fuel delivered to consumers/energy inputs to produce and deliver the fuel) × 100), e.g. 100 MJ of energy input results in 80–87 MJ of gasoline delivered to the consumer.
combustion of the fuel in the vehicles. Results for GHG emissions from the WTT portions of the studies (Fig. 18) vary greatly from large negative amounts (resulting from carbon sequestration during feedstock growth) in the GM work, particularly for the woody biomass option to large positive values (releases of GHG emissions from corn ethanol production) for Delucchi. Since the corn ethanol production utilizes large amounts of fossil fuels in its production and in associated fertilizer production (offsetting any carbon sequestration benefits), these results are not unexpected.

Overall, the variation in GHG emissions from the various ethanol studies results from several sources; the assumed feedstock, the amount of fossil fuels used in the fuel production (which generate CO₂), consideration or exclusion of N₂O since there are significant amounts resulting from fertilizer use essential to producing the fuel (more fertilizer is required for corn than for lignocellulosic feedstocks), assumptions about land use and carbon sequestration, year of study (assumed technological changes, particularly larger amounts of lignin used in cellulosic ethanol production offsetting fossil fuel use), and whether a credit is given for selling excess electricity to the grid and therefore offsetting CO₂ emissions from conventional electricity generation.

Table 6 summarizes the ranges reported in the LC studies for the WTT efficiencies and GHG emissions for each of the fuels. The efficiencies are highest for the fossil fuels: gasoline, diesel and CNG. In addition, due to their known and set production pathways, the ranges reported for these fuels are much smaller than those of the other fuels. All of the fossil fuel production results in significant GHG emissions. When only fossil energy is considered the lignocellulosic ethanol WTT portion is highly efficient and has the potential for low GHG emissions. Hydrogen results, both for efficiency and GHG emissions, vary greatly from moderate to low efficiency and moderate to very high GHG emissions. Electricity generation using current generation mixes for the US and Canada has a low efficiency and high GHG emissions.
6.12.2. Fuel cycles and vehicle operation (well-to-wheel, WTW)

As mentioned above, comparing LC results for vehicle options is difficult. The lack of comparability of vehicles considered severely limits meaningful quantitative comparisons even for the basic metrics of energy use and GHG emissions that are reported in the majority of studies. We limit our WTW quantitative comparison to that of the GHG emissions reported in the studies since many studies do not report WTW efficiencies. These estimates include emissions resulting from the WTT and TTW components of the LC.

When evaluating overall efficiency of fuel/vehicle systems, it is necessary to consider both the efficiency of fuel production and the efficiency of vehicle operation. With conventional vehicles, the high efficiencies of the petroleum fuel cycles are generally combined with the relatively low efficiencies of ICE vehicles (on the order of 20% for gasoline). For the FCVs, the opposite is true. A low efficiency fuel cycle is combined with a higher efficiency powerplant. However, the hydrogen production efficiencies may be low enough to offset the high efficiencies of FCVs. Table 7 (range values taken from Figs. 19–24) provides an overall summary of the ranges for the WTW GHG emissions for the fuel/propulsion systems examined in the studies.

Fig. 19 reports the WTW GHG emissions from gasoline fueled SIPI vehicles. GHG emissions from the WTW of current gasoline SIPI ICE sedans are on the order of 250–300 g CO₂ equiv./km. The full range goes from just under 150 to almost 350 g CO₂ equiv./km. For gasoline, the largest portion of the GHG emissions is CO₂ that is emitted in proportion to the amount of fuel used and is related to vehicle weight. Therefore, results for the GM study showing higher GHG emissions from the full size pickup truck and for the MIT study showing much lower emissions from the ‘evolved’ (lighter with higher fuel economy sedan) vehicles are as expected. Additionally, we remind the reader that the results of the GM/Argonne analysis for all of the fuels, due to their choice of a full size pickup truck, a less fuel efficient vehicle than the ‘sedans’ evaluated in the other studies, makes this study particularly difficult to compare with the other studies. Small increases in GHG emissions for the lower sulfur content gasolines are reported by Lave and Levelton.

Trends for diesel vehicle emissions are similar to those of the results for gasoline vehicles above (Fig. 20). Due to the combined higher WTT efficiency of the diesel fuel cycle and higher TTW efficiency of the CIDI vehicles (and the only slightly higher carbon content of the diesel fuel), the diesel options result in lower WTW GHG emissions (about 23% reduction for Levelton low sulfur options). Only one result is given for F–T diesel [69], reporting slightly higher GHG emissions than the low sulfur petroleum-based diesel.
For HEV fueled with gasoline and diesel, GHG reductions depend on the assumed increase in fuel economy for these options compared to the baseline vehicle (Figs. 21 and 22). Diesel HEV have the potential of high efficiency (low GHG emissions) since they combine the advantages of the high powerplant efficiency of the diesel engine and the improvement in efficiency possible with a HEV configuration.

Of the FCV options, the LC studies include vehicles that use hydrogen directly and those that reform methanol or gasoline to hydrogen onboard the vehicle and then use the hydrogen in the FC. Fig. 24 shows the WTW GHG emissions for the hydrogen, methanol and gasoline FCVs. The direct hydrogen options have the potential both for the largest reductions and largest increases in GHG emissions. This results from the variation in the WTT results and the

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Fig. 23. Ethanol spark ignition vehicle well-to-wheel greenhouse gas emissions reported in life cycle studies. GM E85 cell. = E85 (85% ethanol, 15% gasoline), ethanol from cellulosic feedstock [70]; Lave E100 SIDI cell = E100 (100% ethanol) in spark ignition direct injection engine, ethanol from herbaceous cellulosic feedstock (with electricity credit) [10]; Lave E100 SIDI cell = as above except with no electricity credit; Lave E100 SIDI cell = as above except from woody feedstock with electricity credit; Levelton E100 SIDI cell = as above except without electricity credit; Levelton E85 corn = E85 from corn feedstock [164]; Levelton E85 cell. = E85 from cellulosic feedstock.

