ON THE ROAD IN 2020

A life-cycle analysis of new automobile technologies

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Executive Summary

This report is a description of work done at MIT during the past two years to assess technologies for new passenger cars that could be developed and commercialized by the year 2020. The report does not make predictions about which technologies will be developed nor judgments about which technologies should be developed—issues for the marketplace and for public policy that are not examined here.

The primary motivation for this study was the desire to assess new automobile technologies which have the potential to function with lower emissions of greenhouse gases (GHGs) widely believed to contribute to global warming. The GHG of most concern here is carbon dioxide (CO_2), but methane (CH_4) and nitrous oxide (N_2O) can also be important. If public policy or market forces result in constraints on GHG emissions, automobiles and other light-duty vehicles—a key part of the transportation sector—will be candidates for those constraints since the transportation sector accounts for about 30% of all CO_2 emissions in OECD countries, and about 20% worldwide.

Methodology

To assess and compare future technologies validly, the methodology must include three main elements:

1. Assessment of the total system over its entire life cycle.

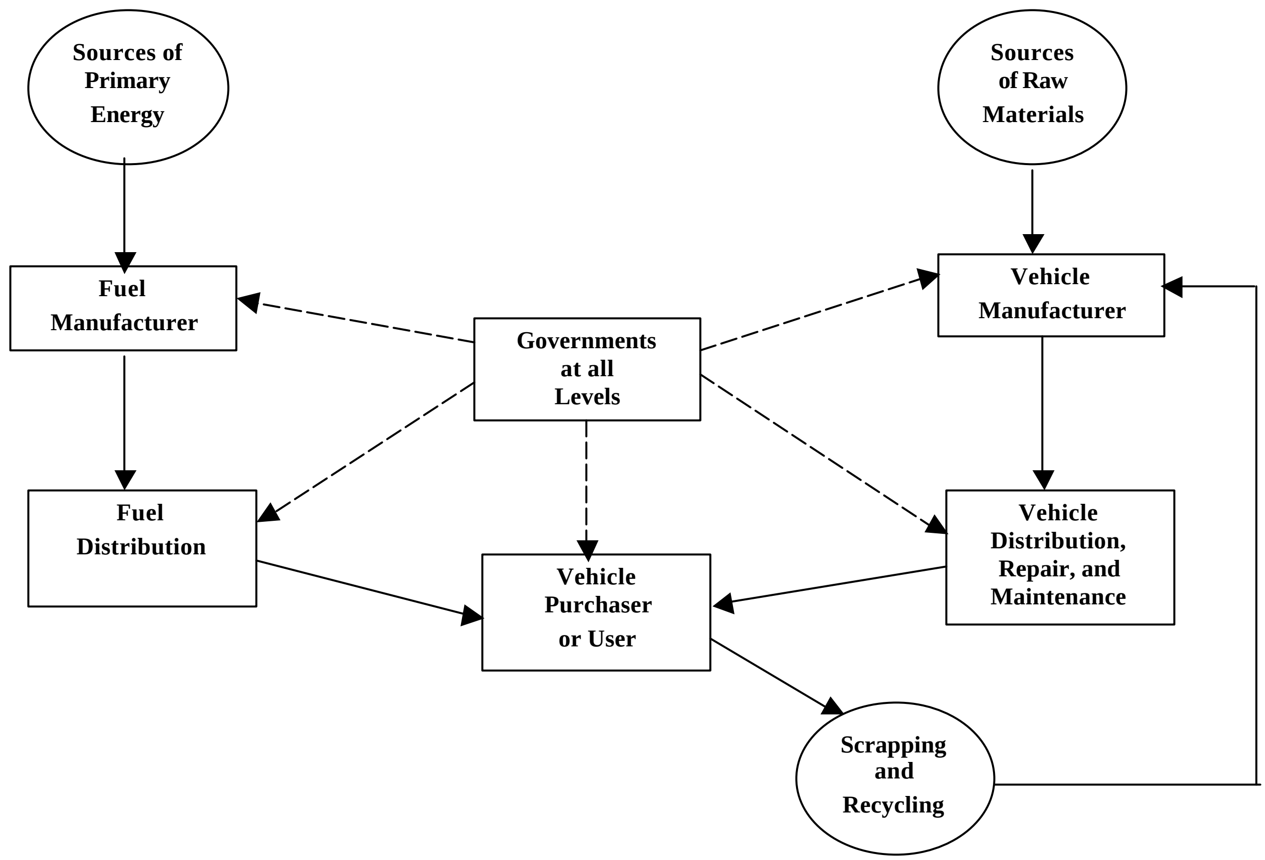
2 Assessment of all the important characteristics of the technology at the same future date.

3. Assessment of the impacts of each of those characteristics and transitional changes on each of the main stakeholder groups.

The life cycle of automotive technology is defined here to include all the steps required to provide the fuel, to manufacture the vehicle, and to operate and maintain the vehicle throughout its lifetime up to scrappage and recycling. An example of why life-cycle assessment is essential is the case of an automobile using a new fuel that permits the automobile to consume less fuel and emit less CO_2 per kilometer traveled while on the road. But there may be no net benefit if more energy and more CO_2 emissions are required to manufacture that new fuel instead of the established fuel before fuel ever gets into the automobile tank. The key steps in the life cycle are shown in Figure ES-1.

"Primary energy sources" such as petroleum or natural gas are considered from the point of their recovery from underground resources through transportation to refineries or manufacturing plants where those sources are converted to fuels for vehicles. The fuel must then be distributed up to deposit in the vehicle's tank. The total of these steps is defined here

Figure ES-1 Steps in the Life Cycle of Automobile Technology



as the "fuel cycle"—or "well-to-tank." Analogously, the vehicle cycle begins with ores or other raw materials necessary to make the parts included in a vehicle, fabrication and assembly of those parts, and distribution of the finished vehicle to the customer. The vehicle is then operated by the first or subsequent customer, with maintenance and repair requirements, until the end of its lifetime when the vehicle is scrapped and recycled.

The characteristics of each technology are categorized here as (a) cost, or price, characteristics, (b) environmental, health, and safety characteristics, or (c) other often less-quantifiable matters such as performance, drivability, convenience, reliability, or familiarity. Since each "technology" includes both fuel and vehicle components, a complete inventory of characteristics must include all the characteristics of fuel and vehicle components of that technology for all the steps shown in Figure ES-1.

The stakeholder groups of concern here (shown in rectangles in Figure ES-1) include the six major groups whose buy-in is required for successful development, introduction, and penetration of a new technology. Those groups include (a) fuel manufacturers,(b) fuel distributors, (c) vehicle manufacturers (including materials and parts), (d) vehicle distributors (including maintenance and repairs), (e) customers for vehicles and fuels, and (f) governments at all levels whose cognizance covers environmental, safety, zoning, and other aspects of new technologies including promoting their development. A complete assessment should consider the impact of each characteristic of each technology on each of these groups; a change that may be trivial to one group may be critical to another group.

An important objective in developing and describing our methodology was to make it transparent and usable by other analysts. Other analysts then have the opportunity to calculate the consequences of assumptions other than the ones we used, and can make use of new information in the future as technologies develop.

Our calculations of the cost, energy consumption, and GHG emissions associated with the production and distribution of each fuel were based primarily on published data. Estimates of future costs included ranges reflecting uncertainties about future prices of petroleum and natural gas and about capital costs of new technologies. Published data were also used to calculate the characteristics of producing, fabricating, and assembling the materials and parts making up the vehicles. The design criteria, performance, and costs of new vehicles were calculated using computer simulations updated and expanded by MIT, and based on previous work at ETH (Eidgenossiche Technische Hochschule) in Zurich; our calculations reflect optimistic but plausible projections of future technologies. The characteristics of all three phases of each life cycle were then combined to make valid integrated comparisons of the technologies assessed.

Scope

The methodology described above was used to characterize technologies with various combinations of the following fuels and vehicle technologies:

- Fuels:
    - Gasoline from petroleum
    - Diesel fuel from petroleum
    - Fischer-Tropsch synthetic diesel from remote natural gas (F-T diesel)
    - Methanol from remote natural gas
    - Compressed domestic natural gas (CNG)
    - Hydrogen from domestic natural gas
    - Electric power from the US grid mix of primary energies
- Vehicle Propulsion System
    - Spark ignition internal combustion engines (SI-ICE)
    - Compression ignition (diesel) internal combustion engines (CI-ICE)
    - ICE-hybrids (combined ICE and battery power plants)
    - Fuel cell (FC) hybrids (combined FC and battery power plants)
    - Battery-powered electric vehicles
- Other Vehicle Components
    - Automatic, mechanical, continuously variable, and electric drive transmissions
- Evolutionary chassis-body and advanced lightweight designs

Limitations

The most important limitations of our assessment to date are the following:

- We have not considered the often-crucial problems of transition from current to new technologies. We recognize and discuss the transition barriers, conspicuously in introducing new fuels, but have assumed that the barriers have been largely dealt with by 2020 and that new quasi-steady states exist.
- Our analysis is confined to mid-size passenger cars with comparable consumer performance (such as range, acceleration, passenger and cargo capacity) for all technologies. Results for much smaller or much larger vehicles like SUVs, or for other than "standard" US driving cycles, may be different although we expect directional trends to be similar.
- We assume that, aided by the introduction of low-sulfur fuels, all technologies will be able to reduce emissions of air pollutants to levels at or below US Federal Tier 2 requirements; therefore, non-GHG emissions have not been considered except for exhaust treatment cost to achieve Tier 2 demands.
- We have evaluated only those fuel and vehicle technologies that we think could be developed and commercialized by 2020 in economically significant quantities assuming aggressive development efforts.

There is considerable uncertainty in both the technical and economic results as a result of uncertainty of price (for petroleum and natural gas, for example) and uncertainty about the pace of technical development especially for young technologies such as fuel cells and new batteries.

Results

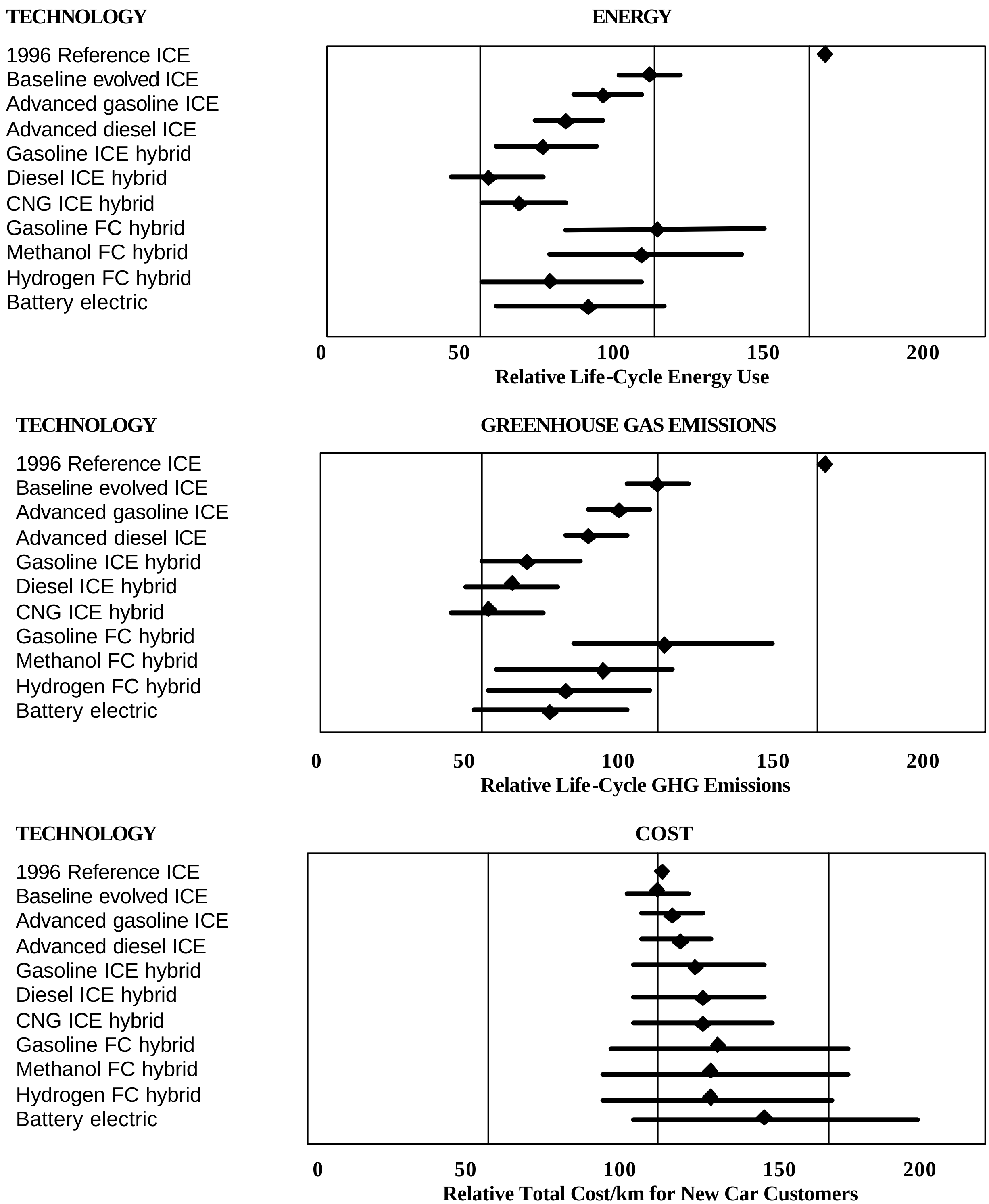
The key results of this study compare the different technologies we assessed along three dimensions over the entire life cycle in each case. The comparisons assume similar lifetimes and similar driving distances for all vehicles. The three dimensions are: (1) life-cycle energy use, (2) life-cycle GHG emissions, and (3) consumer cost per unit of distance driven. Consumer costs are calculated for a new car buyer and include all fixed and variable costs including typical US fuel taxes. However, fuel taxes can add as much as 6.5¢/km for a less-efficient car driven in the high-tax UK compared to as little as 0.6¢/km for a highly-efficient car driven in the low-tax US.

In each case, the more advanced technologies in 2020 are compared to an "evolved baseline". That baseline is a mid-size passenger car, comparable in consumer characteristics to a 1996 "reference car", in which fuel consumption and GHG emissions have been reduced by about a third by 2020 through continuing evolutionary improvements in the traditional technologies used now.

Figure ES-2 charts energy use, GHGs, and costs for all the new 2020 technologies relative to the 1996 reference car and the 2020 evolved baseline. (The battery-electric car shown is an

Figure ES-2 Life-Cycle Comparisons of Technologies for New Mid-Sized Passenger Cars

- All cars are 2020 technology except for 1996 “Reference” car
- ICE = Internal Combustion Engine, FC = Fuel Cell
- 100 = 2020 evolutionary “baseline” gasoline ICE car
- Bars show estimated uncertainty



exception in that it is not "comparable" to the other vehicles; its range is about one-third lower than other vehicles.) The bars shown are meant to suggest the range of our uncertainty about the results but, as expected, even the uncertainties are uncertain. We estimate uncertainty at about plus or minus 30% for fuel cell and battery vehicles, 20% for ICE hybrids, and 10% for other vehicle technologies.

Conclusions

The results of this study depend importantly on the methodologies and assumptions we chose. The following broad conclusions are drawn from calculations for specific combinations of technology as used in a mid-size passenger car operated over the standard US urban/highway driving test cycles. All our quantitative results are subject to the uncertainties expected in projecting 20 years into the future, and those uncertainties are larger for rapidly developing technologies like fuel cells and new batteries.

- A valid comparison of future technologies for passenger cars must be based on life cycle analysis for the total system, which includes assessment of fuel and vehicle manufacture and distribution in addition to assessment of vehicle performance on the road.
- Successful development and penetration of new technologies requires acceptance by all major stakeholder groups: private-sector fuel and vehicle suppliers, government bodies at many levels, and ultimate customers for the products and services. Therefore, the economic, environmental, and other characteristics of each technology must be assessed for their potential impacts on each of the stakeholder groups.
- Continued evolution of the traditional gasoline car technology could result in 2020 vehicles that reduce energy consumption and GHG emissions by about one third from comparable current vehicles and at a roughly 5% increase in car cost. This evolved "baseline" vehicle system is the one against which new 2020 technologies should be compared.
- More advanced technologies for propulsion systems and other vehicle components could yield additional reductions in life cycle GHG emissions (up to about 50% lower than the evolved baseline vehicle) at increased vehicle purchase and use costs (up to about 20% greater than the evolved baseline vehicle).
- Vehicles with hybrid propulsion systems using either ICE or fuel cell power plants are the most efficient and lowest-emitting technologies assessed. In general, ICE hybrids appear to have advantages over fuel cell hybrids with respect to life cycle GHG emissions, energy efficiency, and vehicle cost, but the differences are within the uncertainties of our results and depend on the source of fuel energy.
- If automobile systems with drastically lower GHG emissions are required in the very long run future (perhaps in 30 to 50 years or more), hydrogen and electrical energy are the only identified options for "fuels", but only if both are produced from non-fossil sources of primary energy (such as nuclear or solar) or from fossil primary energy with carbon sequestration.

Again, these conclusions are based on our assessment of representative future technologies, with vehicle attributes held at today's levels. The expectations and choices of customers may change over the next 20 years and such changes can affect the extent to which potential reductions in GHG emissions are realized.

Chapter 1. Overview

1.1 Introduction

In October 1998, our group at MIT began work on a project to assess the broad impacts of new fuel and vehicle technologies for road transportation. The first phase of that project is now complete and this report describes the results.

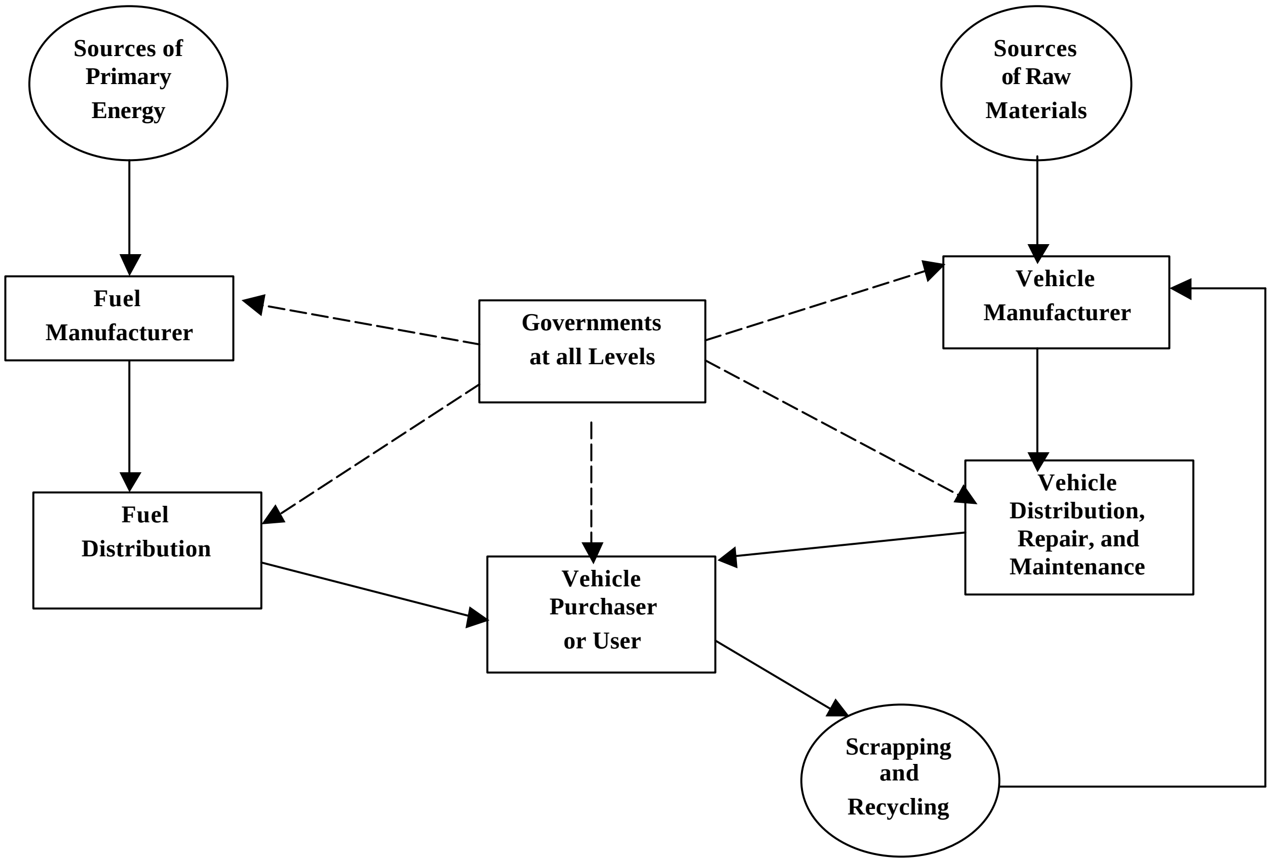
As the demand for transportation inexorably increases, most rapidly in developing countries with growing economies, one environmental consequence of transportation takes on increasing potential importance and provides the impetus for looking at new technologies. That consequence is the emission of greenhouse gases (GHG), mostly CO_2, in huge amounts; for example, the transportation sector now accounts for about one third of all CO_2 emissions in the US and road transportation is three quarters of that third. At some future date, public policy or market forces may result in the transportation sector having to reduce GHG emissions by introducing new technologies. Passenger car manufacturers in Europe have already committed themselves to increase average fuel efficiency and thereby reduce CO_2 emissions from about 187g CO_2 per km traveled in 1995 to 140g/km in 2008 (a reduction of about 25%); a further reduction to 120g/km by 2012 is under consideration (ACEA, 1999).

This first phase of our project has been designed to evaluate in a consistent way major new vehicle <u>and</u> fuel technologies which have the potential to reduce significantly the emissions of GHGs. These evaluations are evaluations of total systems over their entire "well-to-wheels" life cycles. We are concerned with all the potential effects of new technologies on all the major stakeholder groups, i.e. all the groups affected ranging from fuel and vehicle manufacturers to customers. Those effects include estimating the technical characteristics of new technologies, characteristics such as greenhouse gas and other emissions, energy efficiencies, and costs. But they also include other characteristics such as consumer-perceived performance, convenience, safety, and reliability.

All these characteristics must be satisfactory for consumers to accept new technologies. Failure to achieve even one of them could result in technologies not being widely accepted in the commercial market, regardless of their environmental desirability.

The total system for fuel and vehicle technology is illustrated in Figure 1.1. It includes all the major elements making up the life cycle of that system. At the upper left of Figure 1.1, the fuel section of the life cycle begins with the primary energy in its place of origin, say, crude oil in underground reservoirs. The primary energy must then be transported to a manufacturing site, in this case an oil refinery, where it is converted to the fuel suitable for a vehicle, say gasoline or diesel fuel. That fuel must be distributed, namely moved from the refinery by various means to the retail service station where it is deposited in the tanks of vehicles. That sequence constitutes the "fuel cycle" part of the total automobile technology life cycle.

Figure 1.1 Steps in the Life Cycle of Automobile Technology



At the upper right of Figure 1.1, the vehicle section of the life cycle starts analogously with metal ores and other primary materials that eventually are converted to components of the vehicle. These primary materials are transported to the vehicle manufacturer (taken here to include not only assembly but manufacturers of parts, metals, and other vehicle constituents) where they are supplemented by materials recycled from scrapped vehicles. The vehicle itself is fabricated and assembled from these inputs and transported to distributors (taken here to also include the functions of repair and maintenance).

Vehicle and fuel cycles come together in the lower-most rectangle of Figure 1.1, which represents the purchaser of both vehicle and fuel. At the end of its lifetime, the vehicle is scrapped and recycled.

There are six rectangles in Figure 1.1. A rectangle designates a major group of "stakeholders" in the total automobile technology system and life cycle. The stakeholder group not yet described is "government", which may operate at all levels to affect the behavior of other groups—from local zoning, construction, and safety codes for service stations up through sub-national governments with their tax and environmental regulations and ultimately to national governments imposing tax, emission, safety, or other requirements on fuels and vehicles.

This Chapter 1 provides an overview of the methodology and results presented in more detail in the remainder of this report. It represents, in a sense, an intermediate level of detail between the Executive Summary and Chapters 2 to 5. Chapters 2 to 5 cover:

Chapter 2. Fuels

Chapter 3. Vehicle Design, Performance, and Costs in 2020

Chapter 4. Energy Use and Emissions in Vehicle Materials Production, Assembly, Distribution, Maintenance, and Disposal

Chapter 5. Integrated Impacts and Stakeholder Views of New Technologies

1.2 Methodologies and Limitations

1.2.1 Methodologies

Our assessments of each new fuel and vehicle technology cover characteristics grouped in three broad areas:

- Direct financial costs such as new investments in manufacturing or infrastructure, operating costs, raw materials or feedstocks.
- Environmental, safety, and health considerations such as emissions during manufacture or use, wastes, or fuels posing new toxicity problems.
- Other characteristics that can pose barriers to technology introduction such as needs for new skills, uncertainties about reliability, or convenience.

Each characteristic of each technology is assessed for its impact on each of the six groups of stakeholders identified previously and in the rectangular boxes in Figure 1.1. Each technology is assumed to be applied in a vehicle whose capacity and performance are comparable to those in a "base case" mid-size family car. The six stakeholder groups are:

- Fuel manufacturers (from raw material to product at manufacturing site).
- Fuel distributors (from manufacturing site to vehicle tank).
- Vehicle manufacturers (including production of materials and parts).
- Vehicle distributors (including new and used car dealers, maintenance, and repair).
- Government (at all levels).
- Customers (vehicle and fuel purchasers).

For the basis of comparison, the "base case" referred to above, we have chosen a gasoline-fueled internal combustion engine (ICE) vehicle with capacity and performance similar to those of a mid-size family car like the Toyota Camry; we assume evolutionary improvements in both fuel and vehicle over the next 20 years or so, similar to the improvements achieved during the past 20 years. The cumulative effect of those evolutionary improvements is likely to be significant, as past experience suggests. Therefore, the predicted environmental advantages of new technologies over established technologies are smaller than they would be if compared to the current state of established gasoline vehicle technology.

Our assessments consider combinations of vehicle and propulsion technologies that could be available commercially in about 2020—a date far enough in the future to allow for development and introduction of new technologies, but not so far that we cannot reasonably identify those technologies that could be in competition. Our assessments are not predictions about what will be available or judgments about what should be available; those are issues for the marketplace or for public policy and we have not considered them.

We assume that each new technology in question could be produced and used at a volume great enough to capture most of the economies of scale—say, a few percent of the new car market. This assumption avoids (for now) the difficult and important issues of how we get from here to wherever we may want to go. However, our first task is to help readers decide where they may want to go; transition problems of how to get there come next.

The sources used for our assessment are of two main types. Sources on fuels are largely recent published reports (including follow-up responses by authors to our questions) but they also include some unpublished work which has been made available to us. Sources on vehicles are largely engine/power train/vehicle computer simulations, MIT enhancements of simulations developed at ETH Zurich (Guzzella, 1998) to estimate fuel economy of various technology combinations. Data published by different individual or organizational authors may report widely different results for some characteristics of some technologies; sometimes the differences are explainable by different ground rules (such as rates of return) or different professed degrees of optimism (such as "likely" or "best" case), but sometimes the reasons for differences are not clear. In any case, the MIT group is solely responsible for its choices from disparate data sources.

In presenting our assessments, we have tried to be clear about the major assumptions involved. We want our methodology to be transparent for three reasons: first, so readers will easily understand it; second, so readers can comment and propose alternative data or interpretations more fruitfully; and third, so readers can estimate for themselves the impacts of assumptions different from ours such as different future crude oil prices or investment costs or rates of return. In addition, we hope the methodology can be useful to other analysts in the future who can make use of new information that becomes available as technologies develop.

1.2.2 Limitations

Our assessment, like any assessment, has boundaries on its scope and makes simplifying assumptions in order to conclude the work with the resources and time available. In addition, there are uncertainties about the future that might be reduced but cannot be eliminated regardless of the resources available. Therefore, there is uncertainty[1] about both the technical and economic results we present and about qualitative judgments. We cannot quantify that uncertainty simply. As an approximation, we estimate the uncertainties about newer technologies such as fuel cell systems or new batteries at about ±30%, about hybrid systems at about ±20%, and ICE-alone systems at about ±10%.

Listed below are the major boundaries and assumptions in our assessments which could affect the results of our calculations.