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Fig. 24. Fuel cycle vehicles well-to-wheel greenhouse gas emissions reported in life cycle studies. GM HEV = Silverado pickup fuel cell hybrid electric [70], MIT HEV = fuel cell hybrid electric sedan [69], Methanex = fuel cell sedan [166], Pembina = fuel cell Mercedes A-class [79], Lave HEV = fuel cell hybrid electric sedan [10], Levelton = fuel cell sedan [164], Methanex CH2 = automobile fuelled with gaseous hydrogen from natural gas [166], Methanex LH2 = automobile fuelled with liquid hydrogen from natural gas, Methanex CH2elect = automobile fuelled with gaseous hydrogen from electrolysis, Pembina Ngref. = Mercedes A-class equivalent fuelled with gaseous hydrogen from natural gas reforming (centralized) [79], Pembina Ngref.dec = Mercedes A-class equivalent fuelled with gaseous hydrogen from natural gas reforming (decentralized), Pembina dec.el = Mercedes A-class equivalent fuelled with gaseous hydrogen from electrolysis (centralized), Levelton H NG = fuel cell automobile fuelled with gaseous hydrogen from natural gas [164], Levelton H elect = automobile fuelled with gaseous hydrogen from electrolysis, average electricity generation mix, Levelton H elect hydro = automobile fuelled with gaseous hydrogen from electrolysis, 100% hydro power.
Table 7
Comparison of life cycle inventory studies: well-to-wheel greenhouse gas emissions

<table>
<thead>
<tr>
<th>Fuel/propulsion system</th>
<th>Greenhouse gas emissions (g CO₂ equiv./km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline SIPI(^a)</td>
<td>248–333 (342,157) (^b)</td>
</tr>
<tr>
<td>Diesel CIDI(^d)</td>
<td>211–231 (298,120)</td>
</tr>
<tr>
<td>Gasoline HEV(^d)</td>
<td>169–176 (286,94)</td>
</tr>
<tr>
<td>Diesel HEV(^e)</td>
<td>152 (242,81)</td>
</tr>
<tr>
<td>Ethanol SIPI: lignocell.(^f)</td>
<td>4–161 (112)</td>
</tr>
<tr>
<td>Gasoline fuel cell</td>
<td>133–201 (224,161)</td>
</tr>
<tr>
<td>Methanol fuel cell</td>
<td>151–161 (199,120)</td>
</tr>
<tr>
<td>Hydrogen fuel cell</td>
<td>70–241 (186,107)</td>
</tr>
</tbody>
</table>

\(^a\) Gasoline SIPI: gasoline fuelled spark ignition port fuel injection.
\(^b\) Table results are generally for near term midsize sedan. Results are dependent on vehicle size and efficiency. Since the GM/Argonne [70] results are for a Silverado pickup truck and MIT [69] results are for substantially improved Toyota Camry sedan (high efficiency, low weight), these results are indicated in parentheses following the range of result of the other studies. E.g. (GM result, MIT result).
\(^c\) Diesel CIDI: diesel fuelled compression ignition direct injection.
\(^d\) Gasoline HEV: gasoline fuelled hybrid electric vehicle.
\(^e\) Diesel HEV: diesel fuelled hybrid electric vehicle.
\(^f\) Ethanol SIPI-lignocell.: ethanol (from lignocellulosic feedsstocks) fuelled spark ignition port fuel injection.

\(^g\) GM result only: MIT did not include ethanol in its study. Table does not include outliers.

Vehicle efficiencies. The use of hydrogen directly, eliminates the need for energy to power a fuel reformer, therefore lowering GHG emissions. Some of the hydrogen FC WTW options emit more GHG than conventional vehicles. Due to the Levelton [164] assumption of producing the hydrogen through electrolysis using hydropower, this WTW estimate is small. Pembina reports the lowest hydrogen FC GHG emissions from NG (70–80 g CO₂ equiv./km). These estimates are considerably lower than those of the other studies. There is not sufficient detail presented in the studies to determine the sources of the difference.

Fig. 24 shows that the results for the GHG emissions from the WTW for the methanol FC vehicles are generally lower than those of the gasoline FCV. The processing of the methanol onboard the vehicle results in lower GHG emissions per kilometer than for gasoline reforming due to the lower carbon content of methanol and the higher methanol reformer efficiency. The lower gasoline WTW GHG emissions estimate of Lave [10] is due in part to the assumption of a smaller vehicle (e.g. Toyota Corolla) than the other studies.

The two options that have potential for the largest GHG emissions reductions are the ethanol (Fig. 23) and hydrogen fueled vehicles (Fig. 24) if the fuels are produced with little or no fossil fuel inputs. Results depend on the issues discussed in Section 6.12.1) regarding WTT assumptions, as well as ethanol blend assumptions (% gasoline) and engine efficiency. For the ethanol vehicle, Lave [10] assumes a SIDI engine and associated thermal efficiency improvements over a conventional port fuel injection. However, we are not aware of any experience with ethanol in DI engines.

Table 7 summarizes the ranges for the WTW GHG emissions reported in the LC studies. Since the GM/Argonne [70] and MIT [69] studies have vehicles that have considerably different performance than the automobiles examined in the remainder of the studies (for GM, the Silverado pickup truck and for MIT, an advanced sedan for the baseline), we report these results separately from the ranges given for the other studies. All of the fossil fueled vehicles result in large GHG emissions. Ethanol or hydrogen with little to no fossil fuel inputs are the only fuels with the potential for significant GHG emissions reductions. FCVs fueled with gasoline, methanol or hydrogen (except as noted above) would continue to contribute substantially to GHG emissions.

6.12.3. Summary of LCA studies

Since it is difficult to compare the overall results of the studies due to their considering different alternatives, differing vehicle attributes, assumptions, etc. in this section we report a brief summary of the conclusions of each of the LC studies discussed above.

A primary conclusion of Kreucher [75] was that there were tradeoffs with any of the fuel/vehicle options. No single option best satisfied all objectives considered. As with other studies, Kreucher found that life cycle CO₂ emissions are lowest with cellulosic ethanol. Methane from NG had lower CO₂ than the baseline while methanol from NG had higher CO₂ than the baseline. The electricity generation mix influenced the attractiveness of BPV. Kreucher did not isolate fossil from total energy, therefore, from an energy efficiency perspective, the diesel CIDI option was preferred.

For the time frame up to 5 years from the study date, IEA [163] reported GHG emissions reductions through the use of biodiesel, methanol, and ethanol from cellulosic feedstocks. In the longer term (15–25 years), the authors reported the options of biomass fuels and hydrogen from ‘clean’ electricity but noted that any substantial reductions would be very dependent on technological developments. From a WTW energy consumption perspective, diesel from petroleum was the best option, except that fossil fuels were not isolated from total energy and therefore, the renewable options did not appear attractive for energy efficiency. Hydrogen from electrolysis had much higher energy use than gasoline.

Levelton [164] reported GHG reductions from the baseline SIPI gasoline ICE ranging from 23 to 43% for CIDI diesel ICE and gasoline and diesel HEV. CNG and LPG were reported to have the potential to reduce GHG emissions by 26%. Cellulosic ethanol had more GHG
emissions benefits than corn ethanol due to the lower emissions assumed from land use change and for fuel production. BPV based on the national electricity mix had the potential of 70% reduction. For FC vehicle options, reductions from the various options were as follows: methanol 39%, hydrogen from NG 53%, electrolysis using national mix 49%, and electrolysis using 100% hydroelectric power, 85%. The cost effectiveness ranged from $21/ton CO₂ equivalent reduced (a cost saving) for conventional diesel cars, to $235/ton CO₂ reduced for the hydrogen FC vehicle.

Lave [10] concluded that there was no overall winner, no ‘vector dominant’ alternative. Lave predicted that “Absent a doubling of petroleum prices or stringent regulation, ICE using ‘clean’ fossil fuels will dominate the market for the next 20 years.” Although both HEV and FC vehicles promise improvements in fuel economy and emissions, in the near term, these did not justify their higher costs. Ethanol from biomass sources was a likely contender if there was a strong focus on GHG emissions, although the fuel price was expected to be more than double petroleum prices (net of taxes) at that time.

MIT [69] found that emerging technologies such as FC vehicles would have a difficult time to compete with the ‘evolved’ baseline. New technologies had the potential to be more efficient and lower emitting (HEV using either ICE or FC power plants were the most efficient and lowest-emitting technologies they assessed), but at a much higher cost. ICE HEV appeared to have some advantage over FC HEV with respect to LC GHG emissions, energy efficiency, and vehicle cost, but the differences were within the uncertainties of the results. If large reductions in GHG emissions were required in 30–50 years, hydrogen and electricity produced from non-fossil sources were the only options considered in the study that satisfied these requirements. The study did not consider biofuel options. Overall, MIT [69] concluded that with little benefit to consumers, the new technologies were likely to succeed only if government action was taken and successful large-scale use of new technologies requires acceptance by all of the stakeholder groups.

Hackney [78] recommended that the most cost-effective option for polluted regions is RFG. An ICE HEV running on gasoline had the potential of 33% higher fuel efficiency than the baseline. Neat methanol or M85 from NG were also recommended options for good performance, reasonable cost, and compatibility with the current fuel distribution system. Longer term options viewed as having some potential included fuel cells fueled with liquid HCs. The fuel pathways for the alcohol fuels did not include lignocellulosic feedstocks and therefore were not reported to reduce GHG compared to conventional petroleum fuels. LPG was not attractive due to its low resource base.

Consistent with Kreucher, IEA, and Lave, GM/Argonne [70] also reported that ethanol-based fuel/vehicle pathways had the lowest GHG emissions. Gasoline SI and diesel CIDI HEV and diesel CIDI ICE had significant energy and GHG emissions benefits over the baseline. Methanol fuel cell HEV were not an improvement over gasoline or NG fuel cell HEV options. CNG conventional and gasoline SI conventional options were almost identical with respect to energy use and GHG emissions. Crude oil-based diesel vehicle pathways had slightly lower total system GHG emissions and better energy total energy use than the F–T diesel CIDI options. Liquid hydrogen and electrolysis-based hydrogen FC HEV had ‘significantly higher energy use and equal or higher GHG emissions’ than the gasoline FC HEV with a fuel processor and the gaseous hydrogen fuel cell HEV.

Delucchi [150] found the largest potential GHG reduction from the baseline with E90 with ethanol from lignocellulosic feedstocks (with estimated 70% reduction in 2020), and among fossil sources, some benefits with CNG, LPG, and diesel (about 30% reduction). Methanol (from NG) was found to have little benefit over gasoline.

The overall conclusion of Brekken [77] was as follows: “When comparing vehicles of equal performance and when energy required to create alternative fuels is included in the analysis, purported efficiency improvements of alternatives largely disappear”. Brekken found that hydrogen produced from reforming NG and then used in a FC vehicle was the most efficient option but it was only slightly more efficient than a gasoline ICE. BPV were the least efficient and were much less efficient than today’s gasoline vehicles.

Ogden [104] found that from an energy efficiency perspective, hydrogen FC vehicles were more efficient than those with onboard fuel processors due to the conversion losses in the fuel processor.