- We assume that all vehicles will meet regulatory national requirements for tailpipe emissions, whatever those requirements are. We have not defined the emission control technologies needed, but we have increased the estimated costs of future vehicles in order to provide controls meeting US federal Tier 2 requirements. Beyond that, we have not considered air pollutants other than GHG emissions. Air pollutants such as NO_x and particulates from sources in the life cycle other than vehicle operation usually come from point sources which ordinarily can be controlled if environmentally necessary, although at a cost.
- We assume that all technologies could, with varying levels of aggressiveness in development, be in commercial use by 2020 long enough and on a scale large enough to benefit from learning and to capture most economies of scale. (For example, production of 300,000 cars a year would amount to only 1% of the new cars sold in OECD countries during 1998.) We have analyzed specific combinations of technologies in promising configurations but have not optimized those configurations.
- We have not coped yet with the costs and other difficulties of transition—of getting from where we are now to new fuel and vehicle technologies. We have assumed that the new technologies are in place by 2020 and that most transition issues have been dealt with, but this is a very large simplifying assumption for introducing new fuels.
- We have set the boundaries of our physical system such that second-order energy, material, and environmental effects are not counted. For example, we have estimated the energy consumed and emissions during operation of a methanol plant, but we have not included energy and emissions involved in making the steel, concrete, or other elements embodied in the plant itself, and so on upstream.[2]
- The data we have used are biased toward US experience because of the comprehensive data in English available for the US compared to data for other regions accessible to our research team. We expect our comparisons to be as valid

[1] An example of trying to express uncertainty formally and more quantitatively is the work of Contadini, et al. (2000) on probabilistic expressions of energy use and emissions in the fuel cycle using expert opinion to establish input parameters. We have not attempted that formalization.
[2] Researchers at Carnegie Mellon University (e.g. Maclean, 1998) have attempted to capture embodied energy and emissions through Economic Input-Output Life-Cycle Analysis, but our analysis is confined to first-order effects.

qualitatively in non-US industrialized countries, but we have not tried to make quantitative comparisons.

- Our results apply to mid-size family passenger cars; at this time they cannot be extrapolated to light trucks including vans and sport-utility vehicles, but the results should be directionally similar.
- A final limitation is that we have evaluated only those new fuel and vehicle technologies which we believe could be economically significant by 2020. The technologies chosen could be commercialized by 2020 if there was serious development work before then. Each one seemed to have the potential for significant improvements in the efficiency and emissions of the road transportation system and each could be deployed, at a cost, on a scale large enough to begin to make an impact on the environment. There are advocates for other technologies which may have attractive specialized applications by 2020, or may be more promising longer range, but we have not tried to be all-inclusive at this stage.

The technologies assessed here fall into three categories: fuels, vehicle propulsion systems, and other (non-propulsion system) characteristics of the vehicle.

Table 1.1 Technologies Assessed

Fuels	Propulsion System	Other Vehicle
Petroleum Gasoline Petroleum Diesel Compressed Natural Gas Fischer-Tropsch Diesel Methanol Hydrogen Electric Power	CIDI ICE* SIDI ICE Various Transmissions Hybrids Fuel Cells Batteries	Evolutionary Advanced**

*CI (Compression Ignition), DI (Direct Injection), SI (Spark Ignition), ICE (Internal Combustion Engine).
**Light weight (aluminum-intensive) body and chassis, minimized losses in tires and drag.

1.3 Fuels

In this section covering the fuel cycle, we describe the fuels assessed in this report--the costs of manufacturing and delivering those fuels to the vehicle, and the energy consumed and GHG emissions released during manufacturing and delivery. More details can be found in Chapter 2.

All fuel costs and prices are expressed in 1997 $US; published costs expressed in dollars of other years were adjusted to 1997 dollars using the US Consumer Price Index.

Energy consumption is expressed here as one or both of two forms. It may be expressed as MJ/MJ, the amount of energy consumed in any or all steps of the fuel cycle required to deliver one MJ (LHV) of fuel to the vehicle tank. Or it may be expressed as percent efficiency, the energy in the product of any step in the fuel cycle divided by all the energy inputs to that step including all feedstocks.

The GHGs considered here are CO_2 and CH_4. N_2O was neglected because its greenhouse contribution for each of the fuel cycles assessed totals less than 1% of the other GHGs (Wang, 1999a; EIA, 1997). The GHG contribution of CH_4 was calculated by multiplying its concentration by 21, the effect relative to CO_2 for a 100-year time horizon (EIA, 1997). GHGs are expressed here in units of gC equivalent which are equal to $(CO_2 + 21\ CH_4) \times 12/44$ where 12 is the molecular weight of carbon and 44 the molecular weight of CO_2.

1.3.1 General Assumptions

The fuels listed in Table 1.1 can be described as follows:

Gasoline from Petroleum: We assume that the properties of gasoline in 2020 will evolve from current properties toward very low sulfur with possible changes in volatility, aromatics, or other specifications. We also assume that, with advancing technology, the ex-feed cost of refining specification gasoline in 2020 will be marginally greater than the cost now.

Diesel Fuel from Petroleum: Again, we assume that the properties of diesel fuel (for heavy duty engines, at least) in 2020 will evolve from current properties toward very low sulfur with possible changes in volatility, aromatics, cetane, and other specifications. We again assume that the ex-feed cost of refining specification diesel fuel in 2020 will be marginally greater than the cost now.

Compressed Natural Gas (CNG): We assume that CNG will be supplied to vehicles essentially as it is supplied today with no significant changes in quality or technology for manufacture or distribution.

Diesel Fuel from Natural Gas Conversion: Diesel fuel from Fischer-Tropsch (F-T) synthesis or other GTL (gas-to-liquid) processes for converting natural gas is superior to current petroleum diesel in most qualities, conspicuously in its high cetane number and zero sulfur content. An ultra-clean fuel might make it possible to significantly reduce exhaust gas emissions from advanced diesel engine systems. We assume that GTL technology will continue to improve and that GTL diesel products could be commercially available in 2020 from large plants, at sites having very cheap natural gas, for use as blending stocks or as neat fuels if their properties can be exploited in engines. The extent of GTL penetration vs. petroleum diesel will depend on the relative costs of the feedstocks—remote natural gas and crude oil respectively —as well as on the investments required for advancing petroleum and GTL conversion technologies, and on regulatory requirements.

Methanol from Natural Gas Conversion: We assume that if methanol fuel use is widespread in 2020, methanol will be manufactured, as F-T diesel will be, in very large new plants at locations where cheap remote natural gas is available. Significant additional investments in infrastructure will be required for new or converted facilities to transport, store, and dispense methanol.

Hydrogen from Natural Gas Reforming: We assume that if hydrogen is in widespread use in 2020 for private passenger cars, it will be manufactured by reforming natural gas at decentralized refueling stations. We assume the hydrogen will be dispensed at about 5000 psi into tanks on fuel cell powered vehicles. Other currently more expensive niche options for providing hydrogen include generating hydrogen at the service station by electrolysis of water, or reforming natural gas in large centralized facilities and piping compressed hydrogen, or trucking liquid hydrogen, to service stations. In all cases, large new investments will be required for manufacturing, storing, and dispensing hydrogen.

Electric Power: We assume that passenger cars with storage battery power plants (alone or in hybrids) would ordinarily be charged overnight at home using off-peak power from the national grid. In the US, average actual power generation is roughly 60% of peak capacity assuming 24-hour generation every day at peak capacity. In addition, actual total US generation of electrical energy is about 20 petajoules per year, compared to the supply of about 15 petajoules of gasoline energy per year. Therefore, the initial introduction of electrical vehicles could pose local distribution problems if battery vehicles were used in clusters, but would not stress national generating capacity. "Fuel" costs and environmental impacts are assumed to be those of the national grid in 2020.

1.3.2 Fuel Costs, Energy Consumption, and GHG Emissions

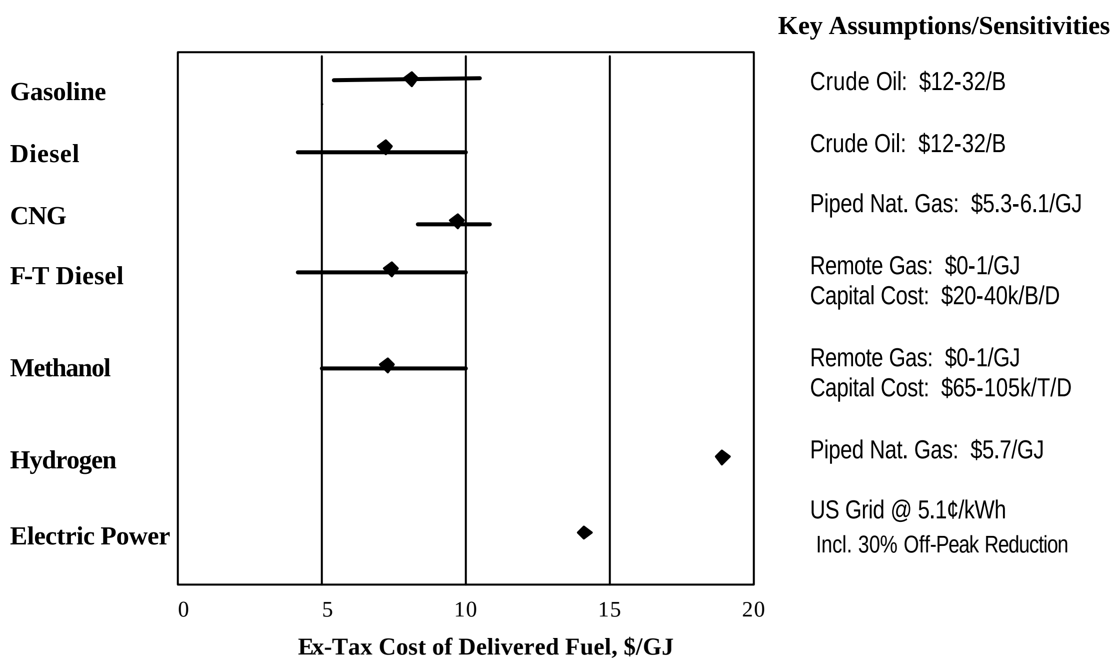
Costs of fuels in 2020 were estimated in most cases as the sum of three steps in the fuel cycle: costs of raw materials, costs of converting raw material to final fuels, and costs of distribution—delivering those fuels to the tanks of customer vehicles. Energy consumption and GNG emissions were estimated similarly as three-step sums. Chapter 2 describes the details of these estimates.

For most fuels, uncertainties about future costs are greater than uncertainties about future energy consumption and GHG emissions. High cost uncertainty results largely from uncertainty about the prices of raw materials and from uncertainty about the capital costs of building plants for large-scale production of new fuels. For example, crude oil is the raw material for gasoline and diesel and it accounts for the largest share (compared to conversion and distribution) of total delivered cost. In the 21 months from December 1998 to September 2000, spot prices for crude oil have risen almost four-fold. Therefore, estimating *a* cost for gasoline, or for most other fuels, 20 years from now is not credible.

In Figure 1.2, we show our estimates for the 2020 costs to customers of the seven fuels assessed. (Details are given in Tables 2.2, 2.5, 2.6, 2.8, and 2.9). For the sensitivities considered, the costs of the four liquid fuels (gasoline, diesel, F-T diesel, and methanol) are similar; all costs fall within the range of $4 to $10.5/GJ, and all median costs are in the range of $6.5 to $8/GJ, which is ±10% of the average. Therefore no confident choice of liquid fuels can be made now solely on the basis of delivered cost of energy to the customer; however, the cost of energy delivered to the customer will not be the only criterion for fuel selection. Liquid fuels are cheaper than non-liquid fuels (CNG, hydrogen, and electric power) under our assumptions. The costs of these non-liquid fuels depend largely on energy supplied by national grids—natural gas or electric power—which are not likely to experience price excursions as large as those of crude oil. The costs of retail stations to compress natural gas (for CNG) or to convert the gas to hydrogen, account for about 40 and 60% respectively of total delivered costs under our assumptions. Advances in station technology may be able to reduce those costs in the future; we have not assessed those advances.

Although our current estimated costs for hydrogen and electric power are about two or more times the average cost of liquid fuels, a unit of energy delivered to vehicles designed for hydrogen or electric power can fuel those vehicles over a greater distance than vehicles designed for other fuels (see Chapter 3). Therefore, from a customer perspective, fuel cost (ex tax) should be judged in terms of cost per vehicle-kilometer traveled which combines cost per unit of energy loaded into the tank (the data in Figure 1.2), and kilometers traveled per unit of energy.

Figure 1.2 Ex-Tax Costs of Fuels in 2020



Although we cite fuel costs here ex tax, taxes in major industrialized countries may account for as much as 77% (rates in the UK as cited in the *Wall Street Journal*, 2000) of what the customer sees as total fuel costs. For the 2020 vehicles we assessed, fuel costs ex tax range from a minimum of about 2% to a maximum of about 5% of the total ex tax costs per kilometer of operating a new car. If all fuels were taxed at the same rate per MJ as recent UK taxes on gasoline, the range of fuel costs would rise to about 10 to 21% of the total and thus would be more visible to customers. Section 2.7 provides a brief discussion of taxes, but we make no assumptions about what fuel taxes may be in the future, particularly on non-traditional fuels that governments may want to encourage or discourage.

Energy consumption and GHG emissions during the fuel cycle do not necessarily track each other closely. GHG emissions do ordinarily depend on the amount of energy consumed, including primary energy raw materials, but they also depend on the chemical composition of the raw material consumed* and on the processes used for converting raw material to final fuel. For example, in converting natural gas to methanol we assume that the methanol energy is equal to about 68% of the energy in the feed natural gas, but that the carbon in the methanol is equal to about 83% of the carbon in the feed natural gas, i.e. a "carbon efficiency" of 83%. If all of the carbon in all of the energy sources employed, including all raw materials fed, appeared in the fuel, the carbon efficiency would be 100%. If none of that carbon was contained in the fuels, as in the case of hydrogen and electric power, the carbon efficiency would be 0%.

In Ttable 1.2 we summarize the energy use and GHG emissions for each of the seven fuels assessed; Table 1.2 results cover only the fuels cycle. They do not include consumption of energy or GHG emissions during operation of vehicles on the road. GHG emissions on the road per MJ of delivered fuel range from zero for hydrogen and electric power, to 15 gC/MJ for CNG and 19 to 21 gC/MJ for each of the liquid fuels (see Table 2.1).

Table 1.2 Energy Use and GHG Emissions During the Fuel Cycle

Per MJ of fuel delivered to the vehicle

Fuel	Energy Use		GHG
	MJ/MJ	Efficiency	gC/MJ
Gasoline	0.21	83%	4.9
Diesel	0.14	88%	3.3
CNG	0.18	85%	4.2
F-T Diesel	0.93	52%	8.9
Methanol	0.54	65%	5.9
Hydrogen	0.77	56%	36
Electric Power	2.16	32%	54

1.4 Vehicles

This section describes the characteristics of vehicles using new technologies which we believe could be in commercial use by 2020. All of these vehicles are medium-size passenger cars similar to a current Toyota Camry with respect to load capacity, range, performance, and auxiliary equipment. The key characteristic sought here is fuel consumption as affected by vehicle technology. Fuel consumptions reported in this section

* Burning one MJ of natural gas releases only about 75% as much GHG as burning one MJ of crude oil. Leakage of about 2% of that gas (unburned) would offset the GHG advantage.

exclude energy consumed in the fuel cycle and in vehicle manufacturing. That is, they reflect the familiar "miles per gallon" or "liters per 100 kilometers" numbers and are *not* well-to-wheels values. In all cases we assume that exhaust gas emissions of criteria pollutants are equal to or better than US federal Tier 2 standards, which include average limits of 43.5 mg/km for NO_x and 6.2 mg/km for PM10. Additional details on vehicle characteristics can be found in Section 3 of this report.

1.4.1 Methodology

In contrast to the data sources used for fuels in Section 1.3, data on vehicles are based not on critical review of published data, but on the results of vehicle computer simulations. Our simulations are updated and enhanced versions of the Matlab Simulink simulation programs originally developed at ETH, Zurich, by Guzzella and Amstutz (1998).

These simulations require the vehicle to go through specified driving cycles. Fuel consumption during the cycle is calculated from performance models for each major component of the propulsion system and for each vehicle driving resistance. The overall simulations can be characterized as aggregate engineering models which quantify component performance in sufficient detail to be reasonably accurate but without the level of detail that would be difficult to justify in predicting the state of the art in 2020.

It is important to keep the results of these simulations, shown in the following section (1.4.2), in context. The results are projections of what practicable vehicle and propulsion system improvements might produce by 2020 in terms of fuel economy with other vehicle performance attributes at about today's level. The projections assume that the technology combinations would be in mass production and that they have gone through extensive engineering development to improve performance and reduce costs. These are estimates of what *could* happen if development is pursued vigorously, not necessarily what we believe *will* or *should* happen.

Two other qualifications: Although fuel economy is calculated and listed for US Federal urban and highway driving cycles, real-life fuel consumption is worse on the average than these driving cycles would indicate; thus, fuel consumptions for different technologies are best compared relatively (in percentage differences) rather than absolutely (fuel consumption per kilometer). In addition, the vehicles described here are significantly lighter than their current counterparts; although their performances are the same at base load occupancy and cargo, losses in performance will be greater at heavier loads.

Lighter vehicle weight also raises safety issues. We have allowed for an extra 25 kg of mass in all 2020 vehicles to help respond to safety needs. Future advances in collision avoidance and crashworthiness may allow lighter vehicles to meet national safety goals. However, vehicle mass would still affect vehicle deceleration rates in collisions.

Overall, in view of the preceding qualifications, our fuel consumption and cost estimates should be regarded as plausibly optimistic.

1.4.2 Vehicle Technologies Assessed

Our simulation methods have been used to describe ten different specific vehicle technologies. Again, all ten vehicles are similar in interior and trunk space, driving range, acceleration, and conformance to safety and emissions regulations.

One of the ten technologies is a 1996 vehicle, a family car similar to a Toyota Camry, shown to serve as a "reference" point against which to compare changes in the other nine technologies for 2020. One of those nine 2020 technologies is our "base case", a representation of a passenger car vehicle that is likely to evolve over the next 20 years without radical new technologies or major cost increases, but responsive to calls--government or market--for improved fuel economy. The other eight 2020 technologies all include advanced technologies in the propulsion systems, and make extensive use of lightweight materials and reduction of other driving resistances, aerodynamic drag and rolling resistance. An eleventh technology, battery-electric, is not comparable in range.

The engine systems assessed fall into five general groups:

- Current and evolving gasoline ICEs
- Evolving direct-injection ICEs, both gasoline and diesel
- Parallel hybrids, using batteries and evolving direct-injection ICEs
- Fuel cell hybrids, using batteries and fuel cells with and without fuel reformers
- Pure battery electric motors.

Four different transmissions are combined with these engine systems:

- Current 4-speed automatic transmission
- 5-speed automatically shifting clutched transmission
- A continuously variable transmission
- Direct electric motor drive

The ten specific combinations of technologies assessed, summarized in Section 1.2.2, are listed in more detail here in Table 1.3.

1.4.3 Vehicle Fuel Consumption

The most meaningful comparison of future technologies would evaluate both new technologies and traditional technologies at the same time in the future—giving both the same opportunity to display improved fuel economy. Therefore, our first assessment has been the "base case" vehicle referred to previously: a gasoline-fueled internal combustion engine vehicle with an improved propulsion system, lower vehicle weight, and lower other driving resistances—changes which represent evolutionary development rather than abrupt advances and which can be introduced with small vehicle cost increases.

Table 1.3 Vehicle Technologies Assessed

Year and Technology	Fuel	Engine(s)	Transmission
1996 (Reference)	Gasoline	SI	Auto
2020 Evolutionary (Base Case)	Gasoline	DI SI	Auto-Clutch
2020 Advanced Vehicle ICE	Gasoline	DI SI	Auto-Clutch
	Diesel	DI CI	Auto-Clutch
2020 Advanced Vehicle ICE Hybrids	Gasoline	DI SI + Battery	CVT
	Diesel	DI CI + Battery	CVT
	CNG	DI SI + Battery	CVT
2020 Advanced Vehicle Fuel Cell Hybrids	Gasoline	Reformer-FC + Battery	Direct
	Methanol	Reformer-FC + Battery	Direct
	Hydrogen	FC + Battery	Direct
2020 Advanced Vehicle Electric	Electricity	Battery	Direct

Abbreviations: ICE – Internal combustion engine
SI – Spark ignition
CI – Compression ignition
DI – Direct injection
FC – Fuel cell
CVT – Continuously variable transmission

The characteristics and fuel consumption of that base case vehicle are shown below, Table 1.4, for comparison with the 1996 reference vehicle. Fuel economy—1.76 MJ/km (43.2 mpg) for the 2020 car versus 2.73 MJ/km (27.8 mpg) for the 1996 car—is a value that weights US Federal driving cycles as 55% urban/45% highway. As noted in the introduction to this Section 1.4, the fuel economies reported in this section include only energy consumed on the road and not energy consumed in making and delivering fuels and vehicles.

Table 1.4. Base Case and Reference Gasoline ICE Vehicles

Year	Vehicle	Loaded Mass, kg	Power/Wt. Ratio, W/kg	Fuel Consumption		
				MJ/km	mpg	% of Base
1996	Reference	1444	76.0	2.73	27.8	156
2020	Base Case	1236	75.0	1.75	43.2	100

The key conclusion from Table 1.4 is that about a 35% decrease in fuel consumption could be obtained by development of current technologies without sacrifice of capacity, performance or convenience characteristics important to consumers. A corollary of that conclusion is that new technologies introduced in the future have smaller advantages over traditional technologies than they would seem to have if compared to the current state of the art rather than to the evolved car of 2020.

To achieve the next increment of fuel economy, our assessments moved to technologies using advanced body designs emphasizing lighter-weight materials along with the evolving improved ICEs. (We judged that further ICE improvements would be modest and the cost high.) This step results in fuel consumption decreased by 12% (for the SI version) to 23% (for the CI diesel version) over the base case vehicle as shown in Table 1.5. Fuel economies are expressed here, and elsewhere unless otherwise stated, in MJ/km or as miles per energy-equivalent gallon of gasoline regardless of the actual fuel.

Table 1.5 Fuel Economies for Advanced ICEs and Bodies

Vehicle	Loaded Mass, kg	Power/Wt. Ratio, W/kg	Fuel Consumption		
			MJ/km	mpg	% of Base
Base Case SI ICE	1236	75.0	1.75	43.2	100
Advanced SI ICE	1136	75.0	1.54	49.1	88
Advanced CI ICE	1191	75.0	1.36	56.0	77

Still larger gains in fuel economy with ICE vehicles result from taking one more step in vehicle complexity and cost—hybrid systems using parallel combinations of advanced DI ICEs and storage batteries with associated inverters, controls, motors, and regenerative braking. The storage battery characteristics assumed for specific pulse power (800 W/kg) are somewhat higher than those of today's nickel metal hydride batteries but within the expected development potential for this battery technology. The specific energy for these hybrid EV batteries is high enough to not be a critical factor. Section 3.4.1 discusses the effects of battery technology on vehicle mass and efficiency. Taking this step, as Table 1.6 shows, gives fuel consumptions relative to the base case vehicle of 61% for the gasoline SI car, 59% for the CNG car, and 53% for the diesel CI car.

Table 1.6 Fuel Economies for Advanced ICE Hybrid Vehicles

Vehicle	Loaded Mass, kg	Power/Wt. Ratio, W/kg	Fuel Consumption		
			MJ/km	mpg	% of Base
Base Case SI ICE	1236	75.0	1.75	43.2	100
Advanced Gasoline SI ICE	1154	75.0	1.07	70.8	61
Advanced CNG SI Hybrid	1172	75.0	1.03	73.4	59
Advanced Diesel CI ICE	1192	75.0	0.92	82.3	53

A more dramatic change in technologies, but not in fuel consumption, results from replacing ICEs with fuel cells. We have assessed three hybrid fuel cell technologies, all using PEM fuel cell stacks, with hydrogen feed from (a) a gasoline reformer, (b) a methanol reformer, and (c) compressed hydrogen in on-board tanks. Since none of these fuel propulsion system components has been developed and introduced on a commercial scale, there is considerable uncertainty about ultimate weights, volumes, performance, and costs and our assessments are accordingly qualified as noted at the beginning of this Section 1.4. For fuel cell hybrids, we made the same assumptions about batteries and associated electrical equipment as in the case of ICE hybrids.

Table 1.7 gives our results for fuel cell hybrid vehicles. The methanol and gasoline reformer vehicles we evaluated have no fuel economy advantage over ICE hybrids—in fact they are not as good. However, hydrogen fuel cell vehicles are about 12% more efficient than the best other technology assessed, the diesel ICE CI hybrid, judging by consumption of fuel on board and neglecting the fuel cycle. (An advantage of 12% is indicative but inconclusive, given the uncertainties in our results.) A critical assumption in our hydrogen fuel cell system concerns on-board hydrogen storage. That is, we assume that hydrogen tanks can be developed with capacity, weight, volume, and shape that will permit competitive driving range without compromising other qualities such as passenger and cargo space.

Table 1.7 Fuel Economies for Advanced Fuel Cell Hybrid Vehicles

Vehicle	Loaded Mass, kg	Power/Wt. Ratio, W/kg	Fuel Consumption		
			MJ/km	mpg	% of Base
Base Case SI ICE	1236	75.0	1.75	43.2	100
Gasoline Reformer FC	1458	75.0	1.79	42.3	102
Methanol Reformer FC	1375	75.0	1.33	56.9	76
Hydrogen Gas FC	1314	75.0	0.81	94.1	46

Finally, we assessed one other technology, the battery-electric car assuming that battery technology will achieve by 2020 the commercial goals of the US Advanced Battery Consortium, namely a specific energy of 150 Wh/kg and a specific power of 300 W/kg (US ABC, 2000). These targets represent the battery performance required to produce an acceptable EV. They are not currently attainable. The results are shown in Table 1.8.

Table 1.8 Performance of Battery-Electric Vehicles

Vehicle	Loaded Mass, kg	Power/Wt Ratio,W/kg	Fuel Consumption			Range, km	
			MJ/km	mpg	% of Base	City Driving	Highway Driving
Base Case SI ICE	1236	75.0	1.75	43.2	100	541	743
Battery-Electric	1312	75.0	0.51	149	29	360	494

The electric vehicle design reported in Table 1.8 is not fully comparable to other systems because it has a range of only about 2/3 of the range of the baseline vehicle, or any of the other vehicles assessed. However, that range may be acceptable to many customers and changing the design to match the range and other capabilities of other technologies would result in large increases in weight and cost of an already-costly vehicle, and would decrease interior space. See Chapter 3 for more details.

1.4.4 Vehicle Prices

Vehicle prices were estimated by adding to or subtracting from the price of a baseline vehicle (our 1996 "reference" gasoline ICE car) to allow for adding or subtracting components which change the vehicle configuration. Some changes that increase vehicle fuel efficiency will add to the price, such as the substitution of aluminum for steel. But experience suggests that other changes may not; for example, tires have improved in rolling resistance, lifetime, and braking without increasing in cost.

Among the projected vehicle retail prices, the major uncertainties are associated with fuel cell vehicles—both the fuel cell stacks themselves, the reformers required to convert liquid fuel to hydrogen, and the auxiliary equipment needed to make a total power plant system. We have assumed a fuel cell system price of $60/kW which is near the lower, and optimistic, end of published estimates.

Details of our assumptions for developing vehicle prices can be found in Table 3.6 of Chapter 3. Table 1.9 summarizes the prices and fuel consumptions for the ten 2020 vehicles we assessed. We have focused so far on the quantified energy and cost characteristics of these various promising new vehicle technologies. Many other propulsion system and vehicle attributes are important, too, especially to vehicle purchasers/users. Examples are: safety features, convenience attributes (such as widespread fuel availability, fast refueling, starting ease, substantial trunk cargo space, towing capacity, interior climate control, easy viewing, ease of entry and exit); enjoyment attributes (such as smooth driveability, responsiveness, low interior and exterior noise); design and manufacturing attributes (such as technology scaling over a wide range of vehicle sizes, durability, reliability, warranty issues); distribution, sales, and service attributes (such as reliability, ease of service, mid-life replacement of expensive components such as batteries). New technologies are likely to be different from mainstream technologies in many of these attributes. It is important to remember that it takes many iterations for vehicle technologies to evolve to the point at which they satisfy market (and thus indirectly manufacturing) requirements. We discuss these issues more fully for the different major stakeholders in Chapter 5.

1.4.5 Vehicle Summary

In this section we summarize the results from Table 1.9 on vehicle prices and energy consumption presented previously. The uncertainties in our calculations should be kept in mind although we did not calculate sensitivities to particular assumptions as we did for fuels. A rough estimate of those uncertainties is about ±10% for technologies with non-electric propulsion system components, about ±20% for hybrid ICE technologies, and about ±30% for the newer developing technologies of fuel cells and new batteries. GHG emissions have not been discussed in this section since the consumption on the road of 1 MJ of energy of any fuel assessed results in the emission of GHGs in accordance with the data of Table 2.1.

- Evolutionary development of traditional gasoline ICE vehicle technologies could result in a "baseline" vehicle that cuts fuel consumption by 35% from current cars with only a small, say 5%, increase in vehicle price.