Methanex [166] concluded that FC vehicles had the potential to offer ‘very significant reduction in GHG emissions compared to the gasoline powered ICE driven vehicle’. The choice of fuel and geographical location substantially impacted the GHG benefit. For Canada, NG to hydrogen via steam methane reforming (SMR) offered the greatest theoretical reductions. If the hydrogen was produced using partial oxidation (POX) technology rather than SMR, half of the reduction was lost. In countries without pipeline NG, methanol from NG was reported to have the greatest GHG reductions. ‘NG to methanol offers the most consistent reduction of GHG emissions for the various production scenarios and countries examined’. An interesting study result was that the difference in the carbon intensity of the electricity generation between Canada and the US significantly influenced the reductions and rankings of the fuel options for each of the countries.

Pembina [79] found that the source of the hydrogen greatly impacted GHG emissions reductions. Specific results included: the decentralized NG reforming system posed the fewest technical challenges (e.g. infrastructure) and was expected to be the most cost-effective hydrogen production system with the potential of 70% reduction of GHG emissions compared to a gasoline ICE. Decentralized electrolysis resulted in little reduction unless the electricity...
was produced from renewable resources. Onboard fuel processing of methanol or gasoline resulted in 20–30% reductions in GHG compared to the baseline.

6.12.4. Summary of study results

6.12.4.1. Crucial assumptions. Results depend on assumptions, but not all assumptions are equally important. Here, we highlight a few of the most important assumptions. We begin by recognizing that a fair, informed comparison of fuels or propulsion technologies is impossible without a LCA. Each of the alternatives has particular attributes that are attractive. No fuel/propulsion combination is most attractive with respect to all attributes. Without a careful LCA, an analyst can find a comparison that favors a particular fuel/propulsion pair; examining these comparisons in particular aspects of the process could lead even an impartial analyst to conclude that one alternative is better. Conducting a careful LCA is difficult and time consuming, but there is no alternative if the goal is to obtain informed results.

A second obvious conclusion is that the analysis must consider the full range of relevant alternatives. Some alternatives can be dismissed without a full analysis, since they have no chance of supplying at least 5–10% of new vehicle sales (e.g. battery powered cars), but each alternative must be considered in sufficient depth to conclude that it is not a serious candidate. In particular, a propulsion technology must be considered with the full range of fuels, since a fuel that did not appear at first to be attractive might turn out to be the best alternative.

Since we seek to evaluate vehicles that will be used over the next three decades, we need to evaluate technologies that are not currently feasible, e.g. fuel cells. While there will be technological change making fuel cells more attractive and lowering their cost, there will also be technological change for the established technologies, such as gasoline powered ICE. A fair comparison requires equally optimistic assumptions about technological progress in all the fuel/propulsion technology alternatives. That statement is easy to make, but exceedingly difficult to implement. In comparing the studies, we found it impossible to adjust the individual studies to reflect the same degree of optimism about future technological progress.

For some of the fuels, there are multiple production pathways. Even gasoline can be produced from petroleum, natural gas liquids, NG (via Fischer–Tropsch), heavy oil, or even coal. Hydrogen can be produced in even more ways, such as from NG, petroleum, other fossil fuels, biomass, or water. The attractiveness of a hydrogen-powered fuel cell depends on which process is used to produce, transport, and store the fuel onboard the vehicle.

To be fair, a comparison must examine ‘comparable’ vehicles. For example, a study that contrasted the General Motors EV-1 with a Ford Expedition is unlikely to be enlightening. Unfortunately, it is easy for an analyst to mislead himself and his readers. For example, since the batteries on the original EV-1 had such little energy storage, it was tempting to test range by switching off all the parasitic power drains, from lights to air conditioning to radios. The results of such a test would not be representative of the way most Americans drive. Each fuel-technology combination must be examined with respect to the full array of attributes desired by car owners or society. The analysis will be incomplete, and likely biased, if some attributes are omitted.

A good study will report the models employed to provide the inputs and perform the adjustments and calculations for the modeling of vehicles and fuels as well as the LCA. All of the models should be available for examination. For example, the recent GM well-to-wheels study [70] uses the same vehicle throughout, measures a wide range of attributes, and most of the models used are available to the reader. In contrast, the earlier US Automotive Materials Partnership study [144] was confronted with confidentiality problems and so the detailed data were not available to all of the study participants, much less to a reader.

Finally, the fuels and technologies are evolving constantly and projections about the world of 2030 are extremely uncertain. A good study will identify and discuss the uncertainties. An excellent study will examine these uncertainties in a sensitivity analysis to identify assumptions and parameter values that are critical. Even if the reader is uncertain about the future, she may have a strong opinion about whether, for example, the price of petroleum is likely to remain above $50 per barrel.

Assumptions about the future significantly impact the results of the studies. This is particularly the case with FCVs, where there are large uncertainties regarding the assumptions (fuel production and vehicle operation), resulting in some studies finding the vehicles very attractive (e.g. Ogden, Methanex) and others, much less so (e.g. Lave, MIT). MIT’s assumption of a considerably improved baseline gasoline ICE vehicle lessens the advantages of the competing vehicle options (Table 7). None of the other studies considers significant improvements in the efficiency of conventional vehicles. There has been significant progress in conventional vehicles in recent years and these vehicles will keep improving. Whether improvements will be utilized to increase fuel economy or whether they will be used to, for example, add more power to the vehicles will depend on consumers’ and regulators’ desires. Assumptions about the production of ethanol and technological progress are another case where assumptions play a big role in the alternatives’ attractiveness. Since no one can predict the future or the path of technological change, to evaluate new technologies we must make our best estimates about technological advances. However, in most cases, the analysts have provided little basis for their estimates. Overall, few of the studies are transparent in their assumptions with respect to this matter. The GM/Argonne and MIT studies most clearly present their assumptions. In our judgment, the assumptions made in some of the studies are more realistic than others.
Table 8
Evaluation of attributes for fuel/propulsion technologies relative to a conventional automobile (see scale at bottom of table)