Table 1.9 Summary of Vehicle Operating Fuel Consumption and Price

2020 Technology (ex Reference)	Fuel	Fuel Consumption		Vehicle Purchase Price	
		MJ/km	% of Base	1997$	% of Base
1996 Reference, SI-ICE	Gasoline	2.73	156	17,200	96
Base case, evolutionary SI-ICE	Gasoline	1.75	100	18,000	100
Advanced SI-ICE	Gasoline	1.54	88	19,400	108
Advanced CI-ICE	Diesel	1.36	77	20,500	114
Hybrid SI-ICE	Gasoline	1.07	61	21,100	117
Hybrid CI-ICE	Diesel	0.92	53	22,100	123
Hybrid SI-ICE	CNG	1.03	59	21,600	120
Hybrid reformer FC	Gasoline	1.79	102	23,400	130
Hybrid reformer FC	Methanol	1.33	76	23,200	129
Hybrid FC	Hydrogen	0.81	46	22,100	123
Battery electric	Electricity	0.51	29	27,000	150

- Further development of ICE vehicles, both powertrains and bodies, could reduce fuel consumption to 88% (for gasoline) or 77% (for diesel) of the baseline at cost increases of 8% and 14% respectively.
- An additional change, to ICE hybrids, and a more efficient engine-transmission combination, can reduce energy consumption to 61% (for gasoline) or 59% (for CNG) or 51% (for diesel) of the baseline at cost increases of 17%, 20%, and 23% respectively.
- The change to fuel cell hybrids with liquid (methanol or gasoline) fuel reformers results in higher fuel consumption and higher cost than ICE hybrids. However, hydrogen fuel hybrid vehicles are estimated to be very fuel efficient (46% of the baseline energy use) with costs 23% above baseline.
- If the commercial objectives for battery performance of the US Advanced Battery Consortium can be achieved, battery-electric vehicles would have a consumption of on-board energy much lower than any other technology although with a restricted range and at high purchase cost (50% above the baseline). However, that on-board energy efficiency comes at the cost of high energy inefficiencies in the fuel cycle as section 1.6 shows.
- A potential barrier for new technologies is developing and displaying satisfactory levels of the desirable, less-quantifiable, attributes that customers have come to expect in family cars. Those attributes, discussed above, include elements of convenience, enjoyment, safety, design and manufacturing suitability, and sales and service.

1.5 Energy Use and Emissions in Vehicle Manufacturing

In Table 1.2 we showed that energy consumed in the fuel cycle could range from 14% (for petroleum diesel fuel) to 90% (for F-T diesel fuel) to 216% (for electric power) of the energy in the "fuel" loaded into the vehicle tank. In addition to these fuel cycle losses, a complete life cycle analysis shows that there are additional energy losses incurred in manufacturing the vehicle, so-called embodied losses. They can be significant too and should not be overlooked. For our designs, embodied energy consumption ranges from 13% (for the baseline vehicle) to as much as 53% (for the battery-electric vehicle) of the energy in the fuel loaded into the tank over the life of the vehicle. Those energy losses assume that 95% of vehicle metals and 50% of vehicle plastic will be recycled. If more virgin material is used, embodied energy consumption would be higher. This section deals with vehicle manufacturing energy use and emissions and how they might change as a result of introducing new vehicle technologies. More detail can be found in Chapter 4.

Manufacturing energy is a term used here to include the energy used in producing the materials used to make the vehicle, in forming and assembling those materials, and in distribution—moving the vehicle to the customer.

The production of vehicle materials accounts for the largest share of manufacturing energy. Table 1.10 below lists the energy requirements in MJ per kg of material produced with and without recycling, for typical materials used in the vehicle.

Table 1.10 Energy Required to Produce Vehicle Materials, MJ per kg

	Virgin, No Recycling	100% Recycling
Ferrous Metals	40	30
Plastics (average)	90	45
Aluminum	220	40
Rubber	70	--
Glass	30	15

The importance of recycling to reduce manufacturing energy use is apparent in Table 1.10, especially for aluminum, which is used extensively in all our 2020 vehicle designs except for the baseline. It is not clear how extensively recycled aluminum can be reused in automotive applications; it may have to find other end uses and that may be difficult for the large amounts of aluminum that could be used in automobiles.

The amounts of selected materials used in three of our designs are listed in Table 1.11 (Table 4.1 of Chapter 4 lists all materials for all designs).

Total material energy consumption for each vehicle can be calculated by multiplying the materials usage for each design (Table 1.11) by unit energy consumption for each material (Table 1.10) with assumptions about the degree of recycling for each material. Just as unit energy consumptions were estimated for producing each material, we can also estimate unit CO_2 emissions during materials production and combine those CO_2 values for the whole vehicle just as the energy use values are combined. Table 1.13 shows both energy use and CO_2 emissions for producing all the materials in the same three vehicle designs illustrated above. Two cases are listed, one using all virgin materials and one using all recycled materials.

Table 1.11 Selected Materials Usage in Three Vehicle Designs: kg

	1996 Reference Gasoline ICE	2020 Baseline Gasoline ICE	2020 Hydrogen Hybrid Fuel Cell
Ferrous metals	886	667	477
Aluminum	81	97	355
Plastics	100	97	99
Rubber	54	50	50
Glass	35	35	35
All others	167	162	161
Total materials, kg (ex fuel and payload)	1323	1108	1177

The higher values in Table 1.12 for the hydrogen fuel cell vehicle reflect, as noted previously, the high use of aluminum in all 2020 designs except for the baseline. In fact aluminum accounts for over half of all energy use and CO_2 emissions for virgin materials in that vehicle. The importance of being able to use recycled aluminum is apparent.

Table 1.12 Energy Consumption and CO_2 Emissions During Production of Vehicle Materials

	1996 Reference Gasoline ICE	2020 Baseline Gasoline ICE	2020 Hydrogen Hybrid Fuel Cell
Energy Use (GJ)			
All virgin	78	75	126
All recycled	43	37	43
CO_2 Emissions (kgC)			
All virgin	1580	1490	2280
All recycled	810	700	810

In addition to the energy used for production of materials, we estimate that perhaps another 22-29 GJ of primary energy—with corresponding CO_2 emissions—are required to fabricate the vehicle from its materials and to deliver it to customers. (See Chapter 4 for more details.)

1.6 Integrated Life Cycle Results and Stakeholder Impacts

This section combines the cost, energy use, and emissions data of sections 1.3 to 1.5 (covering the fuel cycle, vehicle operation, and vehicle manufacturing) to give integrated results for new technologies over their total life cycles. It also discusses how those results, and other characteristics of these technologies, affect the major stakeholder groups.

1.6.1 Life Cycle Costs

From the perspective of the owner-operator of a new passenger car, vehicle costs fall into two broad categories: variable costs (such as fuel, which depend on how much the car is driven) and fixed costs (such as finance charges, which are independent of vehicle use). Fixed costs for new cars are much higher. However, as cars grow older and fixed costs decline, variable costs which include taxed fuel become larger and more conspicuous shares of the total.

In Table 1.13 below we have listed both fixed and variable costs for each of the ten 2020 technologies assessed, expressed as ¢ US (1997) per kilometer driven. The key assumptions in this table are:

- The numbers apply to purchasers of new passenger cars in the US.
- Vehicles are driven 20,000 km/year.
- Fuel taxes per MJ are equivalent to current US taxes on gasoline.
- Capital costs (depreciation and financing) are equal to an annual charge of 20% on vehicle purchase price.
- The capital charge, and other costs listed, are consistent with current US experience (Davis, 1999).
- Lacking better data, the table reflects cost changes due to vehicle purchase price and fuel price, but not to other technology characteristics such as need for maintenance and repair.
- Vehicle purchase prices are also shown since they often have more influence over purchase decisions than operating costs.

Table 1.13 Operating Costs for New Passenger Cars in 2020, ¢ (1997)/km

2020 Technology (Vehicle Price)	Total	Fixed	Variable
Baseline gasoline ICE ($18,000)	30.6	25.0	5.6
Advanced gasoline ICE ($19,400)	32.1	26.8	5.3
Advanced diesel ICE ($20,500)	32.8	28.1	4.7
Hybrid gasoline ICE ($21,200)	34.1	29.2	4.9
Hybrid diesel ICE ($22,200)	34.8	30.4	4.4
Hybrid CNG ICE ($21,700)	34.6	29.7	4.9
Hybrid gasoline FC ($23,400)	37.3	31.7	5.6
Hybrid methanol FC ($23,200)	36.5	31.5	5.0
Hybrid hydrogen FC ($22,100)	35.7	30.3	5.4
Battery electric ($27,000)	40.8	36.3	4.5

What is conspicuous, but not surprising, about the costs in Table 1.13 is that total costs per kilometer for a new-car customer are made up primarily of fixed costs (which depend overwhelmingly on purchase price of the vehicle) and not on variable costs which include fuel. If fuel were taxed per MJ at the high U.K. rate for gasoline rather than at the low US rate of Table 1.13, both variable costs and total costs in the table would increase by about 2 to 5¢/km for all technologies assessed (except battery electric cars).

An expanded version of Table 1.13 can be found as Table 5.2 in Chapter 5.

1.6.2 Life Cycle Energy Use and GHG Emissions

Energy use and GHG emissions can also be combined by adding the three different stages of the life cycle, again using the data from sections 1.3 to 1.5 which cover the fuel cycle, vehicle operation, and vehicle manufacturing (embodied energy and emissions). Table 1.14 shows the results. We assume that embodied energy and emissions are prorated over the vehicle's lifetime, 15 years at 20,000 km per year. Also, we assume that 95% of vehicle metals and 50% of vehicle plastics are recycled. These rates are higher than current practice, but recycling is likely to increase in the future, especially if manufacturers are required to accept responsibility for scrapped vehicles. In any case, the relative ranking of technologies will not be affected since the same level of recycling is assumed for all. Other assumptions are the same as in Table 1.13. One additional technology case is added—the use of Fischer-Tropsch diesel rather than petroleum diesel as the fuel in the advanced diesel hybrid technology.

The Table 1.14 ranking of technologies with respect to energy consumption or GHG emissions on a life-cycle basis is not the same as the ranking based solely on vehicle operation on the road, as in Table 1.19; the latter is the familiar "miles per gallon" criterion. To illustrate, Table 1.15 shows how energy consumption and GHG emissions from each technology compare, relative to the baseline, if compared on a life cycle basis and if compared on an operation-only basis.

Table 1.14 Life-Cycle Energy Use and GHG Emissions for New Fuel and Vehicle Technologies

2020 Technologies	Total Energy MJ/km	Total GHG Emitted gC/km
Baseline gasoline ICE	2.34	47
Advanced gasoline ICE	2.08	42
Advanced diesel ICE	1.77	37
Hybrid gasoline ICE	1.53	30
Hybrid petrol. diesel ICE	1.28	27
Hybrid CNG ICE	1.45	24
Hybrid F-T diesel ICE	2.02	31
Hybrid gasoline FC	2.44	49
Hybrid methanol FC	2.32	38
Hybrid hydrogen FC	1.69	34
Battery electric	1.88	33

Further details can be found in Tables 5.3 and 5.4 of Chapter 5.

Table 1.15 Comparison of Energy Consumption and GHG Emissions on Life-Cycle and Vehicle Operation Bases

2020 Technologies	Relative Energy Consumption		Relative GHG Emissions	
	Life Cycle Basis	Vehicle Operation Only	Life Cycle Basis	Vehicle Operation Only
Baseline gasoline ICE	100	100	100	100
Advanced gasoline ICE	89	88	89	88
Advanced diesel ICE	76	77	78	82
Hybrid gasoline ICE	65	61	63	61
Hybrid petrol. diesel ICE	55	53	56	56
Hybrid CNG ICE	62	59	51	45
Hybrid F-T diesel	86	53	66	54
Hybrid gasoline FC	104	102	104	102
Hybrid methanol FC	99	76	80	73
Hybrid hydrogen FC	72	46	72	0
Battery electric	80	29	69	0

Differences between life cycle and operation-only rankings of energy consumption increase as energy consumption (per unit of fuel) in the fuel cycle increases (as in making F-T diesel) and/or as unit fuel consumption during operation decreases (as in hydrogen fuel cell or battery-electric cars).

Differences between life cycle and operation-only rankings of GHG emissions are most conspicuous, obviously, when the on-board fuel contains no carbon at all (as in hydrogen or electric power).

Figure 1.3 (next page) is a graphic summary of the results shown in Tables 1.13 and Table 1.14. The bars of uncertainty are not based on sensitivity analyses but rather reflect our reasonable estimates of uncertainty. Many calculations in this report are expressed in two or three significant figures for consistency and ease in cross-calculations. However, our confidence in our numerical results is expressed better by the bars of Figure 1.3 than by those significant figures.

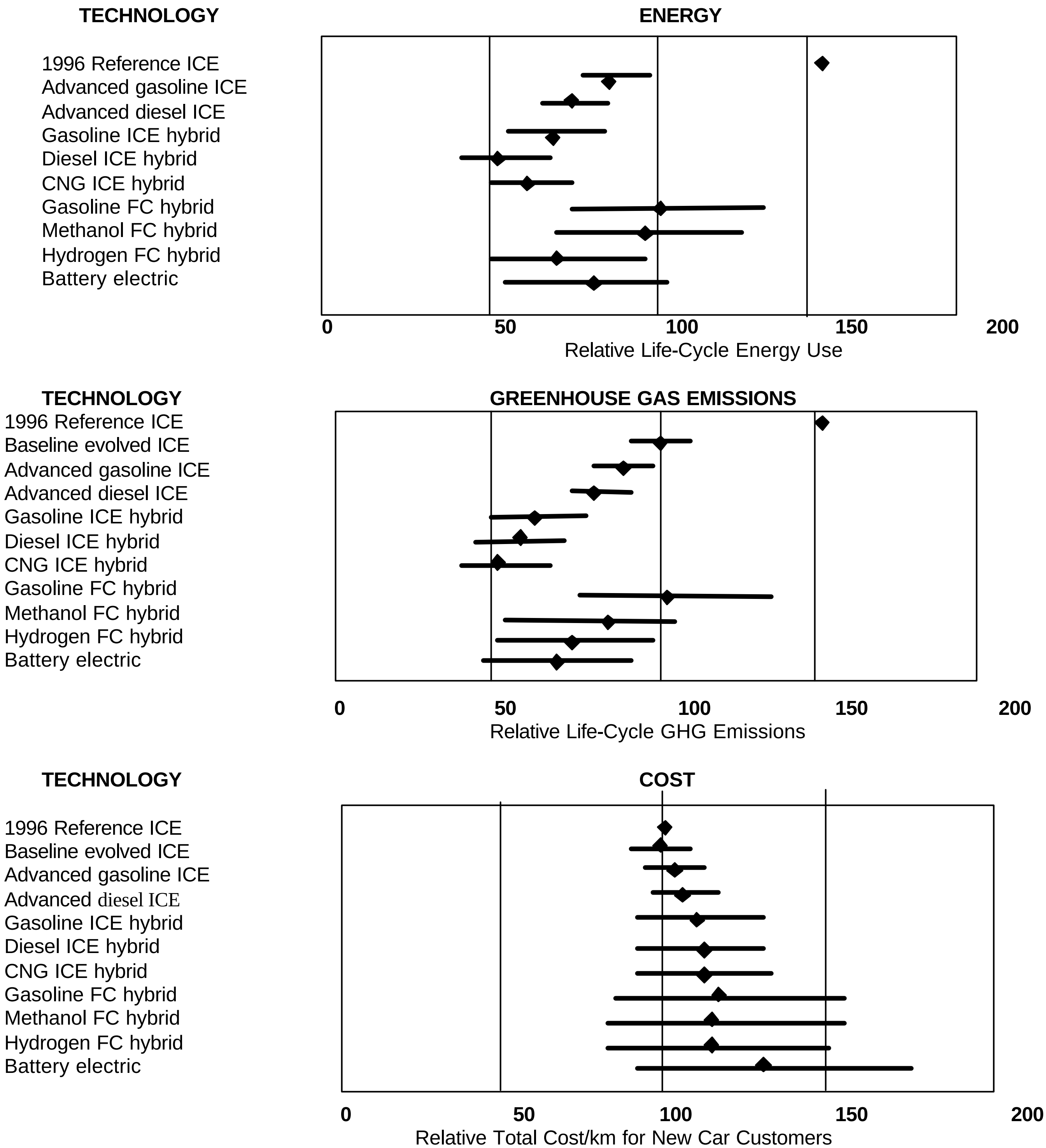
It is worth repeating here some of the qualifications expressed in Section 1.2.2 (Limitations). The results summarized in Figure 1.3 for energy consumption and GHG emissions have been calculated for average-size passenger cars in 2020 with about the same vehicle attributes as today's average cars, and with a specific driving pattern, namely the US FTP combined urban/highway cycles. The expectations and choices of consumers over the next 20 years may change, and new government policies or regulations may emerge, and either or both can affect the degree to which reduction in energy consumption or GHG emissions will be realized in the total on-the-road fleet.

1.6.3 Stakeholder Impacts

The cost, energy use, and emissions characteristics described in sections 1.6.1 and 1.6.2 will affect different stakeholders in different ways. In addition, other less-quantifiable

Figure 1.3 Life-Cycle Comparisons of Technologies for New Mid-Sized Passenger Cars

- All cars are 2020 technology except for 1996 “Reference” car
- ICE = Internal Combustion Engine, FC = Fuel Cell
- 100 = 2020 evolutionary “baseline” gasoline ICE car
- Bars show estimated uncertainty



characteristics of these technologies will be important to different stakeholder groups. We undertook a "template" analysis to identify those other characteristics and to note the potential for impacts on particular stakeholder groups (see Chapter 5A.1). This section summarizes the major impacts of the 2020 technologies on each stakeholder group.

It seemed useful to divide those impacts into two major categories, namely, impacts during transition to new technologies over the next 20 years or so, and continuing impacts at 2020 or beyond once the new technologies are in place.

Transitional Issues for Alternative Technologies over the Next Two Decades. The evolutionary baseline vehicle system is expected to show significant improvements over the vehicle and fuel technologies employed today. These are considered as a normal path of change, and it is assumed that local environmental emissions will continue to decrease through regulatory pressures. Because these evolutionary changes appear to involve the lowest cost among the options considered, they are a likely future path unless pressure to reduce GHG (especially carbon) emissions from the transportation sector becomes a much higher societal or governmental priority. The alternatives considered offer different levels of GHG reduction through a number of system options which have different impacts on different stakeholders.

We also note that market competition, under uncertain future regulatory constraints, also will influence technology choices. Alternative fuels will be facing a robust competitor in the petroleum industry, where prices are substantially higher than production costs today creating room for aggressive price competition. This may inhibit or delay major private investments in alternative fuel infrastructures. In the interim, there are a number of small-scale experiments with a variety of fuels and with alternative vehicle systems. There are many players in these markets today and rapid changes are likely, as experience is gained in technology and with the market performance. Major new infrastructure costs are sufficiently high that responsible investment requires the new infrastructure meet even longer term goals to avoid poor choices and wasted capital. New methodologies are needed to sort out robust strategies that meet the future needs of large groups of stakeholders in various parts of the world and also ensure environmental responsibility.

Here is a summary list by stakeholder, taken from Section 5.3, of the major transitional issues that may be important:

- **Vehicle Purchaser**
  - Increases in costs and/or decreases in performance/amenities
  - Problems with availability and refueling convenience of new fuels (especially in early introduction, although first introduction with fleet applications would reduce this problem)
  - Safety of new vehicle in existing vehicle fleet
  - Uncertainty about technology reliability and serviceability
  - Interest in pioneering new technology?

- **Government (at all levels)**
  - International and national policy actions on GHG reduction
  - Implementation of GHG reduction mandates, if used, by locale, sector, etc.
  - Economic impacts/shifts related to new infrastructure investment
    - Major investments (offshore FT or methanol production)
    - Significant investments (debottleneck or expand natural gas or electric infrastructure, build clean methanol infrastructure)
  - Impacts on competitiveness in global markets
  - Safety management
    - Highway safety (crashworthiness, fleet size, traffic management)
    - Fuel safety (new standards for CNG, methanol, H_2)
    - New local safety and zoning requirements for fueling stations
  - Environmental stewardship and social equity issues

- **Vehicle Manufacturer**
  - Marketing challenges (cost, performance, amenities) – constrained by future government requirements?
  - Technological challenges
    - Clean diesel technology
    - Hybrid and Fuel Cell system refinements
    - Sulfur guards for FC
    - CNG, H_2, and battery energy storage improvements
    - Advanced control systems to optimize performance
  - Recycling challenges (if driven by government requirements)
    - Alloys, plastics
    - Pt group metals for fuel cells and specialized catalysts in advanced after treatment systems
  - New suppliers (more electrical systems, system integrators, fuel cell suppliers, etc.)

- **Vehicle Distributor/Servicing/Recycling/Disposal**
  - New investment (by smaller companies?)
    - New service and inspection equipment for new technologies
    - New fuel facilities for servicing
  - Component recycling (batteries, Pt group metals, etc.)
  - Hiring/training to meet different and higher skill levels for employees

- **Fuel Manufacturer**
  - Major new offshore investment (FT plants, methanol, LNG?)
  - Infrastructure expansion and debottlenecking (CNG, H_2, electricity)

- **Fuel Distributor**
  - Significant investments (by smaller companies?)
    - New distribution infrastructure for ultra clean fuels (methanol, FT diesel, etc.)

        - Fuel station storage and transfer facilities for CNG and methanol
        - Reforming, storage and transfer facilities for H_2
    - Increased safety concerns
        - H_2 facilities including pressure transfer
        - Methanol (corrosion? poisonous? environmental fate?)
        - CNG pressure transfer
    - Longer fueling times (e.g., CNG, H_2)
    - Loss of fuel business (electricity)

Continuing Impacts of Alternative Technologies in 2020. In 2020, assuming that the vehicle and fuel alternatives to support each of the technology combinations evaluated are in place, then the major residual impacts of the change rest with the vehicle purchaser and the government. It is likely that the vehicle production and service companies, as well as the fuel producers and distributors, will have incorporated the impacts of transitional changes into their cost and operational structures. Thus, the major differences that will impact car purchasers and the government appear to be:

- **Vehicle purchaser**
    - Cost of transportation per km (or cost of new vehicle)
    - Safety (crashworthiness of lighter vehicle bodies; fueling)
    - Performance (including acceleration, load and towing capacity, noise, odor, comfort, style, and level of amenities)
    - Fuel availability and refueling convenience
    - Reliability and convenience of servicing

- **Government**
    - Level of GHG reduction and economic impacts
    - Reduction in local pollution problems
    - Change in petroleum dependence
    - Changes in public safety (fueling, vehicle)

To move to most of these new technologies in 2020 will require a change in customer behavior – whether forced by the government or voluntary. It is difficult to foresee how the governments worldwide may react to climate change issues as more information emerges over the next two decades. Auto buyers may ultimately move to different purpose vehicles – perhaps a compact efficient vehicle for local errands and commuting and a larger rented vehicle for a long distance trip. While we do not include behavioral change in this study, it is important to realize that it will be a powerful factor in future choices of road vehicle alternatives.

1.7 Conclusions

The results of this study depend importantly on the methodologies and assumptions we chose. The following broad conclusions are drawn from calculations for specific combinations of technology as used in a mid-size passenger car operated over the standard US urban/highway driving test cycles. All our quantitative results are subject to the uncertainties expected in projecting 20 years into the future, and those uncertainties are larger for rapidly developing technologies like fuel cells and new batteries.

- A valid comparison of future technologies for passenger cars must be based on life cycle analysis for the total system which includes assessment of fuel and vehicle manufacture and distribution in addition to assessment of vehicle performance on the road.
- Successful development and penetration of new technologies requires acceptance by all major stakeholder groups: private-sector fuel and vehicle suppliers, government bodies at many levels, and ultimate customers for the products and services. Therefore, the economic, environmental, and other characteristics of each technology must be assessed for their potential impacts on each of the stakeholder groups.
- Continued evolution of the traditional gasoline car technology could result in 2020 vehicles that reduce energy consumption and GHG emissions by about one third from comparable current vehicles and at a roughly 5% increase in car cost. This evolved "baseline" vehicle system is the one against which new 2020 technologies should be compared.
- More advanced technologies for propulsion systems and other vehicle components could yield additional reductions in life cycle GHG emissions (up to about 50% lower than the evolved baseline vehicle) at increased vehicle purchase and use costs (up to about 20% greater than the evolved baseline vehicle).
- Vehicles with hybrid propulsion systems using either ICE or fuel cell power plants are the most efficient and lowest-emitting technologies assessed. In general, ICE hybrids appear to have advantages over fuel cell hybrids with respect to life cycle GHG emissions, energy efficiency, and vehicle cost, but the differences are within the uncertainties of our results and depend on the source of fuel energy.
- If automobile systems with drastically lower GHG emissions are required in the very long run future (perhaps in 30 to 50 years or more), hydrogen and electrical energy are the only identified options for "fuels", but only if both are produced from non-fossil sources of primary energy (such as nuclear or solar) or from fossil primary energy with carbon sequestration.

Again, these conclusions are based on our assessment of representative future technologies, with vehicle attributes held at today's levels. The expectations and choices of customers may change over the next twenty years and such changes can affect the extent to which potential reductions in GHG emissions are realized.

1.8 Project Management

1.8.1 Research Participants

The work described in this report was carried out by:

- Felix F. AuYeung, Graduate student, Mechanical Engineering

- Dr. Elisabeth M. Drake, Associate Director, Energy Laboratory
- Prof. John B. Heywood, Sun Jae Professor of Mechanical Engineering and Director, Sloan Automotive Laboratory
- Dr. Andreas Schafer, Research Associate; Center for Technology, Policy, and Industrial Development
- Darian Unger, Graduate student, Technology and Policy Program
- Dr. Malcolm A. Weiss, Senior research staff, Energy Laboratory

Dr. Drake, Prof. Heywood, and Dr. Weiss served as Co-Principal Investigators of the work, and Dr. Weiss also functioned as project manager.

The primary authors of the chapters in this report were:

Executive Summary, 1. Overview, and 2. Fuels	Weiss
3. Vehicle Design, Performance, and Costs in 2020	AuYeung, Heywood, Schafer
4. Energy Use and Emissions in Vehicle Materials Production, Assembly, Distribution, Maintenance, and Disposal	Schafer
5. Integrated Impacts and Shareholder Views of New Technologies	Drake

1.8.2 Funding

This study was undertaken under the auspices of the MIT Energy Laboratory and the MIT Alliance for Global Sustainability. Specific support was provided initially in October 1998 by the V. Kann Rasmussen Foundation. Additional support was received in 1999 and 2000 from Chevron Corporation, ExxonMobil Corporation, Ford Motor Company, Norsk Hydro AS, and Saudi Arabian Oil Company.

1.8.3 Peer Review

Earlier drafts of this report were submitted for comment to our industrial sponsors and to eight independent experts in the US and Europe. We received written reviews from all, totaling about 100 single-spaced pages of both general and specific comments.

Sponsor reviewers included members of the staff of:

- Chevron Corporation
- ExxonMobil Corporation
- Ford Motor Company
- Norsk Hydro AS
- Saudi Arabian Oil Company

Independent expert reviewers included the following, with current affiliations shown only for identification purposes:

- John DeCicco, American Council for an Energy-Efficient Economy
- Meinrad Eberle, Paul Scherrer Institute, Villigen, Switzerland
- David Greene, Oak Ridge National Laboratory
- Bernd Hoehlein, Forschungszentrum Julich, Institute IWV-3, Germany
- Fritz Kalhammer, Consultant, PNGV Review Committee
- Craig Marks, University of Michigan, PNGV Review Committee
- Peter Teagan, Arthur D. Little, Inc.
- Michael Wang, Argonne National Laboratory

We invited all reviewers to a one-day workshop at MIT on August 28, 2000. The purpose of the workshop was to discuss the major issues raised in the reviews, to help MIT to better understand the suggestions for revision, and to help the reviewers to better understand MIT's intentions and methods in the report. All reviewers participated in the workshop except representatives of Chevron Corporation and Norsk Hydro, and Meinrad Eberle. Sean Casten substituted for Peter Teagan of Arthur D. Little. All MIT researchers participated except Darian Unger. The reviews and workshop were of significant value to us in preparing a clearer and more focused final report. However, this final report is entirely the responsibility of the MIT researchers listed in Section 1.8.1.

Chapter 2. Fuels

This chapter characterizes the fuel cycles of each of the individual fuels assessed in this study. The fuel cycles extend from recovery of the raw material for each fuel (such as crude oil) through conversion of that raw material to the final fuel (such as gasoline) and delivery of that final fuel into the tank of the passenger car.

Three characteristics of the fuel cycles are of particular concern here, each one quantified per unit of energy, say one MJ, delivered to the vehicle tank. The three are:

- Total energy consumed originating from raw materials or other energy sources
- Total greenhouse gases emitted from raw materials or other sources
- Total costs to the ultimate customer of the final delivered fuel

All three characteristics are assessed at the values we think likely in 2020, reflecting advances in technology, likely changes in product quality, and potential changes in prices of raw materials. All costs and prices are expressed in 1997 $US; the US Consumer Price Index was used to convert dollars of other years to 1997.

Although we have assessed GHG emissions during the fuel cycle, we have not tried to assess other air emissions such as particulates, carbon monoxide, and non-methane hydrocarbons. That choice is based on two considerations: first, the data available to us are limited and disparate; second, since most fuel-cycle non-GHG emissions come from point sources, they can be reduced in the future if necessary although at a cost.

The GHGs considered in this report are CO_2 and CH_4. N_2O was neglected because its greenhouse contribution for each of the fuel cycles assessed here totals less than 1.% of the other GHGs (Wang, 1999a; EIA, 1997). CH_4 was converted to an equivalent quantity of CO_2 using a multiplier of 21, the value for a 100-year time horizon (EIA, 1997). The unit of gC equivalent used here refers to the grams of carbon in the total CO_2 equivalent, i.e. $(CO_2 + 21\ CH_4) \times 12/44$.

2.1 Fuels Assessed

After a preliminary screening, we chose seven fuels for assessment. They include:

- Gasoline refined from petroleum
- Diesel fuel refined from petroleum
- Compressed natural gas (CNG)
- Fischer-Tropsch (F-T) diesel fuel synthesized from natural gas
- Methanol synthesized from natural gas
- Compressed hydrogen gas synthesized from natural gas
- Electric power drawn from the national grid

We concluded that other fuels that have been proposed, such as dimethyl ether or biofuels, are not likely to be used in more than additive quantities (totaling, say, less than 1% of all fuel used) in developed countries before 2020. Therefore, we limited our assessment to the seven fuels listed. In the longer term, other fuels may have more potential as a result of developing technology or changes in other circumstances.

Properties of the fuels assessed are shown in Table 2.1 and are used throughout this report. The heating values stated are all lower heating values (LHV), the convention in internal combustion engine (ICE) analysis. The convention for reporting heating values of some raw materials or fuels is the higher heating value (HHV), and a case can be made for using HHVs in assessing electrochemical conversion in fuel cells. However, we have used LHVs throughout for consistency. The ultimate life-cycle costs and GHG emissions are unaffected by that choice although some energy efficiencies in the fuel cycle (which is only part of the total life cycle) may be affected slightly.

Table 2.1 Fuel Properties

FUEL/RAW MATERIAL	DENSITY		LOWER HEATING VALUE (LHV)				CARBON CONTENT	
	g/l	lbs/gal	MJ/kg	kBtu/lb	MJ/l	kBtu/gal	wt%	gC/MJ
CRUDE OIL	845	7.05	42.8	18.4	36.2	130.0	85.0	19.9
CONVENTIONAL GASOLINE	737	6.15	43.7	18.8	32.2	115.5	85.5	19.6
CONVENTIONAL DIESEL	856	7.14	41.8	18.0	35.8	128.5	87.0	20.8
METHANE (NATURAL GAS)	0.719	--	50.0	21.5	0.0360	--	75.0	15.0
FISCHER-TROPSCH DIESEL	770	6.43	43.0	18.5	33.1	118.8	86.0	20.0
METHANOL	792	6.60	20.1	8.64	15.9	57.0	37.5	18.7
HYDROGEN	0.0899	--	120.0	51.6	0.0108	--	0	0

Source: Wang (1999c) except that methane (100% CH_4) is used here as a surrogate for natural gas, which varies in composition. Liters are stated at 0º C and one atmosphere absolute pressure.

There are uncertainties in all our fuel cycle results as would be expected in projecting 20 years ahead. Obvious sources of uncertainty are potential advances in technology, changes in the prices of energy and other raw materials, or new requirements for product quality. For new fuels such as methanol or hydrogen, the largest uncertainty—and one that we have chosen not to analyze in this report—is transition: the provision of a fuel supply infrastructure that does not now exist, including facilities for manufacturing, storage, and distribution. Provision of those new facilities will require capital and operating expenses that must be reflected eventually in increased costs to the ultimate customer. Those transitional costs are not included in the “quasi-steady-state” numbers we have estimated for 2020.

2.2 Petroleum Fuels

The total costs of petroleum-based fuels delivered to the customer can be divided into three components: the refiner’s cost to purchase crude oil, the cost of refining, and the distribution cost, i.e. the cost of delivering the finished fuel from the refinery to the vehicle tank.

Of those three costs, the largest, and also the source of greatest uncertainty in the future, is the price paid for crude oil. That uncertainty is illustrated by the fact that spot crude oil sold for about $10/barrel (B) in December 1998—less than one-quarter of the maximum prices (in constant dollars) reached during the previous 20 years. However, only 21 months later, in September 2000, the spot NY price had risen to about $38/B. We have no basis for predicting that similar large excursions in price will, or will not, recur in the future. Therefore, we have assumed an average price of $22/B, the "reference" world oil price projected for 2020 by the US Department of Energy (EIA, 1999a), but with an uncertainty band of ± $10/B.

The second component of cost, refining crude oil to gasoline or diesel fuel, is also difficult to assess. Each refinery is unique in its specific facilities and mix of products, and each makes many products from many separate facilities within the refinery. Major products such as gasoline or diesel consist of blends of components produced by different facilities. Therefore, unequivocally allocating specific costs, or energy use, or emissions, to specific end products is difficult.

For this study, we have assumed refining cost to be equal to the refiners margin as reported by the US Department of Energy (e.g. EIA, 1999b). The "refiners margin" is not a "profit" but is simply defined as the average price at which refiners sell a gallon of finished fuel at the refinery gate to fuel resellers, minus the average price paid by the refiners to purchase a gallon of crude oil. The weighted average refiners margin for all grades of gasoline has ranged from 22 to 31¢/gallon since 1982, loosely correlated with crude oil price (perhaps because energy costs during refining tend to move in the same direction as crude oil prices.) For crude oil at $22, the margin we assume for gasoline is 30¢/gallon, the historical average plus 3¢/gallon for future sulfur reduction, with a sensitivity of 7¢/gallon for a change in crude oil price of $10.

Similarly, the average refiners margin for diesel fuel has ranged from about 12 to 20¢/gallon since 1982. For crude oil at $22, the margin we assume for diesel fuel is 20¢/gallon, the historical average plus 3¢/gallon for sulfur reduction, with a sensitivity of 4¢/gallon for a change in crude oil price of $7.

The increment of 3¢/gallon for sulfur reduction provides for additional oil processing to assure that future sulfur concentrations will be no higher than the currently projected US limits of 30 ppm for gasoline and 15 ppm for diesel fuel, far below current levels. Those projected limits may be further reduced by 2020. MathPro (2000) estimates that reducing sulfur concentrations in both gasoline and diesel fuel to 10 ppm will cost the European refining industry about 3¢/gallon. It is possible that other quality specifications for gasoline or diesel fuel will also change and will necessitate additional refining costs; however, we have made no allowance for such changes nor for offsetting improvements in refining technology or practice.

The third component of cost, distribution, can also be calculated from historical data collected by DOE. That cost is the retail price (determined by extensive regular sampling), ex sales and excise taxes, paid by individual customers at refueling stations minus the price charged by refiners to resellers at the refinery gate, referred to above. Distribution costs in the US have averaged about 15 to 16¢/gallon for gasoline and diesel fuel and we assume that they will not change through 2020.

The components of cost for both gasoline and diesel fuel are listed and totaled in Table 2.2. In reasonably rounded numbers, the totals are $8 ± $2½ per MJ for gasoline, and $6½ ± $2 for diesel fuel. The total uncertainties shown are almost one third of the averages.

Table 2.2 Retail Ex-Tax Costs of Petroleum Fuels in 2020
Crude Oil @ $22/B ± $10

	GASOLINE		DIESEL FUEL	
	$/GJ	¢/l	$/GJ	¢/l
CRUDE OIL	4.30 ± 1.96	13.8 ± 6.3	3.87 ± 1.76	13.8 ± 6.3
REFINERS MARGIN	2.46 ± 0.59	7.92 ± 1.9	1.48 ± 0.31	5.30 ± 1.1
DISTRIBUTION	1.23	3.96	1.18	4.22
TOTAL EX TAX	7.99 ± 2.55	25.7 ± 8.2	6.53 ±2.07	23.3 ± 7.4

The determination of energy consumption and GHG emissions during the refining of petroleum products faces the same problem of allocation among products discussed previously for the allocation of refining costs. One option is simply allocating a constant amount of energy use and GHG emissions per unit mass of product, regardless of the product, by dividing total refinery energy consumption and emissions by the total mass of products. However, we have chosen to retain the traditional distinctions between gasoline and diesel. A sampling of results reported by other investigators is shown in Table 2.3 for the total cycle: crude oil recovery and transportation plus refining plus distribution.

Energy consumption in Table 2.3 includes not only the consumption of crude oil during refining but also the consumption of externally supplied natural gas, electric power, or other energy sources in crude production, transportation, refining, and distribution. Consumption is expressed here both as MJ consumed per MJ of final fuel loaded aboard the vehicle, and as energy efficiency, i.e. the LHV of the loaded fuel divided by the LHV of all energy inputs into the fuel cycle.

Table 2.3 Energy Consumption in the Total Petroleum Fuel Cycle

	GASOLINE		DIESEL FUEL	
	MJ/MJ	Efficiency	MJ/MJ	Efficiency
HOEHLEIN (1998)	0.15	87%	0.12	89%
IEA (1999)	0.13 – 0.22	82-88%	0.09 – 0.13	82-92%
WANG (1999c)	0.24	81%	0.18	85%
JOSHI (2000)	0.14 – 0.27	78-88%	0.10 – 0.20	83-91%
ADL (1996)	0.21	83%	0.11	90%
OGDEN (1999)	0.09	92%	--	--
THIS STUDY	0.211	82.6%	0.139	87.8%

The total energy consumptions assumed in this study, shown in the last row of Table 2.3, are presented in more detail in Table 2.4. The numbers in Table 2.4 display our judgments about reasonable average values after examining the references listed in Table 2.3 and elsewhere. Increases of 7% in refining energy use and CO_2 are included in the Table 2.4 numbers to provide for sulfur reduction in the future (MathPro, 2000).

Table 2.4. Energy Use and GHG Emissions for Petroleum Fuels in 2020

	GASOLINE		DIESEL FUEL	
	(MJ/MJ gasoline)	Energy Efficiency of Stage	(MJ/MJ diesel)	Energy Efficiency of Stage
ENERGY USE				
CRUDE OIL	0.042	96.5%	0.040	96.5%
REFINING	0.157	86.6%	0.089	91.9%
DISTRIBUTION	0.012	98.8%	0.010	99.0%
TOTAL	0.211	82.6%	0.139	87.8%
	gC equivalent per MJ gasoline		gC equivalent per MJ diesel	
GHG EMISSIONS				
CO_2	4.2		2.8	
METHANE	0.7		0.5	
TOTAL	4.9		3.3	

2.3 Compressed Natural Gas

Compressed natural gas (CNG) has been used in many countries as a fuel for passenger cars for many years but it has never captured a significant share of the market in Europe, North America, or Japan. Lawrence Berkeley Laboratory (Sathaye, 1988) and the US General Accounting Office (US GAO, 1991) have described some international experiences in trying to introduce CNG and other alternative fuels.

In general, CNG is supplied by local fueling stations which receive natural gas from the pipeline distribution system and which then compress and store the gas for dispensing at about 200 atmospheres to vehicles.

The customer cost for CNG is the cost of pipeline gas to the local station plus the cost of operating the station. For the former, we have used the cost of gas to US commercial customers projected by DOE (EIA, 1999a) for 2020--$5.7/GJ. For the cost of operating the station (with a capital cost of about a million dollars), we have used the cost reported by Wang, 1998--$4.0/GJ. The total cost to the customer is thus $9.7/GJ, as shown in Table 2.5.

Table 2.5 Compressed Natural Gas in the US in 2020

Per MJ or GJ of natural gas delivered to vehicle at 200 atmospheres

		SOURCES
COST OF PIPED NATURAL GAS ($/GJ)	5.7 ± 0.4	EIA (1999a)
SERVICE STATION COSTS ($/GJ)	4.0 ± 0.4	Wang (1998)
TOTAL DELIVERED COST ($/GJ)	9.7 ± 0.8	
ENERGY CONSUMPTION (MJ/MJ)	0.18	Wang (1999a)
CARBON EQUIVALENT EMISSIONS (gC/MJ)	4.2	Wang (1999a)

Energy consumption and equivalent carbon emissions are also shown in Table 2.5. They reflect CO_2 produced and methane leaked in the production, transmission, and local station steps on the way from well to customer. We have used the data of Wang, 1999a, for both energy consumption and emissions.

2.4 Liquid Fuels from Remote Natural Gas

We assume that widespread future use of methanol and Fischer-Tropsch diesel synthesized from natural gas would require those fuels to be manufactured in new large plants located where large quantities of low-price gas are available. At such "remote" locations, gas is priced low because it cannot be moved economically by pipeline to more-rewarding markets. Some remote gas is associated with the production of crude oil and may now be vented, flared, or reinjected into oil reservoirs. Potential supplies of remote gas are located in many places around the world and the differences among those places compounds the uncertainty of estimating future costs of making F-T diesel or methanol.

The specific location of a remote-gas plant affects:

- The extent of the infrastructure that must be built to support the plant itself\
- The costs of constructing and operating the facilities, both plant and infrastructure
- The price of gas available at the site
- The non-technical risks (such as political and cultural) at the site and thus the rate of return required by the investor

An illustration of these site effects was provided by US DOE, 1989, in reporting cost estimates for building plants to make 10,000 tonnes/day of fuel-grade methanol. The costs (in 1987 dollars) ranged from $588M at a "Category I" location like Trinidad, to $1323M at a "Category IV" location like the North Slope of Alaska. The total investments chosen for use in this study are meant to be reasonable illustrative investments covering all the facilities required to operate a new plant at a remote site. Higher, or lower, estimates may be justified for particular circumstances.

For remote gas we have assumed a gas price of 50¢/MJ with a range of zero to $1/GJ. A zero price could reflect a reserve owner seeking to attract local investment. A $1 price is the order of magnitude of the alternative value of the gas if liquefied to LNG and shipped to major gas markets.

Conversion costs (ex feed) in Fischer-Tropsch plants are typically quoted as the plant maintenance and operating costs plus a capital charge on investment. The investment itself is typically quoted as the plant investment required to produce an average of one barrel per day of liquid product over the course of the year. Published estimates of that investment range from under $15/B/D to as much as $40k/B/D (e.g. Singleton, 1997; Agee, 1997; and Thomas, 1996). The large range reflects not only variations in the optimism of the technology developers but, as noted above, differences in plant location, differences in scale, and differences in product slate and product quality—frequently unspecified. Commercial plants are expected to produce 50k B/D or more to be viable. That is about four times the size of the largest existing plant for converting natural gas to F-T liquids, a plant built by Shell in Malaysia which can produce about 12k B/D (Mathijs, 1999). Some reviews of these and other estimates have been published, e.g. (Knott, 1997) and (IPE, 1998). The most recent announcement, by Shell, describes proposed 75,000 B/D plants in Egypt and Trinidad having "reduced capital expenditures to around $20k/B/D" (*World Fuels Today*, 2000). For the purposes of this study, we have assumed an average investment of $30k/B/D, showing the sensitivity to investment changes of ± $10/B/D, and with a capital charge of 20%. We have also assumed an average plant operation and maintenance (O&M) cost of 6% of investment; published estimates range from 4% (Sinor, 1999) to 8% (Nimocks, 1999) to over 10% (Agee, 1997).

We assumed gas costs to correspond to a gas consumption of 10 GJ/barrel of product—a consumption rate used in estimates by Davis, 1999a; Nimocks, 1999, and Agee, 1997.

However, Shell (Mathijs, 1999, and *World Fuels Today*, 2000) states that feed requirements are 8 to 8.3 "MSCF of natural gas" per barrel of total product slate. That consumption rate implies an energy efficiency of conversion of about 63%. Some higher efficiencies for the F-T facilities have been cited, for example in the review by Wang, 1999a. Our estimate assumes that, in addition to F-T feed, some gas is used for product upgrading and other activities at the site, and that there is no outlet for export of surplus steam or power.

Our distribution costs assume that F-T diesel will be shipped by clean tankers from its remote manufacturing site to refineries or terminals where it will be further refined or blended with petroleum diesel to make a final product. Tanker shipping costs were estimated by US DOE, 1989, as ranging from 0.23 to 3.1¢/l, for tankers ranging in size from 40k to 250k DWT and traveling from 5500 to 33,000 round-trip kilometers. To those tanker costs for transportation we added the normal per-liter distribution costs shown in Table 2.2.

Total costs for F-T diesel are shown in Table 2.6 and equal about $6.7/GJ (about 22¢/l) with the large uncertainty of about 40% for the sensitivities considered.

Table 2.6 Retail Costs of Liquid Fuels from Remote Natural Gas in 2020

Remote Natural Gas @ $0.50/GJ ± $0.50
F-T Diesel Investment: $30k/B/D ± $10k
Methanol Investment: $85k/t/D ± $20k
Annual Conversion Charges: Capital charge of 20% + O&M of 6% of investment

	FISCHER-TROPSCH DIESEL		METHANOL	
	$/GJ	¢/l	$/GJ	¢/l
REMOTE GAS	0.95 ± 0.95	3.1 ± 3.1	0.74 ± 0.74	1.18 ± 1.18
CONVERSION CHARGE	4.06 ± 1.35	13.4 ± 4.5	3.01 ± 0.71	4.8 ± 1.1
DISTRIBUTION	1.69 ± 0.42	5.6 ± 1.4	3.52 ± 0.88	5.6 ± 1.4
TOTAL EX TAX	6.70 ± 2.72	22.1 ± 9.0	7.27 ± 2.33	11.6 ± 3.7

Our assumptions about the costs of methanol are similar to those for F-T diesel. Widespread use of methanol as a fuel would be expected to require plants with outputs of 10,000 tonnes/day, which, as in the case of F-T plants, are about four times the size of the largest existing methanol plants.

The published capital cost of methanol plants again depends on the optimism of the technology developer, plant location, and plant scale. For example, one architect-engineer (Foster Wheeler, 1999) cites a capital cost of under $70k/Ton/Day for its Starchem technology, compared to over $100k/T/D for "steam methane reforming", in a 9,000 T/D plant in Alaska. Lange, 1997, cites about $140/T/D for a 2,500 T/D plant at a "remote site". For future plants, Lange estimates "optimistically" that improved technologies could yield capital savings of 25% at the same scale, and perhaps another 25-35% at the scale of 10,000 T/D—reducing the unit capital expenditure to $70-$80k/T/D. Berlowitz, 2000, estimates about $88k/T/D for future technologies and scales. For this study, we have used a total site investment of $85k/T/D with a sensitivity of ± $20k. As in the case of F-T diesel, we again assume an annual capital charge of 20% and an O&M charge of 6% on investment.

We assumed gas costs to correspond to a site energy efficiency of 68% (LHV). Slightly higher efficiencies, 70%, are projected by Allard, 2000, for combined reforming. Lange, 1997, cites best current plants at 67%, and Hansen, 2000, cites a current Statoil plant at 67%. Our use of 68% assumes advancing technology and also consumption of a small amount of gas energy at the remote site in addition to gas fed to the reactors.

Our transportation and distribution costs for methanol make the same assumptions, and use the same numbers per unit volume, as the costs for F-T diesel.

Total costs for methanol are also shown in Table 2.6 and equal about $7.3/GJ (about 12¢/l), with an uncertainty of about 30% for the sensitivities assumed.

Table 2.7 lists the energy consumption and GHG emissions during gas conversion and product distribution to ultimate customers for both F-T diesel and methanol. No provision is made with either fuel for energy consumption or emissions during gas recovery, cleanup, and delivery to the conversion reactors, but in both cases we did assume leakage of ½% of the natural gas fed to the conversion plant.

Table 2.7 Energy Use and GHG Emissions for Liquid Fuels from Remote Natural Gas in 2020

	FISCHER-TROPSCH DIESEL		METHANOL	
	(MJ/MJ F-T diesel)	Energy Efficiency of Stage	(MJ/MJ methanol)	Energy Efficiency of Stage
ENERGY USE				
ON-SITE CONVERSION	0.90	53%	0.47	68%
DISTRIBUTION	0.013-0.061	95-99%	0.027-0.12	89-97%
TOTAL	0.91-0.96	51-52%	0.50-0.59	63-67%
	gC equivalent per MJ F-T diesel		gC equivalent per MJ methanol	
GHG EMISSIONS				
CO_2	7.8		5.1	
METHANE	1.1		0.8	
TOTAL	8.9		5.9	

Notes: Assumed carbon efficiency during conversion of 75% for F-T, 83% for methanol. Methane emissions assume leakage of ½% of gas fed. "Distribution" includes clean tanker transportation from conversion site to port in market region in addition to normal distribution to vehicle.

Overall, manufacture and delivery of one MJ of methanol to the customer consumes roughly 60% of the GHGs as do manufacture and delivery of F-T diesel. For Table 2.7, carbon efficiencies during conversion (grams carbon in the product divided by grams carbon in the gas feed) were taken 75% for F-T diesel and 83% for methanol (Wang, 1999a, and Allard, 2000, respectively) and distribution fuel consumption from US DOE, 1989.

2.5 Hydrogen

If hydrogen is made available widely to supply hydrogen fuel cell passenger cars, we assume that the hydrogen will be manufactured from natural gas at decentralized refueling stations. Other options for manufacturing and distributing hydrogen have been assessed—all involving electrolysis of water or reforming of natural gas. Centralized and decentralized manufacture, and pipeline and truck distribution have been evaluated. The uniform conclusion of Ogden 1998, 1999, Thomas 1998a, 1998b, and Casten, 2000, is that decentralized gas reforming stations can provide hydrogen at lower cost than any of the other options 20 years from now.

In the very long run, say 30 to 50 years from now, hydrogen may be a fuel of choice. If drastic restrictions on the GHG emissions of automobile systems are required at that time, hydrogen will have to be produced and supplied by methods other than decentralized reforming. One possibility is by electrolysis in decentralized facilities using non-GHG emitting electric power. Another possibility is by piped hydrogen manufactured in centralized locations from fossil sources of primary energy using CO_2 sequestration.

The costs of producing hydrogen in decentralized reforming stations include: costs of natural gas feedstock piped to the station, costs of electric power to drive the compressor to compress hydrogen to storage tanks at perhaps 400 atmospheres, and the costs to capitalize and operate the station. Those costs are listed in Table 2.8. Natural gas and electric power unit prices are those projected for the commercial sector in the US in 2020 by DOE (EIA, 1999a). Power consumption is that cited by Casten, 2000, and gas consumption corresponds to a conversion efficiency of methane to hydrogen of 70% rather than the 59% assumed by Casten; higher-efficiency reformers are under development, e.g. Ogden, 1999. Costs to capitalize and operate the station are the costs of Casten, 2000.

Energy consumption and GHG emissions reflect the production and delivery of natural gas (from well to station), gas consumption in the reformer conversion step, and consumption of primary energy in generation of the electric power used for compression. These figures are also shown in Table 2.8.

2.6 Electric Power

We assume that battery electric vehicles used as passenger cars will ordinarily be recharged overnight at owners' residences by connection to the same electric grid serving the residences. Recharging overnight makes use of the very large investment in generation, transmission, and distribution facilities that operate well under capacity during the night.

Table 2.8 Compressed Hydrogen in the US in 2020
Per MJ or GJ of H_2 delivered to vehicle at 350 atmospheres
in decentralized stations reforming natural gas

		ASSUMPTIONS
COST BREAKDOWN ($/GJ)		
PIPED NATURAL GAS	8.1	1.43 GJ @ $5.70/GJ
ELECTRIC POWER	1.3	18.2 kWh @ 7.3¢/kWh
STATION CHARGES (CAPITAL, O&M, LABOR)	9.6	Same as Casten (2000)
TOTAL $/GJ	19.0	
ENERGY CONSUMPTION (MJ/MJ)		
ELECTRIC POWER PRIMARY ENERGY	0.21	32% energy efficiency, primary fuel to site power
NATURAL GAS CONVERSION LOSS	0.43	Conversion efficiency of 70%
NATURAL GAS PRODUCTION AND DELIVERY	0.13	For delivery of 1.43 GJ to site
TOTAL MJ/MJ	0.77	
CARBON EQUIVALENT EMISSIONS (gC/MJ)	36	23 from gas conversion, 11 from grid electric power, 2 from methane leakage (1%)

Notes: Cost breakdown corresponds to Casten (2000) with adjustments to natural gas and electricity prices, and with increase in assumed future conversion efficiency from 59% to 70%. No provision for methane leakage at station.

In the US, kWh generated by electric utilities during the year total less than 60% of the total calculated by assuming that all utilities operated at maximum capacity 24 hours every day. The unused capacity is significant in absolute as well as relative terms since the US utility grid now actually delivers about 20 petajoules of electrical energy to customers annually—a number that can be compared to the 15 petajoules of motor gasoline energy delivered to customers annually.

Recharging from the grid means that the fuel cycle energy consumption and GHG emissions associated with electrical energy depend on the mix of primary energy sources used to generate that electrical energy. In the US in 2020, EIA, 1999a, projects the major constituents of that mix to be coal (52%), natural gas (28%), nuclear (10%), renewables (9%), and petroleum (1%). Transmission and distribution losses of 9% are included in our energy consumption numbers.

We assume that the projected price is the average 2020 price of electrical energy to US residential customers (7.3¢/kWh) discounted by 30% for off-peak use; that discount could be larger, or smaller. Electric power prices, energy consumption, and GHG emissions are summarized below in Table 2.9.

Table 2.9 Grid Electric Power in the US in 2020

Per MJ (0.278 kWh) or GJ of AC energy delivered to vehicle

ENERGY CONSUMPTION (MJ/MJ)	2.16
CARBON EQUIVALENT EMISSIONS (gC/MJ)	54
PRICE (($/GJ)	14
PRICE (¢/kWh)	5.1

Notes: Prices are for average residential customers with assumed off-peak discount of 30%. Carbon emissions include 2 g carbon equivalent for methane releases during coal mining. Losses of 9% assumed during power transmission and distribution.

Sources: EIA (1999a), EIA (1997), EPA (1999)

2.7 Fuel Taxes

Fuel costs in this chapter have all been cited free of excise and sales/value-added taxes imposed at the pump on fuel customers. Significant taxes on traditional highway fuels are imposed in all industrialized countries, the levels depending on the dictates of public policy. In some cases, public policy seems intended to affect fuel choice even between the two traditional fuels, gasoline and diesel. For example, Germany taxes a unit of gasoline energy at about twice the rate of a unit of diesel energy. We make no assumptions about what fuel taxes may be in the future, particularly on non-traditional fuels that governments may want to encourage or discourage.

Fuel taxes in industrialized countries now vary widely as illustrated by Table 2.10 below.

Table 2.10 Taxes on Highway Fuels

US$/gallon, early 2000

	GASOLINE	DIESEL
USA	0.40	0.46
CANADA	0.79	0.61
JAPAN	2.03	1.25
GERMANY	2.48	1.29
FRANCE	2.87	1.53
UK	3.53	3.04

Source: IEA, 2000

At the highest rates of taxation shown, the rates in the UK, taxes cause fuel costs to rise from almost insignificant to quite significant shares of total driving costs. For example, consider two of the vehicle technologies assessed in Chapter 3. One vehicle is our "baseline", a mid-sized passenger car with a gasoline engine that is expected to increase in fuel efficiency about 35% (relative to a comparable 1996 car) by 2020 through evolutionary improvements in traditional technology. Another vehicle is one of the most efficient new technologies for 2020 that we assessed: a diesel hybrid. The table below shows that the impact of taxes at the UK level on the contribution of total fuel costs to operating these vehicles. Impacts are listed both as ¢/km driven and as fuel costs divided by total costs of operating a new car.

Table 2.11 Impact of Taxes on Fuel Costs to Customer

2020 TECHNOLOGY	NO TAX		UK TAXES	
	¢/km	% of Total	¢/km	% of Total
BASELINE GASOLINE	1.4	<5	6.5	21
DIESEL HYBRID	0.6	<2	3.6	10

Advanced technologies are, by intent, more fuel-efficient. Fuel consumption per kilometer on the road can decrease more than ex-tax fuel costs are likely to increase, driving down ex-tax fuel costs to even lower shares of total new car operating costs—below 2% in the case of the diesel hybrids shown in Table 2.11. However, high tax levels increase both the perceived and real concerns of drivers about the importance of fuel costs to driving. An illustration is the demonstrations in Europe in late summer, 2000.

2.8 Summary

We briefly summarize here the total costs, energy consumption, and total GHG emissions during the fuel cycles required to deliver one MJ of each fuel to the vehicle tank. The results are shown in Table 2.12. Costs are deliberately shown as ranges without central values in order to be clear about the uncertainties of the cost data; no cost ranges are shown for hydrogen and electric power since we did not estimate uncertainties.

Energy consumption and GHG emissions are shown as single average values which are uncertain but less uncertain than the cost estimates. The very large GHG emissions for hydrogen and electric power can be deceptive unless it is clearly understood that, unlike all

Table 2.12 Summary of Costs, Energy Consumption, and GHG Emissions During the Fuel Cycle

Per MJ or GJ of Fuel Delivered to the Vehicle

FUEL	COST $/GJ	ENERGY USE MJ/MJ	GHG EMISSION gC EQUIV/MJ
GASOLINE	5.4-10.5	0.21	4.9
DIESEL FUEL	4.5-8.6	0.14	3.3
F-T DIESEL	4.0-9.4	0.93	8.9
METHANOL	4.9-9.6	0.54	5.9
CNG	8.9-10.5	0.18	4.2
HYDROGEN	19	0.77	36
ELECTRIC POWER	14	2.16	54

the other fuels, there are no further GHG emissions in vehicle operation. In fact, on a total life-cycle basis, vehicles fueled by hydrogen or electrical energy are among the lowest-emitting technologies assessed.