<table>
<thead>
<tr>
<th></th>
<th>RFG + SICI</th>
<th>RFG + SIDI</th>
<th>Diesel + CIDI</th>
<th>CNG + SICI</th>
<th>Ethanol + SICI</th>
<th>Battery EV</th>
<th>Gasoline + HEV</th>
<th>Gasoline + fuel cell</th>
<th>H2 Ren. + fuel cell</th>
</tr>
</thead>
</table>

**Environmental**

Near term—local air pollution (vehicle)
- A-1: ozone
  - ++: slightly better
  - -: slightly worse
  - ++: very much better
  - : about the same

- A-2: PM
  - ++: slightly better
  - -=: slightly worse
  - +=: about the same

- A-3: air toxics
  - ++: slightly better
  - +: about the same

- A-4: fuel cycle emissions
  - -=: slightly worse
  - +=: slightly better
  - -=: about the same

**Long term**
- A-5: global warming
  - ++: very much better
  - =: about the same

- A-6: fossil fuel depletion
  - +=: slightly better
  - +=: about the same

**Vehicle attributes**
- B-1: range
  - +=: slightly better
  - -=: slightly worse

- B-2: performance
  - +=: very much better
  - -=: slightly worse
  - +=: about the same

**Costs**
- C-1: vehicle cost
  - +=: very much better
  - -=: slightly worse

- C-2: fuel cost
  - +=: very much better
  - -=: slightly worse

- C-3: infrastructure cost
  - +=: very much better
  - -=: slightly worse

**Other social issues**
- D-1: energy independence
  - +=: very much better

- D-2: safety
  - +=: very much better

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RFG + SICI: reformulated gasoline fuelled spark ignition port fuel injection (SIPI) vehicle; RFG + SIDI: reformulated gasoline fuelled spark ignition direct injection; Diesel + CIDI: conventional diesel fuelled compression ignition direct injection; CNG + SICI: compressed natural gas fuelled SIPI; Ethanol + SICI: ethanol from biomass feedstocks with no fossil fuel inputs fuelled SIPI; Battery EV: battery powered electric vehicle; Gasoline + HEV: gasoline fuelled hybrid electric vehicle with SIPI; Gasoline + fuel cell: gasoline fuel cell vehicle (with reformer); H2 Ren. + fuel cell: hydrogen from renewables fuelled fuel cell vehicle.

Relative to SIPI federal standard gasoline combination. =: fuel/propulsion system combination is about the same; +: fuel/propulsion system combination is slightly better; -: fuel/propulsion system combination is slightly worse; ++: fuel/propulsion system is better; --: fuel/propulsion system is worse; ?: unknown.
The majority of studies do not report a vector dominant alternative, those that do have limited their analyses to judging one or two attributes. Due to the multiattribute nature of the decision problem, most of the studies report results for a vector of energy and environmental metrics. However, they almost always stop short of recommending any alternative or course of action. Kreucher, Lave, GM/Argonne, and MIT provide the broadest coverage of alternatives. The remaining studies have limited their coverage due to resources, judgment on the feasibility of future options, or due to a particular agenda.

There is reasonable agreement among the studies regarding the petroleum-based fuels due to the ‘known pathway’ and the fact that many of the studies used either the Wang or Delucchi models (see summary in Tables 6 and 7). There is much less agreement on the other fuel results. The differences may stem from actual differences (e.g. geographic regions, processes, and pathways), or differences in assumptions (e.g. technology development).

The petroleum-based fuel cycles are very efficient; all other fuels cycles are less so (except for those of renewable fuels if they are produced sustainably and if the distinction is made between total and fossil energy) (Table 6). From an efficiency standpoint, diesel CIDI vehicles are a winner, since an efficient fuel cycle is combined with an efficient powerplant but, as noted earlier, there will be efficiency tradeoffs necessary for these vehicles to meet future PM and NOx emissions standards. All of the petroleum fuel cycles result in large amounts of GHG emissions. Where renewable fuels are included in the studies, those produced using little fossil fuels can result in very low GHG emissions (Table 6). When only total energy is reported (with no reporting of just fossil energy), results can be misleading. Table 6 shows a much larger variation in GHG emissions than efficiency. Some sources of the differences result from several studies including several GHG and others just CO2, differences in composition (e.g. carbon content primarily) of the fuels and the discrepancies in counting of total and fossil energy for biofuels. The production pathway for hydrogen options significantly impacts their efficiency and GHG emissions. However, all of the processes for producing hydrogen are inefficient (Table 6), requiring the fuel cell in which it is used to be highly efficient in order for it to compete from an efficiency standpoint. Ogden and Brekken present results for hydrogen showing much higher WTT efficiencies than the other studies for the NG steam reforming pathway (Fig. 10). Neither of the analysts provides sufficient data about the intermediate steps in the fuel cycle to illuminate the sources of differences in their results. The source of electricity generation is important in evaluating electricity as a fuel itself or its use in producing other fuels. BPV are not attractive unless there is a technology breakthrough resulting in higher vehicle range and lower battery weight.

In Section 3.8, we discuss the comparability issues for each of the studies. Generally, the more recent studies have paid more attention to comparability. However, the overlap of comparability of fuels and vehicles and assumptions of technological advances constrains even the best attempt at comparability. Within comparability and technological advances, the assumption of vehicle options meeting emissions standards is of importance (particularly for diesel options and DI engines).

These current studies span a wide range of competence, methods and assumptions. Since several were done with a particular agenda in mind, sometimes the assumptions are suspicious. However, there is a core group of results that is likely to hold up as uncertainties are resolved. These are discussed in Section 7.

7. Overall results

To provide an overall summary of alternative fuel/propulsion system options, we present the following matrix of fuel/propulsion system options and the attributes by which they are evaluated (Table 8). We evaluate the options with respect to a baseline conventional SIPI conventional gasoline fueled automobile. The rankings are based on previous published scientific literature and the results of our evaluation of the LCA studies in this work. The table structure and entries are discussed. We divide the evaluation attributes into environmental (near term and long term), vehicle attributes, costs, and other social issues with subcategories within each category.

Environmental: near term. Local air pollution, resulting primarily from vehicle emissions, and fuel cycle emissions (A-4) are the two near term environmental issues included. Subcategories within local air pollution include the vehicle options impact on ozone (A-1), particulate matter (PM) (A-2), and air toxics (A-3). Low emission conventional SIPI vehicles fueled with clean gasoline are able to achieve significant improvements over the baseline conventional gasoline fueled vehicle. Much progress in recent years has been made in this area with gasoline vehicles being certified to ULEV and SULEV. This lessens the potential attractiveness of alternative fuels such as CNG and alcohols that had previously been considered to have more potential for lower emissions than gasoline. Direct injection engines continue to be questionable because of their NOx emissions; diesels have the additional problem of relatively high particle emissions. Electric vehicles, such as the HEV and FCV, have the potential of lower emissions than gasoline vehicles, but at a much higher cost. It is important to distinguish between a FCV powered by gasoline, which is transformed to hydrogen onboard the vehicle, and a FCV powered directly by hydrogen. The gasoline-powered vehicle has all the issues associated with the gasoline LC. In addition, the onboard reformer is not terribly efficient, resulting in little or no efficiency gain for a fuel cell compared to a modern ICE. If the fuel cell were powered by hydrogen from renewable sources, the LC would be much cleaner.
Fuel cycle (WTT) emissions are related to the fuel cycles and their efficiencies. The efficiencies are low for most of the fuels other than the petroleum-based or renewable fuels that require little fossil fuel input. The additional upstream energy requirements of the other fuels result in emissions. The additional processing required of reformulated fuels is small.

Environmental: long term. Global Warming (A-5) and Fossil Fuel Depletion (A-6) comprise the long-term environmental issues. The developed world, led by the USA, pours large quantities of GHG into the atmosphere. The potential global change is a concern to many nations. While improved fuel economy could lower fuel use and GHG emissions, this route is unlikely to produce major reductions in emissions. Of greater potential significance are fuels that have no net CO2 emissions, such as ethanol made from biomass with no fossil fuel inputs or electricity or hydrogen from renewable resources or from nuclear. These fuels have the ability to make a major contribution to reducing GHG emissions.

A major concern with sustainability is using almost 100% fossil fuels for transportation. Petroleum can be saved for higher valued uses, such as plastics and advanced materials. Ethanol from biomass as well as electricity and hydrogen from renewable resources or nuclear are the desirable technologies for this aspect.

Considering the above matrix evaluation, alternative vehicles will have to make progress, technologically, economically, and environmentally before they are able to dominate conventional options (gasoline/diesel).

Vehicle attributes. Our table limits vehicle attributes to range (B-1) and performance-acceleration (B-2). The diesel CIDI and HEV vehicles are winners when it comes to long range. However, few drivers appear to value the additional range highly. Of more importance, is the much lower range of BPV and CNG vehicles compared to the conventional baseline vehicle. Solving the range problem for batteries will require a technology breakthrough. Range for CNG vehicles can be extended by designing vehicles specifically suited to carry the CNG cylinders and making the vehicles somewhat larger.

With the exception of the CNG vehicle, due to its heavier weight, the performance-acceleration of all of the SI vehicles is expected to be very similar. The BPV and HEV currently do not have the performance of the baseline. There is not sufficient information to judge the performance of the FCV.

Costs. Costs of the vehicle (C-1), fuel (C-2) and infrastructure (C-3) are the primary cost components and those that differ among the vehicle options. The costs of all of the SI engine vehicle alternatives are expected to be similar, related to there not being significant differences in their manufacture (the CNG vehicle requires the most changes from the baseline due to its fuel storage system). In contrast, all of the electric vehicles are expected to cost substantially more than the baseline within the time frame considered, even if they were manufactured in sufficiently large volume to take advantage of economies of scale. This results from the advanced components and materials required and additional propulsion systems in the case of HEV. However, of the electric vehicles, HEV are likely to be closest in cost to conventional options. For FCV, the cost of fuel cells will have to decline significantly to make them attractive.

From the perspective of fuels, gasoline and diesel are inexpensive. As long as they remain inexpensive, alternative fuels will be able to penetrate in only niche applications. Even if petroleum prices rise or there are severe GHG emissions limits, a breakthrough in electrochemistry would be required for batteries to have a chance. Ethanol from cellulose would become more attractive if petroleum prices rose to $50 per barrel or there were stringent GHG emissions limits. As the technology improves and costs decline, a small rise in gasoline prices or less stringent limits on CO2 emissions would be sufficient to make ethanol attractive.

More than a century of private investment has built an elaborate infrastructure to deliver gasoline and diesel to your car. The infrastructure has a great deal of capacity and accomplishes its tasks cheaply. Any of the other fuels would require moderate to large-scale investments in infrastructure. CNG would probably require the least change while ethanol or hydrogen would probably require the largest investment.

Other social issues. The other social issues are of concern to society generally, but there are so many cars that no individual driver can make an appreciable difference. Thus, these issues must be dealt with by governmental action. The issues in this category that we consider are energy independence (D-1) and safety (D-2).

The United States imports more than half of its petroleum. Since the largest petroleum reserves are in the Middle East, the US must target defense expenditures toward protecting its fuel supply from this region. As the largest petroleum importer, it has a major role in keeping petroleum prices high. If the US ceased to import petroleum and petroleum products, the price of petroleum would be much lower. Thus, there are a host of reasons why the US should seek to lower energy imports.

Gasoline is not a safe fuel. In a crash that ruptures the gas tank, fire or explosion is likely. Gasoline is toxic when ingested and contaminates ground and surface waters. Diesel is a safer fuel in terms of fires or explosions, but it has similar environmental problems. CNG is likely to be safer still, except inside a confined space, such as a garage. CNG is a powerful GHG, but otherwise causes no environmental damage.