Fuel cycle GHG emissions for hydrogen could be reduced (still assuming hydrogen manufacture and compression at decentralized gas reforming stations) if conversion efficiencies could be raised above the 70% assumed or if emissions during hydrogen compression were reduced by using more efficient compressors or less carbon-intensive sources of compressor power. Fuel cycle GHG emissions for electric power could be reduced (still assuming overnight at-home recharging) only by significantly changing the primary energy mix of the entire power grid by 2020 or by introducing CO_2 sequestration.

3.0 Vehicle Design, Performance, and Costs in 2020

In this section of the report, we focus on the design criteria, vehicle performance, and ownership costs of a typical future passenger car for the US market. We will describe the technology choices for future vehicles, the rationale for projecting improvements and advances, and the key assumptions for the performance and cost calculations. We then report on the results obtained by simulating the operation of these future vehicles.

3.1 Technology Assessment Methodology

The current (1999) passenger car fleet size in the United States is about 130 million vehicles; the fleet number has fluctuated little over the past several years, rising from 128 million in 1984. Note, however, that the light truck fleet size has been increasing steadily, and currently comprises almost 40% of the total number of passenger vehicles. The average vehicle miles traveled per year (in 1997) was 11,600 miles, which has increased about 1.3 % per year for the preceding ten years. This fleet of US passenger cars uses about 10% of the total energy consumed and releases about 11% of the total carbon dioxide emitted in the US.

Attempts to evaluate the potential of automobile fuel efficiency improvements started in the early 1970s. Prompted by the two oil shocks, and, more recently, by environmental and climate change concerns, these efforts contributed, step by step, to the growing field of automotive technology assessment. In the next section, we review the key lessons and conclusions from these studies, especially the more recent ones.

3.1.1 Recent Studies

One of the more comprehensive recent assessments is the 1995 OTA study (Office of Technology Assessment, 1995) of low fuel consumption automobiles. It examined the fuel consumption of a Ford Taurus-based vehicle through 2015, using different types of propulsion systems and auto body materials. The OTA study found that by 2005, mass-produced cars could be introduced into the transportation market, with a potential to reduce fuel consumption by one-third to one-half of the then current baseline vehicle, depending on the design and choice of engine and drivetrains. Within the next decade, further reductions of about 20% could be achieved without change in the type of propulsion system. The OTA study, however, predicted that such advanced fuel-efficient vehicles would cost substantially more than their conventional counterparts and that the savings resulting from lower fuel consumption would not offset the higher vehicle price. For instance, reducing fuel consumption by 28–54% by 2005 and by 48–66% by 2015 would result in a net price increase of US$ 360–9100 in 2005 and US$ 1,300–36,000 in 2015, depending on the propulsion system and type of auto body employed. The OTA study anticipated that the associated low commercialization potential could be overcome by ongoing research efforts to reduce manufacturing costs, by developing low-cost alternative designs, by limiting vehicle capabilities such as acceleration, by changes in consumer valuations, or by government policies based on economic incentives or regulations: in our view, these represent a challenging set of expectations.

An extensive report from Sierra Research, Inc., "Automotive Fuel Economy Potential Using Cost-Effective Design Changes" (1997), examined the limits of increasing automobile and light truck fuel economy. Diesel powered vehicles were excluded; it was assumed they could not to meet the Californian LEV emissions standards. While recent trends of increasing vehicle weight and performance without offsetting improvements would reduce automobile fuel economy from 27.5 mpg in 1995 to 25.7 mpg in 2005, the use of cost-effective fuel economy improvement technology (evaluated on a constant fuel price of US$ 1.20/gal and a 7% discount rate) were estimated to increase the 1995 fuel economy only slightly to 27.7 mpg. (The study takes into account a weight penalty of 150 lbs (68 kg) for automobiles and minivans, 75 lbs (34 kg) for pickup trucks, and 125 lbs (57 kg) for sport/utility vehicles, resulting from vehicle design changes that increase occupant safety.) The projected increase in fuel efficiency can be achieved through more efficient packaging of the passenger compartment and enhanced use of high-strength steel, use of lighter-weight components in the vehicle interior, reduced engine friction, reshaped vehicle bodies for lower aerodynamic drag, and reduced tire rolling resistance. By 2010, the study's time horizon, fuel efficiency can be further increased through cost-effective measures including further reductions in aerodynamic drag and tire rolling resistance, and continuously variable transmissions. In contrast, the maximum feasible automobile fuel efficiency improvements were expected to be 34 mpg (23% over the 1995 level) by 2005 and 40 mpg (47% over the 1995 level) by 2010 at a retail price increase of US$ 1600 and US$ 2700, respectively.

Another study (Hoehlein et al., 1998) analyzed the performance of different vehicles, including four fuel-cell vehicles, over the entire fuel and vehicle cycle, from resource extraction through end-use. Besides the gasoline-fueled baseline vehicle, two additional internal combustion engine vehicles were examined, one fueled with diesel fuel and another one with compressed natural gas. The four proton-exchange-membrane (PEM) fuel-cell vehicles were powered with hydrogen either reformed from gasoline or methanol on board, or with compressed hydrogen derived from natural gas off board, or using a direct methanol fuel cell, where methanol is derived from natural gas off board. The comparative evaluation was conducted on the basis of the New European Driving Cycle (NEDC) for two periods, until 2005 and post 2005. The study can only be considered a rough assessment, since it incorporates a number of simplifications. For example, power supply of 40 kW at the wheels is selected for all cars, irrespective of the vehicle weight. The study concluded that—when measured over the entire fuel cycle—primary energy use is comparable for all these different fuel cycles: e.g., the advantages of methanol-fueled fuel-cell vehicles in end-use are largely offset by losses is methanol production. Thus, the major benefit of fuel-cell vehicles is expected to be the reduction of conventional emissions: i.e., carbon monoxide, nitrogen oxides hydrocarbons and particulate emissions. As a necessary requirement for competitiveness to internal combustion engine vehicles, the study concluded that annual fuel cell production rates should be at least 100,000. If this production volume is not large enough to allow for cost reductions to compete with mechanical drive train vehicles, the study concludes that tighter emission standards might be necessary to prompt their further introduction. The study acknowledges that more research and development is necessary to ensure the competitiveness of fuel cells.

In addition to these extensive reports, numerous papers focusing on specific technologies have been produced. For example, a study by Thomas, James, Lomax, and Kuhn, (1998b) looked at a variety of propulsion system options. Based on the baseline vehicle, an aluminum intensive Ford Taurus, weighing about 270 kg less than the current steel intensive commercial automobile, the study examined three types of vehicle propulsion systems and three fuels: conventional ICEs (gasoline, natural gas, and a mixture of 30% hydrogen and 70% natural gas), hybrid vehicles (natural gas, hydrogen, and diesel fuel), and fuel cell vehicles (hydrogen, methanol, and gasoline). To simulate more realistic driving behavior, the speed at each time segment of the combined urban-rural driving cycle was multiplied by factor of 1.25 (which makes comparison of the results with the other studies more difficult). The study concludes that the preferred (lowest cost) propulsion system – fuel combination depends on the environmental requirements (clean air vs. reduction in GHG emissions); satisfying both requirements simultaneously, suggests that natural gas is the fuel or fuel feedstock of choice combined with any of the examined systems.

More recently, Ogden et al. (1998, 1999) have examined three fuel-cell vehicles, equipped alternatively with compressed gas hydrogen storage at 5000 psi, onboard steam reforming of methanol (13 gal of fuel), and onboard partial oxidation (POX) of gasoline (13 gal of fuel). The vehicle (without propulsion system) has reduced weight, rolling resistance, and aerodynamic drag compared to today's midsize vehicles. The propulsion system was sized according to the goals of the PNGV program: i.e., to sustain a speed of 55 mph (88 km/h) on a 6.5% grade, and the total output power of the (fuel cell system plus peak power device (spiral wound, thin film, lead-acid battery)) to allow acceleration for high speed passing of 3 mph/s at 65 mph. Using the federal test procedure (55% urban and 45% highway driving) as a reference for evaluating vehicle fuel economy and range, the authors conclude that direct hydrogen fueled vehicles are more energy efficient, lighter weight, simpler in design, and lower cost than those vehicles equipped with a fuel processor.

A systematic comparison of these studies, with the intent to assess vehicle technology potentials and impacts, is only possible by taking into account the fuel and vehicle cycles together. The recent studies also indicate the obvious sensitivity of vehicle performance predictions to assumptions made concerning the performance characteristics of key vehicle and propulsion system components. They start to suggest the complexity of bringing more costly new technology into mass production when the direct advantages to vehicle purchaser and users are modest, at best. However, they also suggest that there is much potential to reduce energy consumption in vehicles.

It is useful here to summarize three broad conclusions from this review of these automotive technology assessment literature:

(i) The expected improvement of the baseline or mainstream technology over time (e.g. through use of improved steels, better performing internal combustion engines) must be evaluated, since this defines the "baseline."

(ii) Predicting the performance of new technology is a major challenge and has substantial uncertainty, since these new technologies are usually in the prototype stage and are still developing. Also, such new technology assessments often focus only on vehicle efficiency and performance, and the more pragmatic, often difficult to quantify but important attributes (e.g. start-up time, refueling ease) are frequently omitted in the evaluation.

(iii) Assessments of the time required to develop and design mass-production feasible versions of new automotive technologies have been consistently too optimistic.

In our own study reported here, we have paid special attention to these three important challenges.

3.1.2 Approach and Vehicle Concepts Examined

We have examined several potentially promising future powerplants and vehicle technology combinations using a propulsion system in a vehicle computer simulation. This simulation "drives" the vehicle through a specified driving pattern or cycle, and calculates the fuel consumed and thus the carbon dioxide emissions produced. Inputs for the calculations are the vehicle driving resistances (mass or inertia, aerodynamic drag, and tire rolling friction), and the operating characteristics of each of the major propulsion system components (e.g. engine and transmission performance and efficiency for a standard internal combustion engine). These vehicle fuel consumption predictions are made for combinations of technologies that could plausibly be in mass production in 2020. Their estimated performance characteristics relative to today's performance include improvements that we judge could be implemented in production by 2020. However, the more sophisticated of these technology combinations, which could provide substantially improved fuel economy, are likely to be significantly more expensive.

The assumption concerning production in 2020 is intended to indicate that we have assumed (as best we can) that the technologies included have been developed to the point where at last <u>some</u> attributes of each technology combination are attractive relative to the baseline, and that their performance is consistent with the robustness and low manufacturing cost requirements of the light-duty vehicle market. Thus, we are evaluating these potentially attractive technologies in their mass-production form. Later we show that these more efficient and lower CO_2 technology combinations are expected to be more expensive, at least initially. Whether or not they are likely to be promising candidates for mass production is, therefore, an open question. The response of vehicle purchasers and users to these more fuel efficient but more expensive vehicles is uncertain, and market acceptance (whether encouraged by regulation or tax incentives or not) is essential for any large-scale production. Thus, our predictions indicate the fuel consumption and CO_2-reducing *potential* of various future propulsion systems and vehicle technologies in a specific mid-size passenger car, with attributes equal to those of today's median US car, and do not express our judgments about either the desirability or the likelihood of these various technologies being in large scale production by 2020.

The vehicle and powerplant technologies we examine include the following. Powerplants: improved gasoline and diesel internal combustion engines with mechanical drivetrain; gasoline and diesel internal combustion engines in a parallel hybrid[1] system utilizing both

[1] In the parallel hybrid system examined here, both the engine and the battery, in parallel via a mechanical transmission and electric motor, respectively, can drive the wheels. See Section 3.4.

mechanical and electric power plants; gasoline, methanol, and hydrogen fueled fuel cell hybrid systems with electric drivetrain; and pure battery electric drivetrain. Vehicle Technologies: various lighter-weight materials for chassis and body; more efficient vehicle auxiliary systems; lower aerodynamic drag body shapes; lower rolling resistance tires. These technologies were chosen from a larger set of possible powertrain and vehicle developments as having the highest potential for reaching production and the market. Table 3.1 categorizes the combinations of propulsion system (engine and transmission) and fuels examined into three families: mechanical, hybrid (combined mechanical and electrical), and electrical.

FAMILY	TRANSMISSION	POWER UNIT	FUEL
Mechanical	Auto-Clutch	Spark Ignition ICE Compression Ignition ICE	Gasoline Diesel
Dual	Continuously Variable	ICE with Batteries and Electric Motor	Gasoline, Diesel, Natural Gas
Electrical	Single Ratio	Fuel Cell (with reformer for gasoline, methanol) Battery	Gasoline, Methanol, Hydrogen Electricity

Table 3.1 Powerplant and Fuel Combinations Examined

An important issue in this future passenger car technology assessment is the relevant baseline. We have used as a baseline an evolutionary average-size (US) passenger car: i.e., a steadily improving gasoline-fueled spark-ignition engine, a more efficient conventional technology transmission, and low-cost vehicle weight and drag reductions. These baseline technology improvements are based on historical and current technology trends, and are projected to 2020. The baseline vehicle represents the likely average passenger car technology in 2020 that will not incur extra costs other than those necessary to keep up with the market. Features of the baseline vehicle are distinguished from the advanced vehicle in section 3.3.1.

A second issue is the performance and operating characteristics of these various vehicle and powerplant combinations. Ideally, each combination should provide the same (or closely comparable) acceleration, driveability, driving range, refueling ease, interior driver and passenger space, trunk storage space, and meet the applicable safety and air pollutant emissions standards.

Only some of these attributes can be dealt with quantitatively now. All propulsion system and vehicle combinations are adjusted to provide the same ratio of maximum power to total vehicle mass, and provide 600 km driving range, except for the special case of the pure electric vehicle, whose battery constraints will be discussed later. The vehicle size (including vehicle frontal area for drag estimation) is roughly constant. Driveability issues (e.g. ease of start up, driving smoothness, transient response for rapid accelerations, hill climbing, and load carrying/towing capacity) have not yet been assessed quantitatively for several of these technologies, though we do discuss some of these in Section 5. These are important vehicle operating characteristics, and we acknowledge that our various technology combinations do not necessarily provide equal value in all these different driveability and performance areas.

The emission levels projected to 2020 with these various technologies also cannot yet be quantified. We assume that the strictest current emissions standards (California LEV II, EPA Tier II) for 2004 to 2008 may be further reduced in the following decade, but that these levels can probably be met by improved exhaust gas treatment technology for internal combustion engines, and are within expectations for fuel-cell systems. This assumption is least certain for the diesel ICE. We return to this question later in Section 5.

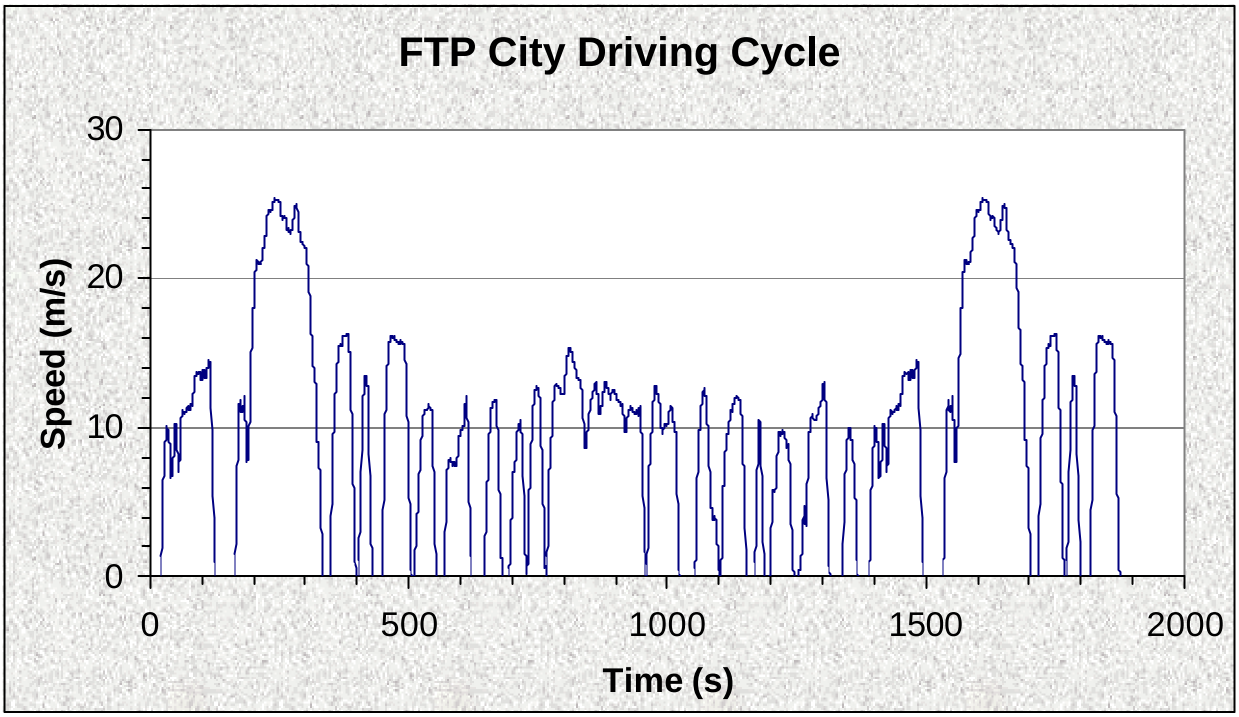
The next two sections address the simulation structure and logic as well as the assumptions made about component technologies and their performance.

3.2 Simulation Model Structure

To estimate fuel consumption to compare various vehicles with different propulsion systems, a family of Matlab Simulink simulation programs was used. Originally developed by Guzzella and Amstutz (1998) at the Eidgenössiche Technische Hochschule (ETH), Zurich, these programs back-calculate the fuel consumed by the propulsion system by driving the vehicle through a specified cycle. Such simulations require performance models for each major propulsion system component as well as for each vehicle driving resistance. The component simulations used, which are updated and expanded versions of the Guzella and Amstutz simulations, are best characterized as aggregate engineering models which quantify component performance in sufficient detail to be reasonably accurate but avoid excessive detail which would be difficult to justify for predictions relevant to 2020. Nonetheless, a substantial number of input variables must be specified for each element or component of the overall model. It is not the intent of this report to document all the details of this simulation here, but rather to provide a basic functional description of the total model. Additional details can be found in AuYeung (2000).

3.2.1 Driving Cycle

One critical component of the simulation is the driving cycle on which all the vehicle calculations are based. For this study, the US Federal Test Procedure (FTP) urban (city) and highway driving cycles are used, as shown in Figure 3.1. These cycles are the ones used by the Environmental Protection Agency (EPA) to measure the emissions and fuel consumption of vehicles sold in the US The results from such tests are reported each year in the EPA Fuel Economy Guide, after multiplying by an empirically determined factor (0.9 for the city cycle and 0.78 for the highway cycle) to take into account additional real-life driving effects. The results presented in this report have <u>not</u> been multiplied by these empirical factors.



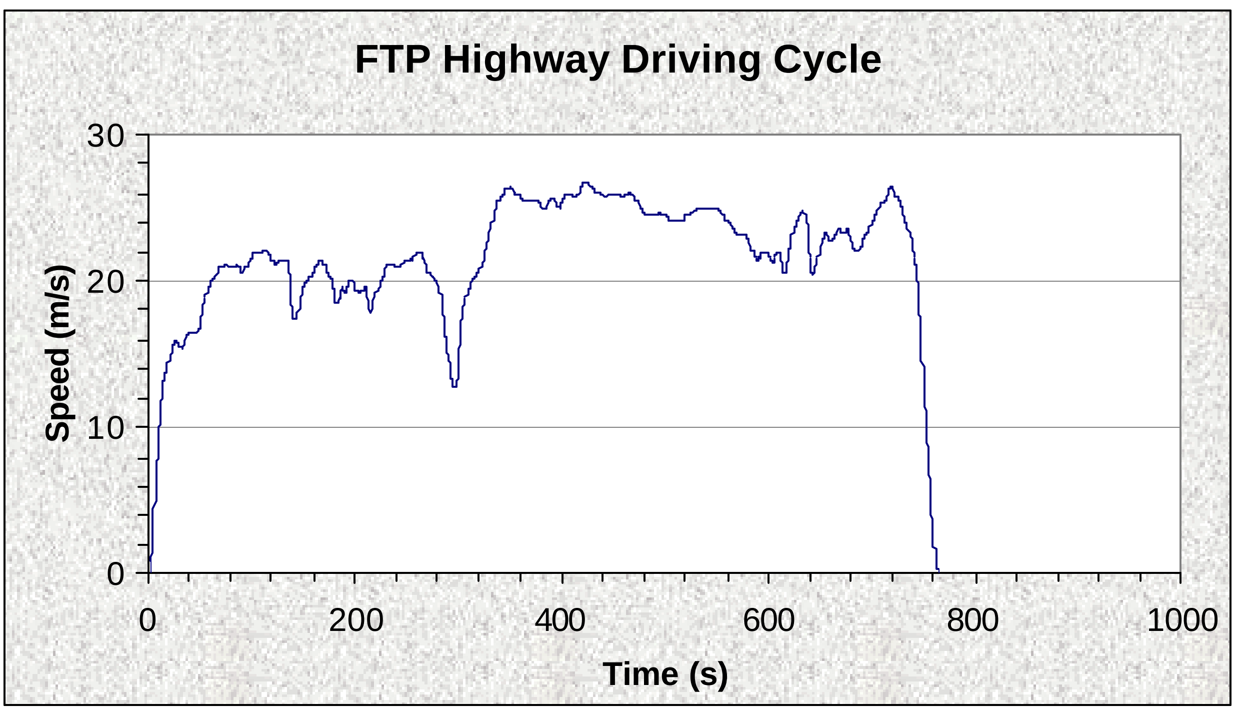


Figure 3.1 Federal Testing Procedure City and Highway Driving Cycles

The fuel consumption values predicted by the simulation for a given technology combination depend on the driving pattern or cycle used (as, of course, does real life fuel consumption). The relative differences between fuel consumption predictions for different technology combinations, for different driving cycles, are also likely to be different. Some preliminary information related to the authors suggests that the fuel consumption benefits of more advanced technology vehicles, with more realistic driving patterns than the FTP, are not as large as those calculated for the FTP cycle. None the less, this combined FTP cycle (city and highway) is the standard cycle used for vehicle fuel consumption and emissions so we have used it. We will give urban (city) cycle and highway cycle results, and combined cycle (55% city and 45% highway weighted fuel consumption) results.

3.2.2 Total Vehicle Simulation Logic

Figure 3.2 Calculation Logic: Mechanical Drivetrain

The base vehicle with an internal combustion engine coupled to a mechanical transmission is related to the specified driving cycle as shown in Figure 3.2. The calculation starts with the chosen driving cycle, specified as an array of vehicle velocity versus time (at intervals of one second). From these two inputs, the vehicle acceleration is calculated. This information is used to calculate the instantaneous power needed to operate the vehicle, by adding aerodynamic drag, tire rolling resistance, and inertial force (vehicle mass times acceleration). The required total power is converted to the torque needed to drive the tires, which through an automatic, manual, or continuously variable transmission is converted to the torque needed at the engine output shaft.

In addition to the power required as engine output, all the engine losses (due to engine cycle inefficiencies, engine friction, changes in rotational kinetic energy, and auxiliary component power requirements) are summed together to obtain the total rate at which fuel chemical energy is consumed. Using the lower heating value[2] (the stored useable chemical energy of a fuel), this "fuel power" is converted to the amount of fuel needed, thus generating the desired result—energy consumption per unit distance traveled. This logic diagram applies to the current, evolutionary gasoline, and the advanced[3] gasoline and diesel vehicles presented in this study.

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[2] Two fuel heating values are defined, a lower and higher, depending on whether the water in the combustion products is vapor or liquid. We follow the usual engine convention here. The energy, fuel consumption and CO_2 predictions are unaffected since the heating value cancels out.

[3] Here, "advanced" is used to denote components where plausibly practical new technologies which improve performance have been incorporated.

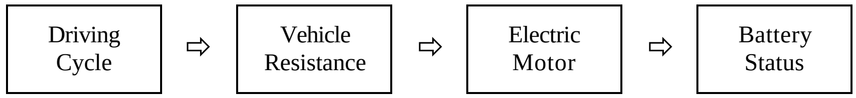


Figure 3.3 Calculation Logic: Battery Electric Drivetrain

The electric vehicle with batteries driving an electric motor is modeled in a similar manner, as shown in Figure 3.3. In many ways, this electric vehicle is simpler, having a single gear transmission, and easier to predict motor and battery characteristics. Again, the model begins with the chosen driving cycle and takes into account vehicle resistances. Then, the total required energy at the tires is converted to the torque needed at the output of the electric motor. With the motor efficiency and the discharging efficiency of the batteries, the desired energy consumption per unit distance traveled can be calculated. With an electric drivetrain, regenerative braking— the conversion of vehicle kinetic energy to stored energy in the batteries during vehicle braking, with losses due to generator (motor) and recharging inefficiencies—is included here, also.

This logic diagram applies only to the pure battery electric vehicle, a case presented in this study primarily to illustrate the required battery performance characteristics for EVs to be competitive. Limits in battery technology (too low energy storage per unit weight, short life, and high cost) currently prevent such vehicles from being commercially viable. Also note that the energy consumption for the EV will be lower than that of an ICE vehicle, because the efficiency of the motor and battery combined is substantially higher than that of any "engine". However, this tank-to-wheels estimate does not take into account the efficiency of electricity generation from the primary energy source and transmission over the grid, or electricity generation at a local recharging station. The losses during the battery recharging process from the grid are accounted for separately.

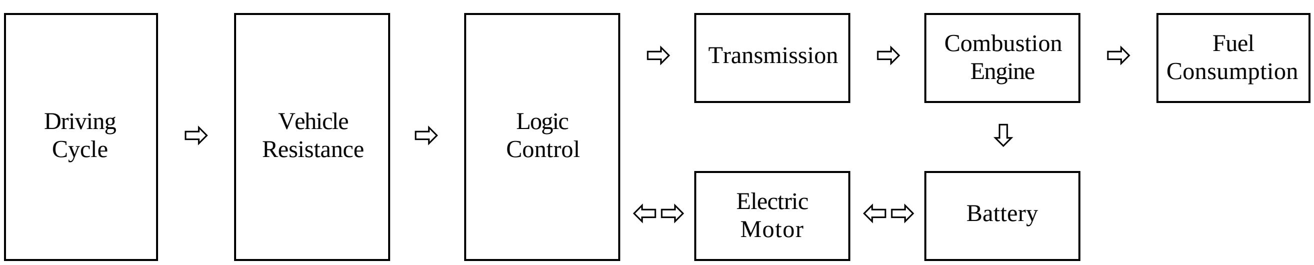


Figure 3.4 Calculation Logic: ICE - Battery Electric Parallel Drivetrain

The parallel hybrid simulation combines the logic of these two models and uses both the combustion engine and the electric motor, as shown in Figure 3.4. The additional logic control block determines the power flow required from the engine and the battery, respectively, based on the amount of power required and the state of charge of the batteries. The objective here is to operate the engine at higher loads where it is more efficient, switch the engine off during idling and low power requirements, and use the battery and engine together at peak power levels so both components can be kept as small and light as possible.

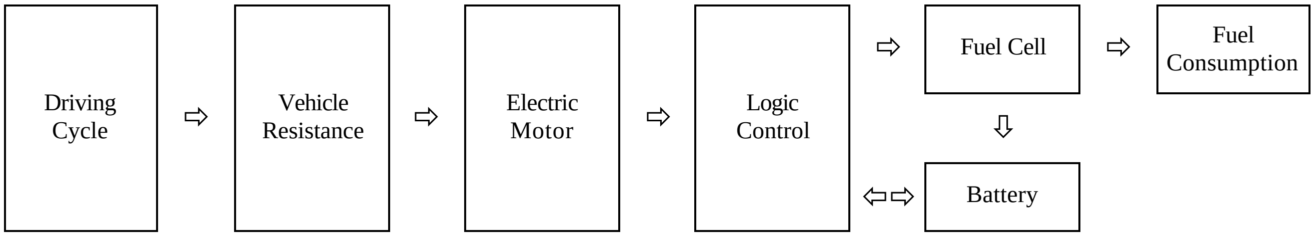


Figure 3.5 Calculation Logic: Fuel Cell - Battery Electric Drivetrain

In fuel-cell powered vehicles, the fuel cell system is combined with a battery, as a hybrid, for similar reasons: to maintain fuel cell operation in its high efficiency (part load) region as much as possible, and benefit from regenerative braking energy recovery. Its logic is shown in Figure 3.5. During idling and low-power operation, the batteries supply the necessary power. Over a certain threshold, the fuel cell turns on; extra power is used to recharge the batteries if they are below a set state of charge. When the power required exceeds the maximum fuel cell stack capabilities, the batteries again supplements peak loading. Since the fuel cell directly converts chemical energy to electrical energy, a mechanical transmission is not required. Also, the fuel cell requires energy, even during vehicle operations when it is not supplying power directly; hence it creates an addition drain on the battery system. Finally, if a liquid fuel (methanol or gasoline) is stored on the vehicle, then a fuel reformer system, which converts the liquid fuel to hydrogen on board, is included.