Methanol and ethanol are not likely to explode, although both could ignite after a crash. The methanol flame is invisible in daylight. Methanol is extremely toxic to humans and other animals, ethanol much less so. Batteries present a crash hazard largely because they increase the mass of the vehicle. The placement of the batteries can be designed so that the mass does not add to the risk of vehicle occupants,
although it increases the risk to occupants of other vehicles in a crash. Hydrogen is a risk with respect to fire and explosion, although it poses no threats to the environment. The primary point is that all fuels have safety issues and handled incorrectly could result in serious hazards to the environment and human health. The central issues associated with the safe use of an alternative fuel are understanding the potential dangers and gaining the required experience in handling, transporting, and using the fuel.

8. Conclusions

None of the currently available or likely future fuel/technology options for LDV dominates in the full range of social and driver concerns. Society will have to evaluate the tradeoffs in attributes among the competing fuel/technology options. Since social and driver goals and available technology have changed markedly during the past half-century, we expect that they will change in the next 20–30 years, making it difficult to predict the winning fuel/technology in 2030.

Notable progress has been made in evaluating the LC attributes of the competing fuel/technology options. Most notable are the recent LC and WTW analyses. Analysts can improve these analyses still more in the future.

Absent major technology breakthroughs, a doubling of petroleum prices, or stringent regulation of fuel economy or GHG emissions, the 2030 LDV will be powered by a gasoline ICE. The continuing progress in increasing engine efficiency, lowering emissions, and supplying inexpensive gasoline makes it extremely difficult for any of the alternative fuels or propulsion technologies to displace the gasoline (diesel) fueled ICE.

This conclusion should not be interpreted as one of despair or pessimism. Rather, the progress in improving the ICE and providing gasoline/diesel at low price has obviated the need for alternative technologies. For example, if the emissions problems can be solved, a HEV with a diesel engine would give greatly improved fuel economy and low CO₂ emissions. Many of the technologies that we examine, such as cellulosic ethanol or Fischer–Tropsch fuels from NG or HEV, are attractive. If there were no further progress in improving the gasoline/diesel fuel ICE, one or more of these options would take over the market. Thus, the fact that the current fuel and technology is so hard to displace means that society is getting what it wants at low cost.

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Appendix A. Fuel terminology and definitions

The following discusses some of the basic fuel properties important for assessing the attractiveness of a motor vehicle fuel. Specific properties of the fuels, generally comparing them to standard gasoline, are discussed in Section 4.1. Fuels can be classified by their characteristics based on a physical and chemical properties or through more precise analytical techniques which are based on the exact structure of the compounds. Guibet [82], Poulton [72], Owen [84], NREL [85], and DOE [83] are good sources for fuel information. It is difficult to determine the effect of any single fuel characteristics alone on engine performance since many of the characteristics are interrelated.

Characterization factor. Many of the distinctions between fuels are as a result of the number of carbon atoms in each of their HC compounds; 3 or 4 for LPG, 4–10 for gasoline, 9–13 for kerosene, 10–20 for diesel fuel. The density of the fuel is linked to the H/C ratio. The amount of carbon in the fuel is directly related to the CO₂ resulting from combustion of the fuel.

State. The state of the fuel (e.g. liquid, gaseous) significantly influences the infrastructure requirements, refueling the vehicle, the vehicle’s fuel system including fuel storage, and use of the fuel in the propulsion system. Gaseous fuels have to be stored under pressure in heavy, costly cylinders while liquid fuels can be stored in lightweight tanks like those used for gasoline on conventional automobiles. The use of gaseous fuels results in some power loss but reduces fuel consumption during cold start, which can give an efficiency advantage and lead to lower emissions. Vehicles using gaseous fuels require vehicle storage in areas that have sensors to detect gas levels. The state of the fuel also influences consumer perception of safety and comfort in the handling. Refueling with gaseous fuels, recharging with electricity.

Density. The density of a fuel is its mass per unit volume (kg/l or lb/gal) and is related to its H/C ratio. Density is important in fuel injection that operates on a volume metering system. A change in density will influence engine output due to the different mass of fuel injected.

Combustion parameters. This section describes fuel properties that apply to the combustion of the fuels in engines.

Stoichiometric air/fuel ratio. This ratio is the exact air/fuel ratio required to combust a hydrocarbon fuel to
water and carbon dioxide. The total mass content of C, H, and O (if alcohols or ethers are used) affects the overall chemical balance of combustion. The number of C atoms in the chain, number of bonds, etc. does not have a direct effect on the overall chemical balance of combustion. Stoichiometry is the combination of fuel and air required to obtain complete combustion according to the equation:

$$\text{CH}_y\text{O}_z + (1 + y/4 - z/2)(\text{O}_2 + 3.78\text{N}_2)(\text{CO}_2 + y/2\text{H}_2\text{O} + 3.78(1 + y/4 - z/2)\text{N}_2$$

Air contains 20.9% O$_2$ and 79.1% N$_2$ by volume. The stoichiometric ratio, \(r\), is the mass of air divided by the mass of fuel when they are combined under stoichiometric conditions. Often combustion conditions in engines do not correspond to stoichiometric conditions, and the mixture is referred to as either rich or lean, depending on the quantity of fuel present compared with that at stoichiometry. The equivalence ratio relates to the composition of the components in the reaction.

Gasoline engines may run on rich, stoichiometric or lean mixtures. Operation at lean mixtures is preferred for cruising speed since it provides better engine efficiency. Rich mixtures provide power for acceleration but result in increases in emissions. (Before 1970, automobile engines were designed to run rich for performance reasons, but this also produced high levels of CO and HC in the exhaust.) A three-way catalytic converter best controls emissions within a narrow range near stoichiometry (an equivalence ratio of between 0.98 and 1.02). Complete combustion aids in controlling of emissions.

**Heating value.** The heating value (or energy content, thermal value, heat content or heat of combustion) of the fuel measures the energy that becomes available when a fuel is burned. It is essential for establishing thermal efficiency of an engine using that fuel. Heating value can be measured in units of mass (kJ/kg) or volume (kJ/l). It is the amount of energy released by a unit mass or unit volume of fuel, when burned completely in a chemical reaction that forms carbon dioxide and water. The reaction is usually at 25 °C. There are two heating values; the gross or higher heating value and the net or lower heating value. The difference between the two is the amount of the heat released by the condensation of the water in the exhaust. The lower heating value is of primary importance for comparisons among alternative motor fuels since vehicles are not designed with power-plants capable of condensing the moisture of combustion.

This fuel property is of utmost importance for determining that the fuel is able to provide energy to fuel the vehicle for a reasonable driving range and be stored onboard the vehicle in a reasonable space. For example, the low heating value of CNG makes it very difficult to store enough fuel onboard the vehicle for a range similar to that of a conventional automobile. Energy density of electrical energy in conventional and advanced storage batteries is perhaps the best example of the limitations of this requirement, measured by volume or weight, batteries have only 1–2% of the energy storage capacity of conventional fuel tanks [9].

**Volutility.** Fuel volatility is an important property with respect to both performance (fuel combustion) and safety. Volatility is expressed in terms of the volume percentage that is distilled at or below fixed temperatures. If a fuel is too volatile, when it is used at high ambient temperatures it is liable to vaporize in the fuel lines of carbureted engines and form vapor locks. This is most commonly a problem in restarting a vehicle since the engine compartment is hot. On the other hand, if the fuel is not sufficiently volatile, then the engine may be difficult to start, especially during low ambient temperatures. Volatility also influences cold-start fuel economy.

Several characteristics express volatility: the distillation curve of a fuel affects the evolution of combustion, vapor pressure and flash point.

The distillation curve represents the change in volume of the distilled fraction at atmospheric pressure as a function of temperature, when measured in a standard apparatus. The method is often called ASTM distillation. The percentage evaporated at a given temperature is usually used to classify the volatility of a fuel.

**Vapor pressure.** The vapor pressure of a mixture (at a given temperature) is the pressure at which liquid–vapor equilibrium is established. Volatility is directly related to vapor pressure. The Reid vapor pressure (RVP) is a common measure and is used to describe the vapor pressure of petroleum fuels without oxygenates at 100 °F.

**Flash point.** Flash point, as defined by ASTM D-93, is a measure of the temperature to which a fuel must be heated such that a mixture of the vapor and air above the fuel can be ignited. Flash point does not directly affect combustion or engine performance but it is important for safety consideration for fuel storage and distribution operations. The US DOT considers a material with a flash point of 93 °C or higher to be non-hazardous.

**Viscosity.** Viscosity is the resistance of liquid to flow. Fuel viscosity is not particularly important for spark ignition engines but is very important for diesel engines.

Heat of vaporization is the heat required to convert 1 mol of liquid to a vapor. It is expressed in J/mol.

**Flammability limits.** Mixtures of air and petroleum vapors will only burn or explode within a certain range of concentrations. The lean limit (lower limit) is where the mixture has just enough HC to burn and the rich limit (upper limit) is where it is almost too rich to burn. Wider flammability limits permit lean operation.

**Octane and cetane numbers.** Octane and cetane numbers indicate desirable properties for spark ignition and compression ignition engines, respectively. A fuel’s octane rating describes a fuel’s resistance to autoignition, anti-knock or preignition, under compression. Octane and cetane numbers are dimensionless numbers and can be compared between fuels. Octane numbers range from 0 to 100 (and can
be extrapolated up to 120). A 0 value is assigned to n-heptane (a fuel prone to knock) and a value of 100 to iso-octane (a fuel resistant to knock). A 95 octane fuel has the performance equivalent to that of a mixture of 95% iso-octane and 5% n-heptane by volume.

There are two commonly used octane scales, Research Octane Number (RON) and Motor Octane Number (MON). Gasoline specifications in different countries use either the RON or MON. Both numbers are determined using specific experimental conditions. The RON tests a production engine to compare the knock performance of a fuel to a defined blend of isoctane and n-heptane. The test is done on a chassis dynamometer or test bench, not on a road. However, the test was originally done on roads and therefore retains this name. The MON test is similar but differs in the engine speed, intake temperature and spark advance from the RON test. In the US both are taken into consideration jointly as an average ((RON + MON)/2), referred to as the Anti-Knock Index (AKI).

A fuel with a higher octane number can be used in an engine with a higher compression ratio, and higher compression ratio engines are more efficient (improved fuel economy) and increased power output. The octane requirement of an engine varies with compression ratio, geometrical and mechanical considerations and its operating conditions.

Fuel additives can increase octane number. For many years, lead-based compounds were added to gasoline to improve the octane rating of the fuel. However, most countries now have banned the use of lead additives in automotive fuel for human and environmental health reasons.

A fuel’s cetane number represents the ability of a fuel to ignite and burn under compression. Fuels with high cetane numbers ignite at relatively low temperatures and burn quickly. As with octane numbers, cetane has a scale from 0 to 100. Cetane and octane number essentially measure opposite characteristics and therefore, fuels with high cetane numbers have low octane numbers.

**Fuel stability.** Stability refers to a fuel’s ability to retain its original composition and characteristics over time and is particularly important with respect to storage and transportation operations that all fuels undergo in reaching a vehicle fuel tank. Fuel degradation can occur due to for example, heating, contact with oxygen and humidity, water, etc. There are methods for improving fuel stability including for example, with diesel fuels, separate application of refinery procedures, and the use of additives.

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