3.3 Component Model Details

As explained in Section 3.2, the vehicles examined in this study are designed to be functional equivalents of today's average passenger car: a mid-sized family sedan such as the Toyota Camry. For the customer, this means the usable interior space capacity and vehicle performance are maintained in future vehicles. A volumetric analysis should be performed to ensure that the propulsion and fuel systems of the advanced vehicles do not take up excessive space. We have not done this due to limited information on propulsion system component size and layout. However, ICE hybrid systems, natural gas fueled ICE systems, and fuel-cell systems (with reformers or with on-board hydrogen storage) are likely to be at a disadvantage here. Also, to ensure equal performance, all vehicles are designed to have a constant peak power to mass ratio of 75 W/kg, which is matched to today's value. This ratio roughly, but not exactly, equalizes vehicle performances, as can be checked with acceleration calculations.

The components, and key component model inputs and details, that come together to form the total vehicle system are described below. We first focus on the vehicle body itself, then focus on each propulsion system technology and its specifications.

3.3.1 Vehicle Body

The main difference between the evolutionary and advanced passenger car vehicle body is the extent to which more radical new technologies are used to reduce vehicle weight.

Table 3.2 reports our projections of vehicle mass by component for all vehicles examined. The estimated mass distribution of the 1996 baseline vehicle is based on the mass distribution of a 1990 Ford Taurus (OTA, 1995) and a study by the Ultra-light Steel Autobody (ULSAB) Consortium that especially examined the mass of vehicle components for a range of recent passenger cars (ULSAB-AVC Consortium, 1999).

Based on the vehicle mass distribution of the 1996 baseline vehicle, the distribution of all other vehicles was projected, using the following simple approach. The 2020 baseline vehicle distribution was derived by multiplying the mass of the body structure, other body parts, and steering and brakes by 0.85 to reflect the approximately 15% mass reduction potential of high-strength steel compared to mild steel. For all advanced vehicles, the 1996 baseline vehicle mass of these same components was multiplied by 0.65 to simulate the 35% mass reduction due to aluminum substitution. The mass change of the propulsion system resulted largely through the vehicle propulsion system modeling described in this section and exogenously specific power-to-mass ratios of the major components, determined at 0.9 kW/kg for an advanced gasoline engine, 0.6 kW/kg for an advanced diesel engine, 1.5 kW/kg for an electric motor, and 0.4 kW/kg for a fuel cell system.

The mass of suspension and frame of any 2020 vehicle was estimated by multiplying the chassis mass of the 1996 baseline vehicle by the ratio of the projected mass of vehicle body, propulsion system, and interior of the 2020 vehicle and the mass of these components of the 1996 baseline vehicle. This simple approach ensures that suspension and frame of all projected 2020 vehicles is sufficiently strong to carry the mass of the projected body, propulsion system, and interior through eventually adding mass to the chassis. The maximum extra support mass is 59 kg for the gasoline fuel cell vehicle, where propulsion system mass increases by 100% compared to the 2020 baseline vehicle.

Other notable changes in component mass from the 1996 baseline vehicle include the transition from automatic transmission to auto-clutch and continuous variable transmission, and a reduction in wheel and seat mass due to a larger use of magnesium.

In Table 3.2, the total vehicle mass is subdivided into four subsystems for comparison: chassis and body, propulsion, battery, and fuel. The chassis and body system mass include everything for an un-powered free-rolling vehicle, including the fuel system without the fuel as well as all structural reinforcement for extra mass on the vehicle. The propulsion system mass include the engine, scaled according to power output for ICEs, electric motors, fuel cell systems and reformer systems, and the transmission, allocated a mixed mass for automatic manual, continuously variable, and direct gear.

The battery and fuel mass are also separated for ease of reference. The battery pack size is determined by the maximum power required by the electric motor in a particular vehicle, resulting directly in a specific battery mass and volume. This sizing assumption does not take into account the voltage and current balance that may affect the motor selection and performance.

The amount of energy the battery pack can store is thus also constrained; this limit has less impact for hybrid systems because the battery pack can be recharged while driving, although care must be taken in the case of sustained peak power supplement to ensure that safe passing and hill climbing are possible. Towing capacity requirements also would impact the battery

Table 3.2 Mass Distribution (kg) by Component for All Vehicles Examined.*

Technology	current	baseline	advanced	advanced	advanced	advanced	advanced	advanced	advanced	advanced	advanced
Propulsion System	SI ICE	SI ICE	SI ICE	CI ICE	SI Hybrid	CI Hybrid	SI Hybrid	FC Hybrid	FC Hybrid	FC Hybrid	Electric
Fuel	gasoline	gasoline	gasoline	diesel	gasoline	diesel	CNG	gasoline	methanol	hydrogen	electr.
Transmission	auto	auto-clutch	auto-clutch	auto-clutch	CVT	CVT	CVT	direct	direct	direct	direct
Body	383	326	249	249	249	249	249	249	249	249	249
Glazing	35	33	33	33	33	33	33	33	33	33	33
Chassis	273	229	216	219	216	219	216	275	25459	244	243
Propulsion System	392	263	252	303	267	303	283	536	475	416	414
Engine	164	103	95	149	64	99	67	0	0	0	0
Electric Motor					19	20	20	73	69	66	66
Fuel Cell System & Reformer								351	278	193	
Battery	12	12	12	12	36	37	37	46	43	41	328
Transmission	90	50	50	50	50	50	50	20	20	20	20
Liquids and Storage	64	45	42	39	34	31	46	33	53	84	
Other (Accessories, Electronics, etc.)	62	53	53	53	64	64	64	14	13	12	
Interior & Exterior	195	214	214	214	214	214	214	194	194	194	194
Other	44	44	44	44	44	44	44	44	44	44	44
TOTAL VEHICLE	1322	1108	1007	1062	1023	1060	1039	1330	1253	1179	1176

*Not represented is the assumed compensating effect of declining interior mass (seats, trim, etc.) and increasing in body mass for improved crash safety.

system size and weight. For the pure electric vehicle, extra batteries may be added to increase energy storage capacity and hence extend vehicle range. These add to the vehicle weight and thus require additional batteries (and weight) to maintain performance.

The pack size or volume occupied by the battery system is of concern because of space limitations on board the vehicle. A volumetric analysis should be performed to determine if the battery pack will fit in the vehicle, and if not, the appropriate penalty in aerodynamic drag factor (C_dA) should be taken into account.

The fuel mass is two-thirds of the amount of fuel needed to achieve approximately a range of 600 km in the combined cycle. Except for the pure electric vehicle, whose special case will be discussed in section 3.3, all vehicles meet the 600 km range criteria.

An occupant and cargo mass is added to the total raw vehicle mass. It is the standard FTP test procedure occupant and cargo mass of 300 lb. This estimated average load for a vehicle, is held constant for all vehicles in this study at 300 lb/136 kg, (e.g., the mass of 1.5 adults at 75 kg per person, with some 20 kg of cargo). Therefore, the total operating vehicle mass is the summation of the chassis and body system mass, the propulsion system mass, the battery mass, the fuel mass, and the occupant and cargo mass. Other key simulation variables for the vehicle and transmission, with their assumptions and descriptions are listed below.

Aerodynamic Drag Coefficient	C_d	**Aerodynamic drag coefficient** is a dimensionless number describing the drag induced by a body traveling in a fluid at a known relative velocity. For this study, the current vehicle has an estimated C_d of 0.33, improving to 0.27 in the evolutionary vehicle and 0.22[4] in the advanced vehicle, both in 2020.
Cross-Sectional Area	A_x	**Vehicle Cross-sectional area** is the largest area in a plane perpendicular to the direction of vehicle motion. When multiplied by C_d, air density, and the square of the relative velocity, the product is the aerodynamic drag force that must be overcome for the vehicle to move at that speed. Note that in this study, it is assumed there is no wind and; the air is still.

$$F_{drag} = 1/2 \rho C_d A_x V^2$$

[4] Ford and GM (ref) have already built prototypes that achieve below 0.22 for the PNGV program. (National Research Council, 2000).

Rolling Resistance Coefficient — C_{rr}

Rolling resistance coefficient is a dimensionless number used to characterize the energy dissipated due to friction between the road and the tires. It is multiplied by the total vehicle weight to obtain the tire resistance force.

$$F_{roll} = C_{rr} M_{tot} g$$

Transmission Efficiency — η_{trans}

Transmissions are modeled with a constant efficiency during all modes of operation, although in practice the efficiency varies among gears. Idling in neutral or in drive (where friction is about double that in neutral) is taken into account, but shifting losses are not. More details on transmission performance could be added in the future; assuming an overall constant efficiency adequately incorporates the power losses in the transmission at this stage.

Five different transmissions are used for this study. For today's vehicle, a 5-speed manual at 94 % efficiency, and a 4-speed automatic at 70 % efficiency city and 80 % efficiency highway are used to verify the accuracy of the model. The future evolutionary and radical gasoline and diesel vehicles use 5-speed automatically-shifting clutched transmissions at 88 % efficiency, while future radical gasoline and diesel hybrids use continuously variable transmissions also at 88 % (Kluger and Long, 1999). An additional benefit from the CVT is that it enables improved engine efficiency by selecting the higher efficiency regions of the engine performance map. Finally, all the electric-drive vehicles, the fuel cell and battery electric vehicles, operative on single ratio direct drive at a speed and power dependent efficiency that averages out to about 93% over the combined cycle.

Auxiliary Load — P_{aux}

Auxiliary load is assumed to be constant at 400 W for the current vehicle, and at 1000 W for all 2020 vehicles, during all times of vehicle operation. While future vehicles may be more efficient in power electronics, they are expected to have more on-board electrically driven systems, drawing even more power. The auxiliary load is held constant for all vehicles. Since all vehicles have similar on-board systems, this study has not focused on determining the auxiliary load more precisely.

3.3.2 Gasoline, Diesel, and Natural Gas Engines

The performance characteristics of gasoline, diesel, and natural gas internal combustion engines are well documented. Historical improvement trends, combined with an assessment of likely practical technologies available over the next two decades, are used to predict the performance of these engines in year 2020. In the model, appropriate assumptions obtained from this logic were used to create an engine performance map.

Engine Torque Curve: A typical maximum torque curve was constructed for a 1.6 L gasoline engine and a 1.7 L turbocharged direct-injection diesel engine. These torque-rpm curves can be scaled over a range of engine displacements, and define the performance of actual engines today.

To project forward, historical trends showing the ratio of gasoline engine power to displaced volume determined by Chon and Heywood (2000) show a nearly linear improvement of about 0.5% per year. Future technological improvements such as increasing use of variable valve timing, gasoline direct-injection, improved turbocharger performance for diesels, and reduced engine friction, are expected to continue this trend. Hence for 2020, the wide-open-throttle (WOT) torque for these engines is increased by 10% overall.

Future gasoline engines are expected to operate and generate peak power at engine higher speeds (rpm) with these and similar advancements. Thus, an extra

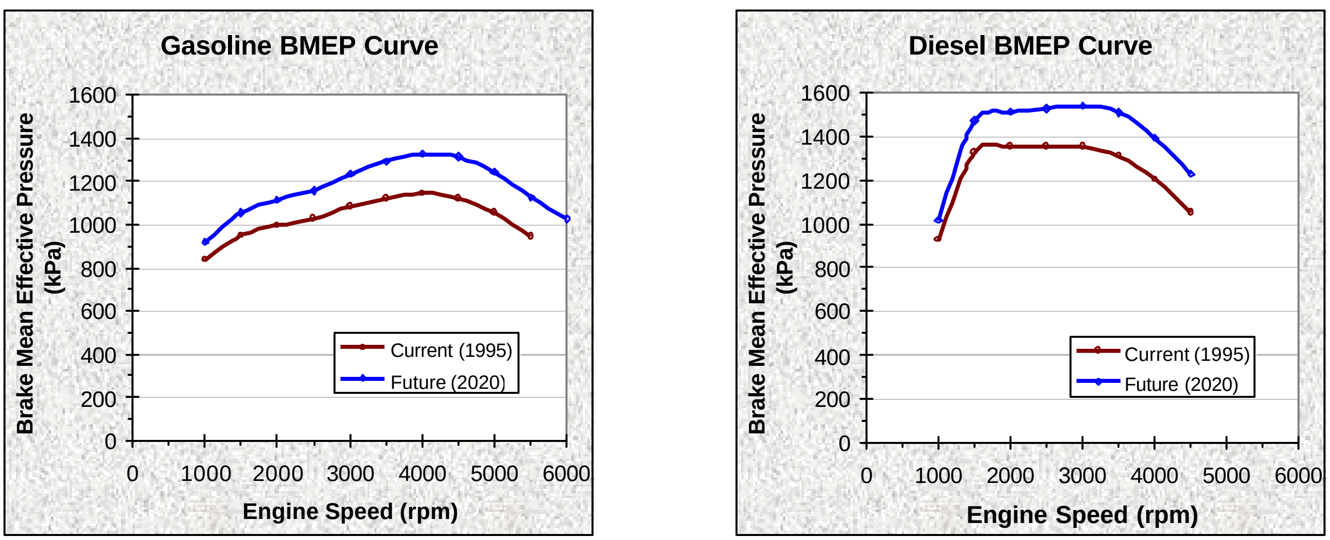


Figure 3.6 Performance Maps for Current and 2020 Gasoline and Diesel Engines.

cumulative 1% increase was added at each 500 rpm interval, as engine speed increases for a 20 % increase in maximum power, as shown in Figure 3.6. Since small diesel engines are limited by a basic process—fuel-air mixing—at high speeds, the diesel engine maximum power increases by less, 17 %. Natural gas-fueled spark-ignition engines are assumed to perform similarly to gasoline spark-ignition engines, with appropriate adjustments for changes in air breathing capacity (intake rather than direct in-cylinder fuel injection, the air displaced by the natural gas volume) and compression ratio. The maximum power per unit engine displaced volume is reduced by 20%.

Efficiency Map: Combustion engine efficiency maps were modeled using a constant indicated energy conversion efficiency (fraction of fuel chemical energy transferred to the engine's pistons as work) and a constant friction mean effective pressure (total engine friction divided by displaced cylinder volume). This simple method is correct in aggregate but does not take into account the effect of increasing engine speed on engine friction. However, over the normal engine speed range, this assumption is adequate for predicting engine brake efficiency. The brake or useable engine output is obtained from the relation:

$$\text{bmep} = \text{imep} - \text{fmep}$$

where bmep is the brake mean effective pressure (work produced per engine cycle/displaced volume). The indicated mean effective pressure is obtained from the indicated efficiency:

$$\text{imep} = \eta_i(m_f Q_{HV}/V_d)$$

where the m_f is the fuel mass per cycle, Q_{HV} is the lower heating value of the fuel, and V_d is the total cylinder displaced volume.

Thus, the brake mean effective pressure used to determine engine torque (by scaling with displaced volume) is obtained from the indicated performance, offset by the friction of the engine. As a consequence, the brake efficiency of the engine varies appropriately with engine load. Values of $h_i = 0.38$ and fmep = 165 kPa are used for current gasoline engines, and $h_i = 0.48$ and fmep = 180 kPa for current diesels. Based on projected technological improvements, the indicated efficiency is assumed to increase by 7.5% to $h_i = 0.41$ for gasoline engines, to 0.44 for natural gas (CNG) engines, and 0.52 for diesels for the year 2020. Meanwhile, engine friction is expected to decrease by 25% to an fmep value of 124 kPa for gasoline and CNG engines and by 15% to an fmep of 153 kPa for diesel engines.

3.3.3 Battery Electric

Data are available to estimate the efficiency of pure electric drive, although its history is brief and uneven, based on the extensive development but poor sales record of recent pure electric vehicles produced. In the model, assumptions for motor and battery improvements were made to estimate the performance of a future EV.

Motor Torque Curve: Since electric motors have been in service for many applications and have been tuned to optimize performance, a motor peak torque and power curve based on today's electric motor can be used for the future as well, as shown in Figure 3.7. For automotive purposes, the most popular choice is an AC induction electric motor.

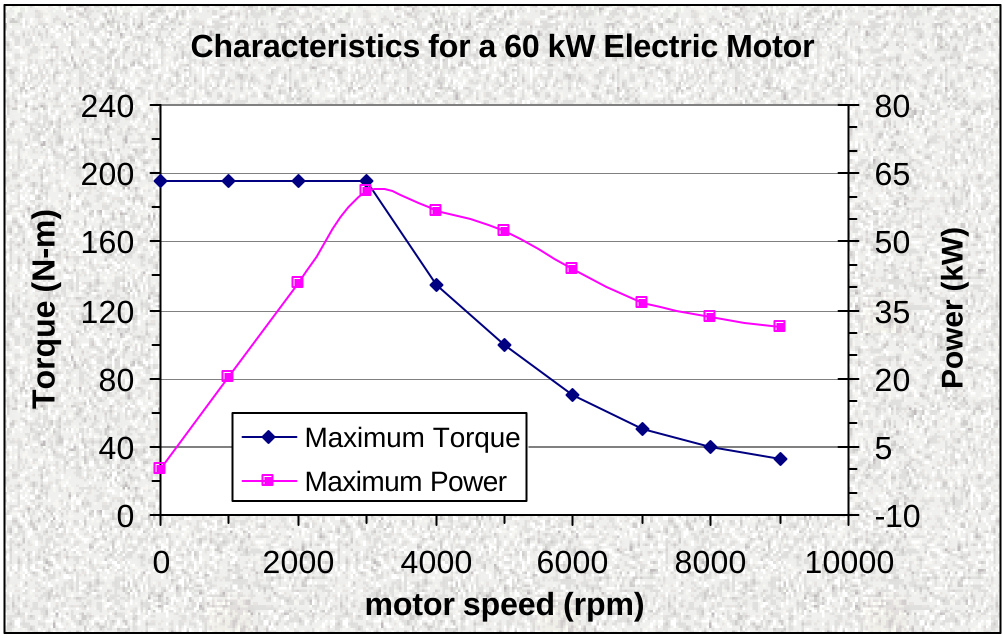


Figure 3.7 Torque and Power Characteristics for a 60 kW Motor

A motor efficiency map (10×21 array) based on motor speed and torque output is used to model motor efficiency, while the power inverter is assumed to have a constant efficiency of 94%. Together with the modeled single gear ratio transmission loss, the total electric motor system efficiency is about 80% over the combined driving cycle. An additional 15% loss is added in turnaround operation when the motor is used in regenerative braking to convert mechanical work to electricity. For electric vehicles, an overall battery charging efficiency of 85% from the station or outlet is included in the vehicle cycle.

Battery Characteristics: Although other technologies are being developed, nickel metal hydride (NiMH) batteries are the technology of choice for automotive applications today both for hybrids and electric vehicles. EV batteries currently have a specific energy of about 70 Wh/kg and a specific power of about 150 W/kg (GM, 2000; US DOE, 1999). For the year 2020, it is assumed that EV battery performance will improve, especially the specific energy, and that battery performance will be close to meeting the Advanced Battery Consortium's (US ABC, 2000) commercial goals of 150 Wh/kg and 300 W/kg. These commercial goals are judged to be the battery performance required to produce acceptable EV performance. Although

NiMH probably cannot reach this potential, another technology such as the lithium-ion battery, may. Its specific energy is significantly higher than that of the NiMH battery technology.

Batteries are not intended to be fully discharged, since this shortens their lifetime and decreases their capacity. Also, topping off the battery at high state of charge is not efficient given the internal resistance of the batteries. Hence, cycled battery applications tend to operate within the state of charge range 20-80%

For the pure electric vehicle, both battery performance and charge density constraints (specific power and specific energy) are important. In addition to providing the power needed for peak motor power, battery energy storage capacity must be sufficient to give adequate vehicle range. However, too low a battery specific energy requires extra batteries which add to the vehicle mass and thus require additional structural support, increased motor power, and more batteries to maintain performance, generating an undesirable compounding effect. Given this constraint, the battery pack is selected based on its power capacity, and no effort is made to augment vehicle range beyond what we estimate the available EV battery technology can provide. Also, the battery volume must also be considered because of its possible intrusion into the interior space.

For hybrid systems, only the batteries specific power is critical, since discharged batteries can be recharged during ICE operation. High power HEV NiMH batteries currently have a specific power of about 400 W/kg and a specific energy of about 40 Wh/kg (at 3-hr rate.) For 2020, it is assumed that battery performance will improve, especially in specific power, and goals of 800 W/kg and 50 Wh/kg are well within reach (Kalhammer, 2000). Again, lithium-ion battery technology may well surpass this goal.

3.3.4 Gasoline/Diesel Electric Hybrid

Data are becoming available for ICE-electric hybrid vehicles: e.g., there are two gasoline hybrids currently in limited production already in the market. With several different types of feasible hybrid configurations, and different drivetrain arrangements within each configuration, the Toyota Prius with its parallel, balanced-loading, CVT hybrid configuration was selected and modified for our model.

Hybrid Configuration: Starting with the most basic distinguishing characteristic, there are series and parallel hybrids. A series hybrid drives the wheels only through the electric motor with the combustion engine generating electricity, whereas a parallel hybrid system powers the wheels directly with both the combustion engine and electric motor.

Within the parallel hybrid family, there is a further separation between dual-mode and power-assist, and between road-coupled and wheel-coupled configurations. A duel-model drivetrain allows vehicle operation with just the engine, or just the motor, or with both, whereas a power-assist drivetrain always draws primary power out of the engine with the electric motor supplementing the engine at high loads. A road-coupled drivetrain has the two power sources, unconnected, and driving different wheels, whereas a wheel-coupled drivetrain combines the engine and motor before transferring power the wheels.

Within the parallel, dual-mode, wheel-coupled family, the electric motor can contribute power before or after the geared transmission for the combustion engine. The Toyota Prius uses a planetary gear setup to couple the engine and the motor prior to the continuously variable transmission. In our study, the motor power bypasses the combustion engine/CVT combination, and drives the wheels directly through a single-speed gear ratio reduction for internal consistency with the pure electric drive vehicles, and for improved efficiency.

Power Logic Control: Controlling the power balance between the combustion engine and electric motor is dependent on many factors, such as driver requirements, power demand, vehicle speed, and battery state of charge. Many options exist and could be very sophisticated. For the simulation, a simplified control model is used. During low power situations, only the electric motor is in operation, thus eliminating engine idling and the less efficient and more polluting modes of operation for combustion engines. Above a preset threshold, the vehicle will be driven only by the combustion engine, except at the higher loads, such as during hard acceleration or hill climbing, when the electric motor serves as a load-leveler and provides the necessary additional power to add to the engine's maximum output.

While all technologies are held to the same peak power to mass ratio, hybrid technologies have an extra factor: balancing the power contribution between the engine and the motor. Having performed a series of calculations of widely varying power combinations, we find a difference in energy consumption of roughly 10%. Arguments for more engine or more motor power must be carefully weighed. A larger engine means smaller battery/motor mass and better highway operation, when the ICE is more efficient; a larger motor means more effective regenerative braking energy capture and better dual-mode operation, when the electric motor is preferred in a city setting. A motor power of 30% of the total available power was used for the advanced ICE parallel hybrids, as an appropriate compromise.

Note that while maintaining an adequate charge in the battery is a reasonable expectation for normal urban driving, in driving that requires high power over extended periods of time (such as long hill climbing or towing at high speeds), the battery charge may be depleted and the total system power will then be reduced to that of the ICE. Conventional ICE vehicles do not suffer this penalty.

It is important to note that both the continuously variable transmission and the hybrid system in the ICE-hybrid vehicle we have analyzed help reduce fuel consumption as compared to the non-hybrid ICE advanced vehicles. Because of the hybrid mode, the combustion engine does not idle or operate below 2 kW. In addition, the motor allows for modest regenerative braking, recovering some of the vehicle kinetic energy that would otherwise be dissipated. The CVT also improves the propulsion system's energy consumption, in addition to the hybrid features, by allowing higher efficiency regions of the engine to be used more frequently.

3.3.5 Fuel Cell Electric Hybrid

Data exist only for prototype fuel-cell systems, and many details about component performance are unavailable. Also, significant fuel-cell system technology improvements are occurring in stack size and weight for a given power, fuel storage methods, reformer performance, and cost. Modeling future production fuel cell systems that currently exist only in prototype form is speculative and uncertain, although overall system component efficiencies can be plausibly estimated.

Hybrid Configuration: In contrast to the combustion engine hybrid, the fuel-cell battery hybrid is a series hybrid, with the fuel cell generating electricity that powers the electric motor and accessories, or recharges the batteries, or does both. Friedman (1999) demonstrates that hybridization of fuel cell vehicles helps conserve fuel, as verified with the model used in this study. Hybridization is also preferred and is likely to be necessary for reformer fuel cell systems to eliminate the lag time of reformer warm-up and response to driver demand. The power logic control operates in a similar manner to that of the combustion engine hybrid.

Fuel-Cell Power Curve: The fuel-cell system efficiency is based on modeling by Directed Technologies (Thomas et al, 1998b). First, the power versus efficiency curve, as shown in Figure 3.8 for a 60 kW stack, is scaled to the stack size required to give the gross power output. Then, 15% of the generated power is diverted to run the needed fuel cell systems.

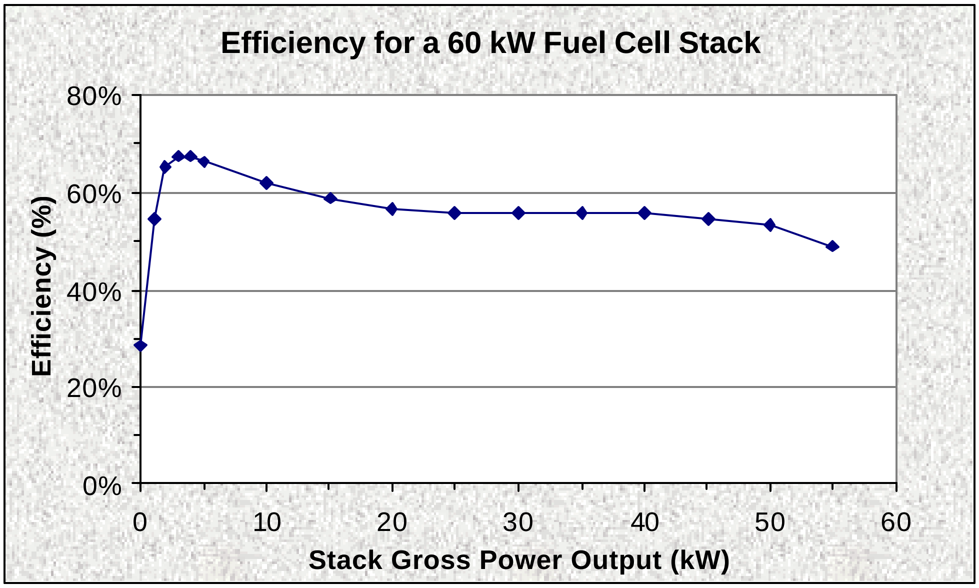


Figure 3.8 Fuel Cell Efficiency for a 60 kW Stack

An additional fuel cell system loss is taken into account for reformer vehicles, where reduced hydrogen concentration in the reformer exit fuel stream results in poorer stack performance and compromised hydrogen utilization. According to Thomas et. al. (1998b), the methanol reformer generates a stream with 75% hydrogen, with a 10% reduction in fuel cell power; the gasoline reformer generates a stream with 40% hydrogen, with a 21.5% reduction in fuel cell power. Because the diluted hydrogen input stream must now be an open flow, both reformer fuel cells have a hydrogen utilization rate of 85%. All numbers from Directed Technologies are taken as an average of the best and probable cases.

> ***Reformer Properties:*** On-board reformer technologies are still in the development stage, making predictions of their performance difficult and uncertain. For our simulation, a constant reformer efficiency is used based on the results from Directed Technologies (Thomas et. al. 1998a,b). Again, the average of the best and probable cases is used: 82% for the methanol steam reformer and 72.5% for the gasoline partial-oxidation reformer.

3.4 Vehicle Simulation Results

We have verified our simulation models on a set of current production and prototype vehicles: The Toyota Camry (4-cylinder manual and automatic transmissions, and 6-cylinder automatic), the 1990 Audi 100 turbo diesel (5-cylinder manual), the Toyota Prius (4-cylinder CVT hybrid), the Ford P2000 prototype hydrogen fuel cell vehicle, and the GM EV1 (NiMH batteries) limited-production electric vehicle. The measured and predicted urban and highway fuel economies are compared in Table 3.3. While not all input details for these vehicles are available and some had to be estimated, the results show reasonable agreement with Federal Test Procedure or company published data. (For the GM EV1, an overall recharging efficiency of 70% - coupling, charger, and battery losses, and a battery discharge efficiency of 90% was used.)

MODEL	numbers in mpg gasoline equivalent power unit	trans.	Published/Reported City	Highway	Unadjusted/Actual City	Highway	Simulation Result City	Highway	Percent Difference City	Highway
Toyota Camry	4-cyl gasoline	manual	23	31	25	39	28.3	39.1	**13%**	**0%**
Toyota Camry	4-cyl gasoline	auto	21	27	23	35	24.1	35.9	**5%**	**2%**
Toyota Camry	6-cyl gasoline	auto	20	29	23	37	22.6	32.2	**-2%**	**-13%**
Audi 100	5-cyl diesel	manual	33.1	41-56	37		37.9	53.0	**3%**	<10%
Toyota Prius	gasoline hybrid	CVT	lower 50's	lower 40's			39.8	46.4	<15%	<5%
Ford P2000	hydrid fuel cell	direct			56	80	55.6	69.9	**-2%**	**-13%**
GM EV1	battery electric	direct			100	113	93.2	120.8	***-6%***	***7%***

Table 3.3 Comparison of Fuel Economy Results with Existing Data. AuYeung et al. (2001).

Then, based on the component details and assumptions described previously, the vehicle simulations were performed. Tables 3.4 and 3.5 summarize the major component input variables and assumptions, and component and vehicle results, from the vehicle simulation calculations. The US Federal Urban (city) and Highway driving cycles were used. Eleven different vehicle and propulsion systems were examined. The first column (on the left) in Table 3.4 is a current (~1996) average-size passenger car (note again that the EPA empirical factor of 0.9 for city and 0.78 for highway are not used for the results); the second column is the evolving baseline average car projected out to 2020. The advanced technology vehicles (in 2020) are then arranged in four groups: internal combustion engine vehicles, internal combustion engine/battery hybrids, fuel-cell hybrids, electric vehicle. All these advanced technology vehicles have reduced vehicle resistances (mass, aerodynamics drag, tire resistance) compared with the 2020 baseline evolving vehicle. Table 3.5 summarizes the key assumptions that go with each line item in Table 3.4.

The results at the bottom of Table 3.4 show energy use, fuel consumption/economy, range, overall vehicle energy efficiency (tank to wheel) for the urban and highway driving cycles, and for the standard 55% urban 45% highway combined energy/fuel consumption average, and CO_2 emissions on grams carbon per average vehicle km traveled. Fuel economy and consumption for the combined cycle are expressed in gasoline equivalents of the energy used. The individual city and highway fuel consumption/economy values correspond to the actual fuel used. The calculated ranges of each of these vehicles are closely comparable (about 600 km) except for the EV, whose range depends strongly on the assumed battery characteristics. Vehicle performance is held approximately constant with a maximum power: weight ratio of 75 W/kg.

Note that the numerical values in Table 3.4, which are given to several significant figures to match with the assumptions made and input variables chosen, do not have that level of precision. Validation studies of the simulation (see Table 3.3) show acceptable agreement (± about 5 to 10%) with Federal Test Procedure or company published data. However, predictions for 20 years into the future obviously depend strongly on the assumptions and input variables and have greater uncertainly. Our judgment is that uncertainties will increase across Table 3.4, from left to right, with the predicted improved performance of mainstream technology being more reliable (± about 10%), and the performance of new technology (such as the fuel-cell hybrid) being less reliable

(± about 30%). Note that all columns show a significant reduction in energy consumption and CO_2 emissions as reductions in vehicle resistances, the corresponding reduction in maximum propulsion system power to match reduced vehicle resistances, and the improvement in propulsion system efficiency (both "engine" and transmission) combine together to produce substantial reductions in energy consumed and CO_2 produced.

We remind the reader that these are individual vehicle simulation results. They are for specific combinations of technologies that we have selected to illustrate the behavior of a range of promising future concepts, with component performances estimated for twenty years hence. These vehicles were driven through a specific driving cycle, the US Urban and Highway Federal Test Procedure. We have attempted to keep many vehicle performance characteristics (e.g. maximum power/vehicle weight), vehicle driving range, and vehicle size constant, as vehicle resistances, propulsion systems, and fuels have been changed. The base vehicle characteristics used correspond to those of the current average US passenger car. These limitations are important as we attempt to interpret these specific results as indications of future light-duty fleet behavior.

3.4.1 Battery Performance Impacts

The degree to which battery technology will improve is uncertain. Battery performance has a limited effect on the ability of ICE and FC hybrids to reduce energy consumption. Using more optimistic battery performance projections (2000 W/kg, 80 Wh/kg) instead of more conservative ones (800 W/kg, 50 Wh/kg) saves about 2-4% in mass, and reduces energy consumption by 1-2%. More important for HEV batteries will be the development of higher specific energy, which would extend the full-power capability of hybrids. However, battery performance has a big impact on the relative performance of the pure battery electric vehicle. Realizing the USABC commercial goals of 150 Wh/kg and 300 W/kg will enable significant range extension from current values. However, if this goal is not reached, then EV range will be significantly reduced below the values in Table 3.4.

To compare the EV results in Table 3.4 with calculations using a more conservative battery technology, we chose the USABC short-term desired goal of 100 Wh/kg and 200 W/kg, which some marketable Lithium ion batteries are approaching today. This more conservative battery performance increases the overall EV mass because a heavier battery pack, stronger motor, and greater structural support (with compounding effects) are needed to maintain the constant power-to-mass ratio. Already deficient in range because of the low energy density of batteries, the EV increases in mass by 34% and in energy consumption by 18%, making it significantly less attractive.

	Date		1996	2020	2020	2020	2020	2020	2020	2020	2020	2020	2020
	Technology		current	baseline	advanced	advanced	advanced	advanced	advanced	advanced	advanced	advanced	advanced
	Propulsion System		SI ICE	SI ICE	SI ICE	CI ICE	SI Hybrid	CI Hybrid	SI Hybrid	FC Hybrid	FC Hybrid	FC Hybrid	Electric
	Fuel		gasoline	gasoline	gasoline	diesel	gasoline	diesel	CNG	gasoline	methanol	hydrogen	electricity
	Transmission		auto	auto-clutch	auto-clutch	auto-clutch	CVT	CVT	CVT	direct	direct	direct	direct
	VARIABLE	*units*											
Mass	Body & Chassis Mass	kg	930	845	756	759	756	759	756	794	778	763	763
Mass	Propulsion System Mass	kg	340	226	217	271	216	251	235	465	390	371	86
Mass	Battery Mass	kg	12	12	12	12	36.0	37.2	36.6	45.5	43.0	41.0	328.0
Mass	Maximum Fuel Mass	kg	40.2	24.7	21.8	20.2	15.8	13.9	13.0	25.2	42.0	4.0	0.0
Mass	Occupant Mass (300 lbs.)	kg	136	136	136	136	136	136	136	136	136	136	136
Mass	**Total Mass (2/3 tank)**	**kg**	**1444**	**1236**	**1136**	**1191**	**1154**	**1192**	**1172**	**1458**	**1375**	**1314**	**1312**
Vehicle	Rolling Resistance Coeff.	---	0.009	0.008	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.0060
Vehicle	Drag Coefficient	---	0.33	0.27	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
Vehicle	Frontal Area	m2	2.0	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Vehicle	Auxiliary Power	W	700	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Vehicle	**Power:Weight Ratio**	**W/kg**	**76.0**	**75.0**	**75.0**	**75.0**	**75.0**	**75.0**	**75.0**	**75.0**	**75.0**	**75.0**	**75.0**
Engine	Engine Displacement	cm3	2500	1790	1645	1875	1114	1284	1360				
Engine	Transmission Efficiency	---	0.7-0.8	0.88	0.88	0.88	0.88	0.88	0.88				
Engine	Indicated Efficiency	---	0.38	0.41	0.41	0.51	0.41	0.51	0.44				
Engine	Frictional MEPressure	kPa	165	124	124	154	124	153	124				
Engine	**Max Engine Power**	**kW**	**109.7**	**92.7**	**85.2**	**89.4**	**57.7**	**59.6**	**58.6**				
Motor	Hybrid Threshold	kW					2.0	2.0	2.0	3.3	3.0	3.1	
Motor	Gear Efficiency	---					0.66	0.65	0.66	0.93	0.93	0.93	0.95
Motor	Electric Motor Efficiency	---					0.76	0.76	0.76	0.80	0.80	0.80	0.82
Motor	**Max Motor Power**	**kW**					**28.8**	**29.8**	**29.3**	**109.3**	**103.1**	**98.5**	**98.4**
Fuel Cell	H2 Flow Concentration	%								40%	75%	100%	
Fuel Cell	Fuel Cell System Efficiency	---								0.41	0.47	0.52	
Fuel Cell	Reformer & Utilization Eff.	---								0.62	0.70		
Fuel Cell	Peak Stack Power	kW								72.9	68.7	65.7	
Fuel	Lower Heating Value	MJ/kg	43.7	43.7	43.7	41.7	43.7	41.7	50	43.7	20.1	120.2	
Fuel	Fuel Density	kg/L	0.737	0.737	0.737	0.856	0.737	0.856	0.16	0.737	0.792		
Battery	Battery Discharge Efficiency	---					0.95	0.95	0.95	0.95	0.95	0.95	0.95
Battery	Specific Energy	Wh/kg					50	50	50	50	50	50	150
Battery	Specific Power	W/kg					800	800	800	800	800	800	300
	RESULTS												
City	Fuel Energy Use	MJ/km	3.195	1.997	1.786	1.582	1.200	1.029	1.153	2.038	1.513	0.904	
City	Battery Status	MJ/km					0.002	0.000	0.002	0.000	0.001	0.000	0.579
City	**Combined Energy Use**	**MJ/km**	**3.195**	**1.997**	**1.786**	**1.582**	**1.209**	**1.029**	**1.160**	**2.038**	**1.517**	**0.905**	**0.579**
City	Combined Fuel Consumption	L/100km	9.92	6.20	5.55	4.43	3.75	2.88	14.50	6.33	9.53		
City	Combined Fuel Economy	mpg	23.7	37.9	42.4	53.1	62.7	81.6		37.2	24.7		
City	Range (fuel only)	km	550	541	533	532	575	563	564	540	558	532	360
City	Tank-to-Wheel Efficiency	%	13.0%	16.9%	16.2%	19.0%	26.4%	31.8%	27.8%	17.6%	22.5%	36.2%	61.5%
Highway	Fuel Energy Use	MJ/km	2.152	1.454	1.246	1.070	0.919	0.807	0.895	1.520	1.138	0.698	
Highway	Battery Status	MJ/km					-0.004	-0.005	-0.005	-0.009	-0.009	-0.009	0.422
Highway	**Combined Energy Use**	**MJ/km**	**2.152**	**1.454**	**1.246**	**1.070**	**0.900**	**0.788**	**0.876**	**1.489**	**1.107**	**0.684**	**0.422**
Highway	Combined Fuel Consumption	L/100km	6.68	4.51	3.87	3.00	2.79	2.21	10.95	4.62	6.95		
Highway	Combined Fuel Economy	mpg	35.2	52.1	60.8	78.5	84.2	106.5		50.9	33.8		
Highway	Range (fuel only)	km	816	743	765	787	751	719	726	724	742	689	494
Highway	Tank-to-Wheel Efficiency	%	17.1%	19.4%	18.1%	21.7%	25.7%	29.8%	26.6%	17.5%	22.7%	35.8%	58.8%
combined	**Equivalent Energy Use**	**MJ/km**	**2.726**	**1.753**	**1.543**	**1.352**	**1.070**	**0.921**	**1.032**	**1.791**	**1.332**	**0.805**	**0.508**
combined	**Gasoline Eq. Consumption**	**L/100km**	**8.46**	**5.44**	**4.79**	**4.20**	**3.32**	**2.86**	**3.20**	**5.56**	**4.14**	**2.50**	**1.58**
combined	**Gasoline Eq. Economy**	**mpg**	**27.8**	**43.2**	**49.1**	**56.0**	**70.8**	**82.3**	**73.4**	**42.3**	**56.9**	**94.1**	**149.0**
combined	**Cycle Carbon Emission**	**g C /km**	**53.3**	**34.3**	**30.2**	**28.2**	**20.9**	**19.2**	**15.5**	**35.0**	**24.9**	**0.0**	**0.0**

Table 3.4 Summary Results for Test Vehicles

	VARIABLE	*units*	
Mass	Body & Chassis Mass	kg	see vehicle mass distribution
	Propulsion System Mass	kg	see vehicle mass distribution
	Battery Mass	kg	see vehicle mass distribution
	Maximum Fuel Mass	kg	except for electric vehicle, fuel is scaled for ~600km range.
	Occupant Mass (300 lbs.)	kg	assumed 1.5 occupants with cargo = 110 kg.
	Total Mass (2/3 tank)	kg	sum of all masses on board
Vehicle	Rolling Resistance Coeff.	---	assumed constant, = 0.009 for current, 0.008 for evolutionary, 0.006 for advanced.
	Drag Coefficient	---	assumed constant, = 0.33 for current, 0.27 for evolutionary, 0.22 for advanced.
	Frontal Area	m2	assumed constant, = 2.0 for current, 1.8 for future.
	Auxiliary Power	W	assumed constant, = 400 W during vehicle operation.
	Power:Weight Ratio	W/kg	maximum total power available / total mass, held constant at 0.75 W/kg.
Engine	Engine Displacement	cm3	chosen according to engine power desired.
	Transmission Efficiency	---	assumed constant, = 0.7 for current city automatic, 0.8 for current highway automatic, 0.88 for automatice clutch and continuously variable.
	Indicated Efficiency	---	assumed constant, = 0.38 for current gasoline, 0.41 for future gasoline, and 0.51 for future diesel.
	Frictional MEPressure	kPa	assumed constant, = 165 kPa for current gasoline, = 124 kPa for future gasoline, and 153 kPa for future diesel.
	Max Engine Power	kW	maximum power from combustion engine.
Motor	Hybrid Threshold	kW	power below which hybrids are only driven with batteries.
	Gear Efficiency	kW	modeling result, dependent on load and speed.
	Electric Motor Efficiency	---	modeling result, dependent on load and speed.
	Max Motor Power	kW	maximum power from electric motor.
Fuel Cell	H2 Flow Concentration	%	hydrogen concentration available to fuel cell; affects stack efficiency.
	Fuel Cell System Efficiency	---	modeling result based on energy produced by fuel cell for road use / energy in hydrogen into fuel cell.
	Reformer & Utilization Eff.	---	energy in hydrogen consumable by fuel cell / energy stored in fuel for conversion.
	Peak Stack Power	kW	maximum power from fuel cell stack, contributing 85% of fuel cell hybrid available power.
Fuel	Lower Heating Value	MJ/kg	constants; usual to define ICE efficiency with lower heating value.
	Fuel Density	kg/L	constants.
Battery	Battery Discharge Efficiency	---	assumed constant, = 95%.
	Specific Energy	Wh/kg	US Advance Battery Consortium commercial goal = 150 Wh/kg.
	Specific Power	W/kg	US Advance Battery Consortium commercial goal = 300 W/kg.
	RESULTS		
City	Fuel Energy Use	MJ/km	modeling result.
	Battery Status	MJ/km	modeling result.
	Combined Energy Use	MJ/km	vehicle energy use, specific to city driving cycle; for hybrids, battery use is adjusted by a factor to take into account final battery SOC.
	Combined Fuel Consumption	L/100km	consumption of fuel only.
	Combined Fuel Economy	mpg	equivalent economy of fuel only.
	Range (fuel only)	km	driving range of vehicle based on fuel on board and the city driving cycle, (excludes battery charge depletion at low speeds).
	Tank-to-Wheel Efficiency	%	energy supplied to wheels / total energy use; note regenerated energy not included.
Highway	Fuel Energy Use	MJ/km	modeling result.
	Battery Status	MJ/km	modeling result.
	Combined Energy Use	MJ/km	vehicle energy use, specific to highway driving cycle; for hybrids, battery use is adjusted by a factor to take into account final battery SOC.
	Combined Fuel Consumption	L/100km	consumption of fuel only.
	Combined Fuel Economy	mpg	equivalent economy of fuel only.
	Range (fuel only)	km	driving range of vehicle based on fuel on board and the highway driving cycle, (excludes battery charge depletion at low speeds).
	Tank-to-Wheel Efficiency	%	energy supplied to wheels / total energy use; not regenerated energy not included.
combined	Equivalent Energy Use	MJ/km	combined vehicle cycle energy use, with 55% city and 45% highway operation.
	Gasoline Eq. Consumption	L/100km	total energy use converted to equilvalent gasoline fuel consumption.
	Gasoline Eq. Economy	mpg	total energy use converted to equilvalent gasoline fuel economy.
	Cycle Carbon Emission	g C /km	carbon emitted during combined vehicle cycle.

Table 3.5 Brief Comments on Variables Listed

3.5 Estimated Vehicle System Retail Prices

We next present cost estimates of the examined technology options. Given the lack of a suitable cost model and detailed input data for these future technologies, that would allow an estimate of the manufacturing costs, our retail price estimates are based on a literature review and in most cases were discussed with representatives from the automobile industry (Dietrich et al., 2000).

It is important to note that some technology improvements and changes that enable higher vehicle fuel efficiency do not necessarily increase the retail price. For example, downsizing the engine to adjust to the reduced driving resistances reduces the retail price. Engine parts and materials account for about 25% of total engine costs in large series production (Affenzeller, 1995). For the 6 cylinder, 110 kW, 1997 baseline vehicle engine, engine and material costs account for US$ 825 (US$ 138 per cylinder) at specific engine costs of US$ 30/kW. Due to the engine's other components whose costs are less dependent on the number of cylinders such as mixture system, electronics, etc., we have estimated a credit of US$ 120 per cylinder. In combination with other measures for improving engine fuel efficiency, however, the engine retail price increases.

Another example is automobile tires. Today's automobile tires have 30% lower rolling resistance compared to those in the mid-1980s, 25% increase in lifetime, 15% reduction in noise, and 7% improved wet-road braking, but identical costs (Birch, 1996). Based on that experience, we expect that if new tire technology is introduced gradually into the automotive market, future (2020) tire technology will continue to provide lower rolling resistance at roughly the same price through improving understanding of the problems and opportunities, and market mechanisms. Similarly, a shift toward lower-weight high-strength steel autobodies is widely considered as being largely cost-neutral (e.g., American Iron and Steel Institute, 1995; Renault, 1995).

By contrast, other technology measures increase the retail price; among those is the reduction of aerodynamic drag through panels covering the vehicle underbody, whose retail price increment is about US$ 150 (Dietrich et al., 2000), an aluminum vehicle body of US$ 1,600 (not taking into account possible cost reductions due to recycling) and several measures for improving engine fuel efficiency.

The starting point for our estimates is the price of the 1996 baseline vehicle of US$(1997) 17,200. The retail price of all other vehicles is obtained by adding or subtracting the price of vehicle components that are added to or removed from the baseline vehicle, to create that particular vehicle configuration, to or from the price of the baseline vehicle. The resulting retail price estimates are presented in Table 3.6 for all eleven vehicles (see table notes for assumptions).

The retail price of the evolving baseline vehicle increases by 5% from about US$ 17,200 to 18,000; a rise in mass-specific costs from US$ 13/kg to 16. This increase is broadly in the range of historical cost developments (see Figure 3.9). (The slightly lower retail price of the 1996 baseline vehicle results from it being the base vehicle price, the only price information we could get for all vehicles sold in the US in a given year). An additional factor for the higher historical numbers is the inclusion of minivans and sport-utility vehicles in the data set; these vehicles are typically more expensive than sedans.

The retail price of all other projected vehicles in 2020 ranges from US$ 19,400 (gasoline-fueled advanced mechanical drivetrain vehicle) to US$ 23,400 (gasoline-fueled fuel-cell automobile) and US$ 27,000 (battery-only electric vehicle). The high price of the EV results from the long vehicle range of nearly 500 km and the associated large and expensive battery. Cutting range in half would have a roughly similar effect on battery size and price and result in US$ 22,100.

Each propulsion system/vehicle combination covers a specific portion of this price range. (Note all vehicles except the baseline are "advanced vehicles": i.e., incorporate substantial new technology to reduce driving resistances.) While advanced vehicles with a mechanical drive train are at the lower end of this price range, i.e., between US$ 19,400 and 20,500, ICE hybrid vehicles have a retail price between US$ 21,100 and US$22,100. At the high price end are fuel cell vehicles and the battery electric vehicle with retail prices of US$ 22,100 (hydrogen-fueled) to 23,400 (gasoline-fueled). Table 3-6 reports the cost estimates in more detail.

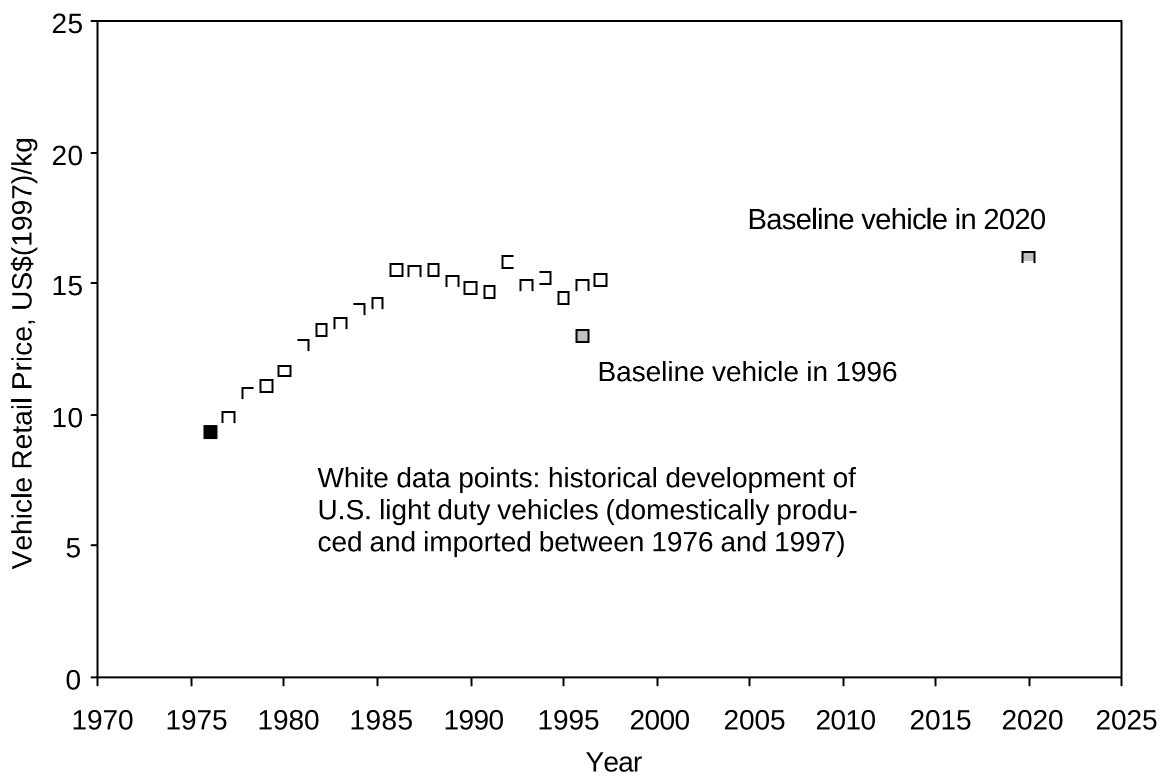


Figure 3.9 Mass-Specific Costs of the Baseline Vehicle in 1996 and 2020 (black rectangles) **and the Historical Development of the New US Automobile Fleet between 1976 and 1997** (white rectangles). The retail price of the baseline vehicle is slightly below the historical level, since (1) it reflects the base vehicle price, i.e., without any extras, and (2) the historical numbers likely include minivans and sport-utility vehicles that are typically more expensive than sedans.

While the uncertainty of the retail price of mechanical and hybrid drive train vehicles is comparatively small (the technology and manufacturing of each of their components is well understood), that associated with fuel cell systems is by far the largest. PEM fuel cells are still in the demonstration phase and complete systems would cost several thousand US$/kW. Most projections of future prices are between US$ 50 and 100/kW (see, e.g., Ogden et al., 1999), however, significant uncertainty exists whether this range will be met at all. Here, we have used a price of US$ 60/kW, which is at the lower end of the indicated range. Even using this, from today's perspective, aggressive number, the fuel cell vehicle's retail price would be still around US$ 1,000 higher compared to ICE hybrid vehicles.

3.6 Vehicle Technology Summary

The vehicle simulation results presented in Section 3.4 suggest that substantial fuel economy and CO_2 emissions benefits may be realizable. Obviously these projected benefits depend on the assumptions made about the performance of the major sub-components of the total vehicle: the vehicle weight and other resistances, and the efficiencies of the engine and transmission components. Especially, these results demonstrate the strong synergies between reducing vehicle weight and drag, reducing engine maximum power and weight as a consequence, and at the same time improving engine and transmission performance and efficiency.

Before we summarize and compare these numerical results it is appropriate to restate the intent of these calculations. They are projections of what potentially practicable vehicle and propulsion system improvements might produce in terms of reduced average passenger car energy consumption and CO_2 emissions, by about 2020, with other vehicle performance attributes roughly at today's levels. These combinations of technologies would need to be in mass production and so have gone through extensive production engineering development. Thus prior to 2020 they would need to have sufficient market appeal to reach the production stage and grow in volume to a moderate production level. These energy consumption numbers represent our estimates of what *could happen* to passenger car fuel consumption over the next 20 years, and not necessarily what we judge will or ought to happen.

There are many numerical inputs to these calculations. We have attempted to be as internally consistent with these inputs as is feasible, but, of course, there are uncertainties in many of these numbers. The uncertainties are significantly less where we are extrapolating from the performance of well established technologies (such as steel chassis and body components, and spark-ignition engines). The uncertainties in performance, weight and cost, increase for technologies that have come into production relatively recently, but whose ultimate potential is still being explored (e.g. extensive use of aluminum, small low-emissions diesel engines, continuously variable transmissions). The uncertainties become much greater for new technologies such fuel cells and high performance batteries, where the performance and cost of current versions of these technologies fall far short of what would be required for market feasibility. Here we have used literature assessments of the future development potential, tempered by our own judgments of plausible long-term technology improvements.

Table 3-6 Retail price estimates of the examined vehicles.

Technology	current	baseline	advanced	advanced	advanced	advanced	advanced	advanced	advanced	advanced	advanced
Propulsion System	SI ICE	SI ICE	SI ICE	CI ICE	SI Hybrid	CI Hybrid	SI Hybrid	FC Hybrid	FC Hybrid	FC Hybrid	Electric
Fuel	gasoline	gasoline	gasoline	diesel	gasoline	diesel	CNG	gasoline	methanol	hydrogen	electr.
Transmission	auto	auto-clutch	auto-clutch	auto-clutch	CVT	CVT	CVT	direct	direct	direct	direct
Baseline Vehicle	17187	17187	17187	17187	17187	17187	17187	17187	17187	17187	17187
Engine				1500							
Credit for Downsizing		-240	-360	-360	-360	-360	-360	-4050	-4050	-4050	-4050
GDI		500	375		375		375				
VVLT		300	225		225		225				
Hybrid/Fuel Cell Systems											
Fuel Cell								4372	4124	3940	
Reformer								1457	1375		
Fuel Tank							500			650	-100
Electric Motor (& pow.el)					433	447	439	1640	1547	1478	1476
Single Stage Red. Transm.								158	154	151	151
Battery					1320	1320	1344	1332	1510	1460	11040
Exhaust Gas Cleaning								-430	-430	-430	-430
Tier 2		300	225	400	152	267	155				
Vehicle											
Weight Reduction			1600	1600	1600	1600	1600	1600	1600	1600	1600
Aerodynamics			150	150	150	150	150	150	150	150	150
TOTAL											
Total Vehicle Price	17200	18000	19400	20500	21100	22100	21600	23400	23200	22100	27000
$ per kg Vehicle Weight	13.1	16.4	19.4	19.4	20.8	21.0	21.0	17.7	18.7	18.8	23.0

Table Notes: The credit for engine downsizing is assumed to be US$ 120 per cylinder and US$ 4050 for the entire engine plus transmission. The retail price increment (RPI) of GDI and VVLT are assumed to be US$ 500 and 300, respectively, for a 4-cylinder engine; we assumed that these figures scale as the number of cylinders (Dietrich et al., 1998). The RPI of satisfying the Tier 2 emission requirements of US$ 300 for a 4-cylinder engine is higher than EPA estimate of US$ 136 but lower than the Dietrich (2000) estimate. In addition, we use a retail price equivalent (RPE) of 100% instead of the EPA's 26% and Dietrich's 73% (Dietrich, 2000, 1997). Again, we assume that the RPI of emission control technology scales as the number of cylinders. We assumed the corresponding RPI of diesel exhaust gas catalyst to be one-third higher compared to the one for gasoline engines, because it represents a completely new system and satisfies two functions: reduction of gaseous emissions and particulates. The RPI of US$ 1600 for vehicle weight reduction results from the extra investments for an aluminum-body and closures and the aerodynamics for panels to cover the rear wheels and the vehicle's underbody (see Dietrich et al., 1998). The RPI of the direct injection, turbo-charge diesel engine is US$ 1500 above a 4-cylinder gasoline engine. The RPI of asynchronous motors, converters, and power electronics are estimated to be US$ 15/kW (Ogden et al., 1998; Kalhammer, 2000) and that of a single stage reduction transmission RPI [US$(1990)]=90+0.62·kW(peak) (Dietrich et al., 1998). The battery retail price of hybrid vehicles is assumed to be US$ 400/kWh plus US plus US$ 600 for thermal and electrical management of subsystems (Kalhammer, 2000); that of EV batteries US$ 200/kWh plus US$ 1200 (Anderman, Kalhammer, and MacArthur, 2000). The RPI of fuel reformers is US$ 20/kW, i.e. in the middle of the range assumed by Ogden et al. (1998). The credit of a three-way catalyst, applicable to all fuel cell and the battery electric vehicle is US$ 430 (DeLuchi, 1989a and 1989b); these vehicles also experience a credit for the drop of internal combustion engine and transmission, assumed to amount to US$ 30/kW, a typical number of the automobile industry. The RPI of fuel cells was assumed to be US$ 60/kW.

The energy/fuel consumption and CO_2 emissions calculations were done for the US Federal urban and highway driving cycles (and then weighted 55:45% and combined). While these cycles are representative of typical driving situations, real life fuel consumption has been found to be worse than measured with these driving cycles (currently by about 15% for past and current ICE vehicles). It is well known that different driving cycles, with a given vehicle and propulsion system technology, result in different fuel consumptions. Also, the automotive industry's experience suggests that current driving patterns, which are more aggressive than the combined FTP cycles, reduce the fuel consumption benefits of new technology vehicles below values calculated for the FTP. Thus comparing these different vehicle and propulsion system combinations is best done in terms of their percentage reduction in fuel or energy consumption relative to the evolving baseline vehicle level in 2020.

Then, a wide range of additional attributes must be considered as well (see Section 5). While performance with average car occupancy (1.5 people) and cargo is held constant, since these are lighter vehicles the loss in performance as occupancy and cargo load increase will be higher than is typical of today's vehicles. Towing and hill climbing capacity will be reduced, for the same reason. For hybrid systems it will be further reduced since the power unit, once batteries are discharged, is significantly less powerful. Lighter vehicle weight raises several safety and handling issues. Vehicle mass and crashworthiness both impact occupant safety. Meeting crashworthiness requirements in mandated government tests could be maintained by the additional features required to compensate for reduced energy absorption as the body is crushed. These may require extra cost and weight that we have not included here. How customers will respond to the safety impacts of lighter weight vehicles is not known. Hybrid and fuel cell propulsion systems add weight and volume relative to the baseline. While the additional weight has been estimated, the impact of additional propulsion system volume has not. For all these reasons, our vehicle fuel consumption and CO_2 estimates should be viewed as indicative, but probably optimistic.

Especially important in interpreting the results of these predictions for specific vehicle technology combinations in an average-size US car, is the response of the market. In the past, improvements in vehicle energy efficiency have been offset in part by increases in vehicle size and weight, increased vehicle performance, and more vehicle convenience features. Whether this historical pattern will continue is unknown. Further the total impact of these various technologies must be assessed in the context of the total fuel supply, vehicle production, and vehicle use system, after the energy consumed and CO_2 emissions produced from these three parts of the total system are appropriately added together, as is done in Chapter 5. Our specific summary conclusions on relative vehicle technology performance and price are as follows; references to fuel consumption or economy refer to fuel loaded on board the vehicle and not to the total well-to-wheels energy consumption:

1. The projected 2020 evolving baseline passenger car improvements, which are likely to be driven by market pressures and some tightening of CAFE requirements, are significant: a 15% reduction in vehicle mass and a 35% reduction in fuel consumption, at about a 5% increase in price, as compared to today's average car.

2. The more advanced vehicle-technology car with lower vehicle resistances, with the same improved baseline gasoline engine and improved transmission, decreases the mass by an additional 8% and the fuel consumption by a further 12% relative to the 2020 evolving baseline car with a price increase of about 8% .

3. The diesel-engined equivalent to this gasoline-engined advanced technology vehicle gives about 10% better gasoline-equivalent fuel consumption than the gasoline vehicle, i.e., a 23% reduction relative to the 2020 evolving gasoline-engine baseline car. The diesel is about $1000 more expensive than the equivalent gasoline-engined car.

4. The ICE hybrid vehicles relative to their non-hybrid equivalent vehicles show an additional fuel consumption reduction of about 30 percent, for both gasoline, CNG, and diesel-engined versions. Part of this is due to the hybrid features, part is due to the CVT. The car prices are about 20% higher than the 2020 baseline. The diesel hybrid is some 10-15% lower in energy consumption than the gasoline and CNG hybrids.

5. The fuel cell system projections underline the importance of the fuel supply issue. The high efficiency of the direct hydrogen-fueled fuel cell, augmented by the hybrid features, leads to *energy* consumption levels that are some 50% lower than the 2020 evolving baseline conventional vehicle (which has a less advanced vehicle body and chassis). However, adding the gasoline or methanol reformer to make these vehicles more practical in terms of market introduction, reduces this fuel-cell benefit relative to equivalent gasoline or diesel-engined hybrids substantially. The methanol-reformer fuel-cell hybrid energy consumption lies between that of the advanced gasoline ICE and gasoline ICE hybrid vehicles. The gasoline-reformer fuel-cell hybrid fuel consumption is comparable to that of the evolving baseline gasoline ICE vehicle. The fuel cell hybrid prices are some 25 to 30% higher than the 2020 evolving baseline, with the lowest increase for the direct H_2-fueled system.

6. While battery electric propulsion systems require the lowest energy input (as electricity) to the vehicle, even with optimistic assumptions about future battery technology, when allowance is made for the efficiency of electricity production and distribution, the total energy input to the electrical system is larger than the gasoline or diesel hybrid (see Chapter 5), and the price is higher, with the battery technology we have considered.

Chapter 4. Energy Use and Emissions in Vehicle Materials Production, Assembly, Distribution, Maintenance, and Disposal

4.1 Introduction

This chapter estimates energy requirements and carbon emissions associated with automobile materials production, vehicle assembly, distribution, maintenance, and disposal. Compared to the life-cycle analysis of automobile usage and fuel production, transmission, and distribution, which were discussed in the previous chapters, the importance of taking into account the "vehicle cycle" was recognized only more recently. Perhaps one of the most passionate debates within this area, which has also contributed to examining the vehicle cycle more thoroughly, is to which extent a reduction in vehicle energy use and emissions may lead to a higher embodied energy, for example, by using lightweight aluminum vehicles. The growing number of life cycle studies focussing on vehicle production has examined both individual vehicle components and the entire automobile. While most studies have pursued an engineering type of analysis by quantifying energy and material flows though all subsystems that together compose the overall system to be examined (e.g., Stodolsky et al., 1995; Schweimer and Schuckert, 1996; Singh et al., 1998; Röder, 2000), others have analyzed energy and material use based on an input-output model (e.g., Maclean and Lave, 1998).

Although broadly consistent, different life-cycle analyses may come to slightly different results. This is because of different assumptions, including a different specification of system boundaries, cross-sectional variability of energy requirements for the production of one and the same type of material (including the assumed electricity mix, and assumptions on materials recycling.

The ultimate system boundaries, within which the analysis is being performed, can be drawn almost arbitrarily large, and differences in technology, raw materials, and the amount and type of employed energy carriers occur. For example, the production process of automotive steel parts can be considered to begin at the gate of the integrated steel plant to which unprocessed and processed raw materials are delivered. Alternatively, the production boundary can be extended to include the extraction of iron ore, ore refining, and transport to the steel plant. Going even farther would be a boundary that includes the machinery necessary to extract the iron ore from the ground, etc. In practice, however, the specification of system boundaries always results from a trade-off between richness in the detail of the production process and the available resources. Here, we carefully define the boundaries for the two dominating materials (ferrous metals and aluminum) and use rough literature-based numbers for all other materials (see below).

In addition, type and amount of energy requirements for material production differ across space and time. A Volkswagen life-cycle study suggests that alone the primary energy requirements for the production of materials can vary by ± 50% (Schweimer and Schuckert, 1996), depending on processes and type of energy carriers used. Due to such cross-sectional variability of energy requirements, we can conduct only a rough assessment of energy use and CO_2 emissions for vehicle material production.

A related source of inconsistency across studies is the employed electricity fuel mix. Electricity-intensive materials, such as aluminum, are typically produced at sites with abundant and cheap hydropower. Thus, it could be argued to assign zero-carbon emissions to aluminum-electrolysis. Here, however, we adopt an economy-wide perspective and use the projected average electricity fuel mix of the U.S. in 2020 (see Table 2.9). The underlying rationale is that hydroelectricity could substitute some carbon-intensive electricity in the absence of the aluminum plant.

A final factor that can result in differences in energy use is materials recycling. Although 95% of all ferrous metals are recycled in the automobile industry, only 25-30% are reused in the automobile (Automotive Engineering, 1995). After its life, a high-value automobile ferrous metal part is melted down and may ultimately be reused in the construction industry with much less quality requirements and thus transformation processes, energy requirements, and costs (a recycling path known as "down-cycling"). Here, we cannot take into account such a value degradation of the recycled material and assume the latter to be reused for the same purpose.

4.2 Stages of Energy Use

The life-cycle energy requirements of an automobile consist of the energy used in materials production, parts forming and assembly, vehicle distribution, maintenance, and disposal. In the following, these stages of energy use are discussed in more detail and applied to all ten vehicles examined in this study.

Materials Production

Energy use and CO_2 emissions from vehicle materials production were projected as follows. First, the material composition of today's baseline vehicle was estimated and that of the future (2020) vehicles projected. Next, in combination with literature-derived energy requirements for the production of the most prominent materials (for both virgin and recycled materials), total energy use for producing any of the examined vehicles was calculated. Finally, carbon emissions were estimated using appropriate emissions factors. In the following, each of these steps will be described in more detail.

Vehicle Material Distribution

Scaling the material distribution of the average new car produced in the U.S. to the 1996 baseline vehicle suggests that the latter automobile incorporates nearly 890 kg of ferrous metals, 100 kg of different types of plastics, roughly 80 kg of aluminum, and about 200 kg of other materials. Based on the distribution of vehicle component weights (Table 3.2) and a literature-based estimate of the share of ferrous metals and aluminum in each of these components, the share of these two materials in the evolutionary baseline vehicle in 2020 was projected. The mass of all other materials was projected using a more aggregate approach. For example, the mass of vehicle glass of 35 kg was kept constant, while the mass of magnesium in the 1996 baseline vehicle was doubled to 20 kg through 2020, to account for the ongoing penetration of this lightweight material into a number of components, including wheels and seats.

A similar aggregate approach was used for estimating the material composition of the advanced gasoline vehicle in 2020, i.e., projecting the mass share of ferrous metals and aluminum in major vehicle components and performing an aggregate estimate for all other materials. The basic material distribution of the chassis and body is identical for all advanced vehicles, except for the addition of structural mass necessary to reinforce the high-strength steel chassis for carrying a heavier propulsion system. Differences in total vehicle mass distribution then resulted essentially through material differences of the propulsion system. Naturally, this simplified aggregate approach allows only a rough assessment of the vehicle's material requirements. A more detailed analysis would require an engineering design tool, capable of examining individual vehicle components.

Table 4.1 illustrates the projected material use for all vehicles examined in this study. Between 1996 and 2020, the baseline vehicle experiences a radical shift from the use of mainly regular steel to high-strength steel; the associated reduction in vehicle mass, including secondary reductions, amounts to 16%. All other vehicles employ an aluminum-intensive vehicle body, which is reflected by a strong decline in the use of steel and a corresponding increase in aluminum usage to about one-third of total vehicle weight for each of the two materials. According to this projection, steel and aluminum continue to be the major automobile materials, together accounting for roughly two-thirds of total vehicle mass. This result justifies the simplified approach we use in estimating the energy requirements and carbon emissions associated with the production of vehicle materials.

Energy Requirements for Material Production

Table 4.2 indicates energy requirements for material production from two different sources, one set of numbers from Automotive Engineering (1996)[1] and another set from a life-cycle analysis conducted by the Argonne National Laboratory (Singh et al., 1998). In addition, the table shows the rounded numbers we have used. As steel and aluminum together account for roughly two-thirds of the mass of the projected fuel-efficient automobiles, we have derived the energy requirements for these two materials with great care; our estimates are illustrated in Figure 4.1. Producing steel body parts through a closed-loop process, i.e., using only production-derived scrap for vehicle production in addition to virgin materials, energy use results to 35.8 GJ of fossil fuels and 634 kWh of

[1] The numbers from the Automotive Engineering article are likely derived from a life-cycle assessment program at the IKP at the University of Stuttgart, Germany.

Table 4.1 Vehicle Mass (in kg) by Material for all Vehicles Considered in This Study. The projection of the baseline vehicle is based on Stark (1997).

Power Plant	current	baseline	advanced	advanced	advanced	advanced	advanced	advanced	advanced	advanced	advanced
Fuel	SI ICE	SI ICE	SI ICE	CI ICE	SI Hybrid	CI Hybrid	SI Hybrid	FC Hybrid	FC Hybrid	FC Hybrid	Electric
Drive	gasoline	gasoline	gasoline	diesel	gasoline	diesel	CNG	gasoline	methanol	hydrogen	electricity
Body	auto	auto-cl.	auto-cl.	auto-cl.	CVT	CVT	CVT	direct	direct	direct	direct
Ferrous Metals	886	667	325	379	350	387	346	640	565	477	425
Aluminum	81	97	342	337	334	330	349	305	304	355	304
Glass	35	35	35	35	35	35	35	35	35	35	35
Magnesium	10	20	20	20	20	20	20	20	20	20	20
Copper	9	9	9	9	10	10	10	21	19	18	13
Zinc	7	7	3	3	3	3	3	3	3	3	3
Lead	10	10	10	10	0	0	0	0	0	0	0
Plastics	100	97	100	108	96	101	104	72	71	99	79
Rubber	54	50	50	50	50	50	50	50	50	50	50
Wood, Felt, etc.	64	64	64	64	64	64	64	64	64	64	64
Paint, coatings	5	5	5	5	5	5	5	5	5	5	5
Nickel	0	0	0	0	10	11	10	13	12	12	93
Others	9	9	9	9	17	17	17	76	62	37	84
Fluids	54	39	36	33	28	26	25	25	42	4	0
Total	1323	1108	1007	1061	1022	1059	1038	1329	1251	1177	1175

Table 4.2 **Energy Use in Vehicle Material Production** in MJ per kg of material for primary and secondary production (recycling). All numbers are expressed in primary energy requirements. The columns "This Study" indicate the rounded numbers that we have employed in this study; as we do not distinguish between iron and steel, energy intensities are identical for both materials and are included in our aggregate category "ferrous metals" (see Figures 4.1 and 4.2 for details). [1] Virgin steel parts; [2] pig iron; [3] main production process only.

	Primary Production (0% Recycling)			Secondary Production (100% Recycling)	
	Automotive Engineering (1996)	Singh et al. (1998)	This Study	Automotive Engineering (1996)	This Study
Ferrous Metals			40.0		30.0
Steel	40.0	52.3 [1]		18.1	
Iron	34.0	19.3 [2]		24.0	
Aluminum			220.0		40.0
wrought	196.0			26.7	
cast	189.0	206.6		26.0	
stamped		205.2			
Plastics	90.0	30.0-78.7 [3]	90.0	45.0	45.0
Glass	30.0	21.6 [3]	30.0	13.0	15.0
Magnesium cast	284.0		280.0	27.2	27.0
Copper	100.0	113.7	100.0	45.0	45.0
Zinc	53.0		50.0	15.9	16.0
Lead	41.1	28.0 [3]	40.0	8.0	8.0
Rubber	67.6	40.5 [3]	70.0	43.6	N/A
Nickel		110.0	110.0		110.0

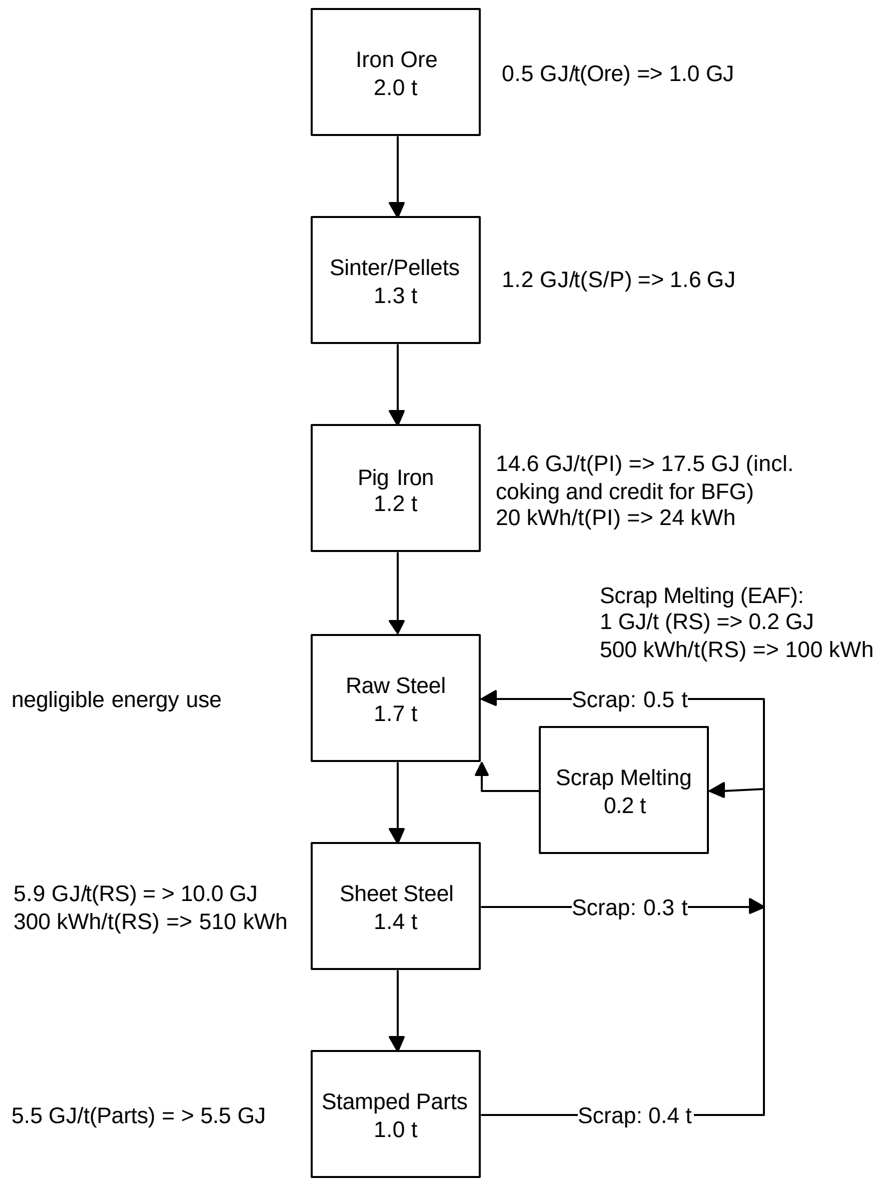


Figure 4.1 Simplified Closed-Loop Production of 1 ton of Automobile Steel Body Parts. Data source for the production processes: Singh et al. (1998), Tillmann et al. (1991), International Iron and Steel Institute and United Nations Environment Program (1997). Total energy use for primary steel auto parts result to 35.8 GJ of fossil fuels and 634 kWh of electricity (6.7 GJ_{th} fossil fuels with a conversion fuel to electricity of 2.9:1); the corresponding energy requirements are 17.2 GJ and 1360 kWh (14.4 GJ_{th}) for parts from recycled material.

electricity. Converting electricity to fuels with a thermal equivalent of 34% (not taking into account transmission and distribution losses), results in 42.5 GJ of primary energy per ton of vehicle parts. In analogy to Figure 4.1, Figure 4.2, reports material and energy use for the production of aluminum body parts.

According to Figures 4.1 and 4.2, the shares of energy use required for each step of materials production differs between primary steel and aluminum. In aluminum parts production, 12% of total energy input is used for extracting bauxite and processing of alumina, 76% for producing aluminum ingots, and the remaining 12% for manufacturing the finished parts from the aluminum ingots. By contrast, in steel production, only 5% of total energy use is required for iron ore extraction and processing, 45% for producing crude steel, and half of total energy use for manufacturing the finished parts from the crude steel. (Obviously these ratios alter with a shift to secondary production.) As a detailed specification of the production processes for the vehicle components was not available, we did not take these differences into account for estimating the exact energy requirement of each individual vehicle component. For example, the vehicle's engine consists of casted, wrought, and stamped ferrous metal parts, each requiring a different amount of energy (see Figure 4.1). While this simplification has only a small effect on the estimated energy requirements for producing vehicle parts from primary aluminum, where the aluminum production process accounts for 88% of total energy use, we slightly overestimate energy requirements for producing vehicle parts from secondary aluminum and ferrous metals.

Total Energy Requirements for Vehicle Material Production

Based on the specific energy requirements per unit mass of material in Table 4.2 (column "This Study") and the mass distribution by material in Table 4.1, Table 4.3 reports total energy use for the production of primary vehicle materials for all automobiles. The production of the 1996 baseline vehicle has a primary energy requirement of 78 GJ or 59 GJ per ton of vehicle. While total energy use for the baseline vehicle remains roughly comparable through 2020, the advanced vehicles, all of which incorporate an energy-intensive aluminum body, require between 115 and 126 GJ, or 90-114 GJ per ton of vehicle.

Material recycling can lead to significantly reduced levels of energy use. In the extreme case of a hypothetical 100% recycling rate of vehicle materials, energy requirements are only 30-40% of those for producing primary materials (Table 4.4), largely because of reduced energy requirements for aluminum production. significantly lower energy requirements for producing secondary aluminum also results in roughly comparable secondary energy requirements for all examined vehicles.

requirements for producing secondary aluminum also results in roughly comparable secondary energy requirements for all examined vehicles.

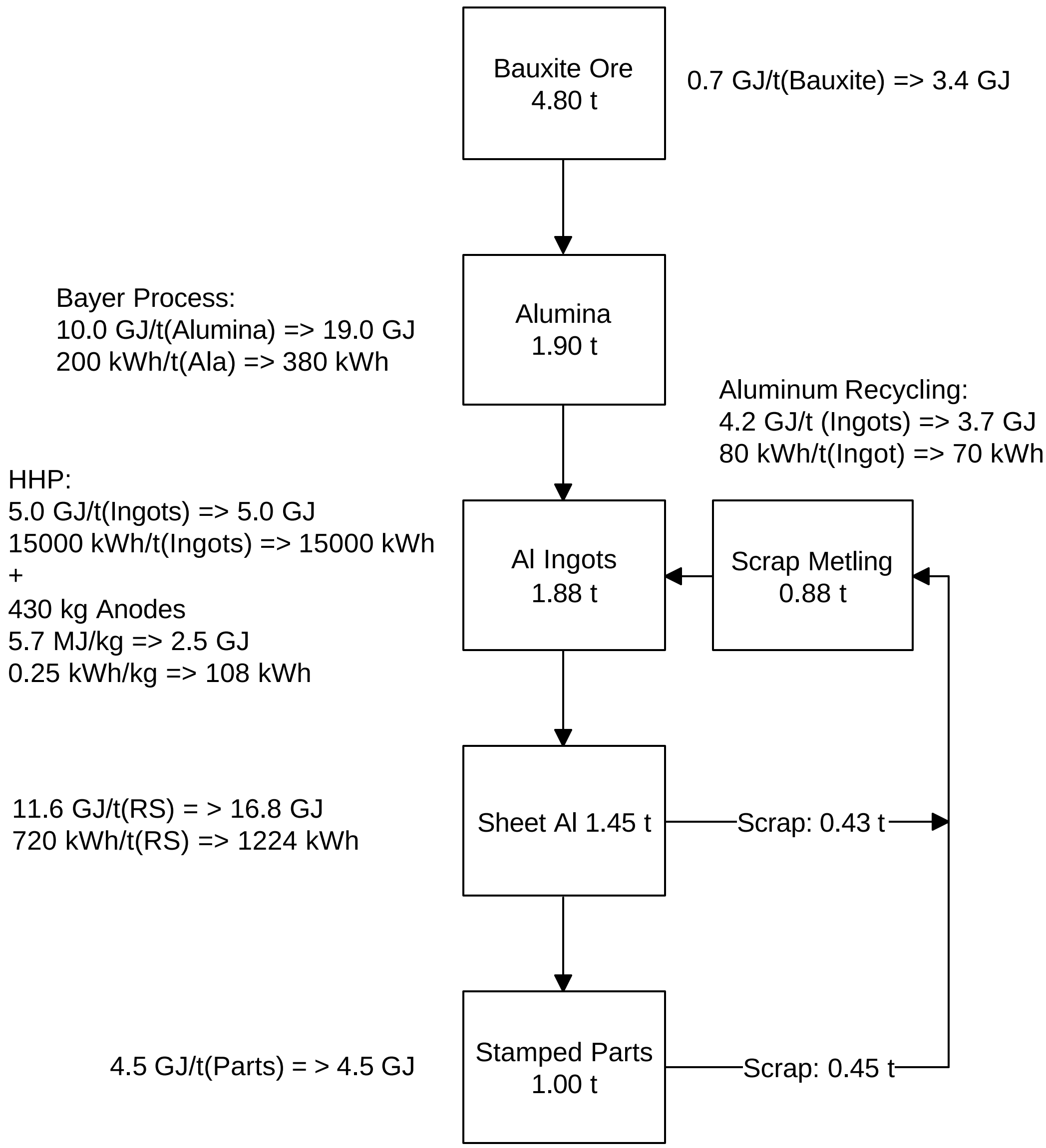


Figure 4.2 Simplified Closed-Loop Production of 1 ton of Automobile Aluminum Body Parts. Data source for the production processes: Singh et al. (1998), Tillmann et al. (1991), Atkins et al. (1990). Total energy use for primary aluminum auto parts results to 55.5 GJ of fossil fuels and 15694 kWh of electricity (166 GJ_{th} fossil fuels with a conversion fuel to electricity of 2.9:1); the corres-ponding energy requirements are 29.2 GJ and 1374 kWh (14.3 GJ_{th}) for parts from recycled material.

Table 4.3 Primary Energy Use (GJ) for the Production of Automobile Components from Virgin Materials for all vehicles considered in this study, by material.

Power Plant	current	baseline	advanced	advanced	advanced	advanced	advanced	advanced	advanced	advanced	advanced
Fuel	SI ICE	SI ICE	SI ICE	CI ICE	SI Hybrid	CI Hybrid	SI Hybrid	FC Hybrid	FC Hybrid	FC Hybrid	Electric
Drive	gasoline	gasoline	gasoline	diesel	gasoline	diesel	CNG	gasoline	methanol	hydrogen	electricity
Body	auto	auto-cl.	auto-cl.	auto-cl.	CVT	CVT	CVT	direct	direct	direct	direct
Ferrous Metals	35.4	26.7	13.0	15.1	14.0	15.5	13.8	25.6	22.6	19.1	17.0
Aluminum	17.9	21.4	75.3	74.2	73.4	72.5	76.7	67.1	66.9	78.1	66.8
Glass	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Magnesium	2.7	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6
Copper	0.9	0.9	0.9	0.9	1.0	1.0	1.0	2.1	1.9	1.8	1.3
Zinc	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Lead	0.4	0.4	0.4	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Plastics	9.0	8.7	9.0	9.7	8.6	9.1	9.4	6.5	6.4	8.9	7.1
Rubber	3.8	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
Wood, Felt, etc.	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7
Paint, coatings	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Nickel	0.0	0.0	0.0	0.0	1.1	1.2	1.1	1.4	1.3	1.3	10.3
Others	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	77.6	74.8	115.1	116.8	114.7	115.8	118.6	119.1	115.6	125.6	119.0
per kg of Vehicle Mass	58.7	67.4	114.3	110.0	112.1	109.2	114.2	89.6	92.2	106.5	101.2

Table 4.4 Primary Energy Use (GJ) for the Production of Automobile Components from Secondary Materials for all ten vehicles considered in this study, by material.

Power Plant	current	baseline	advanced	advanced	advanced	advanced	advanced	advanced	advanced	advanced	advanced
Fuel	SI ICE	SI ICE	SI ICE	CI ICE	SI Hybrid	CI Hybrid	SI Hybrid	FC Hybrid	FC Hybrid	FC Hybrid	Electric
Drive	gasoline	gasoline	gasoline	diesel	gasoline	diesel	CNG	gasoline	methanol	hydrogen	electricity
Body	auto	auto-cl.	auto-cl.	auto-cl.	CVT	CVT	CVT	direct	direct	direct	direct
Ferrous Metals	26.6	20.0	9.7	11.4	10.5	11.6	10.4	19.2	16.9	14.3	12.7
Aluminum	3.2	3.9	13.7	13.5	13.3	13.2	14.0	12.2	12.2	14.2	12.1
Glass	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Magnesium	0.3	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Copper	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.9	0.8	0.8	0.6
Zinc	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lead	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Plastics	4.5	4.4	4.5	4.9	4.3	4.5	4.7	3.2	3.2	4.4	3.6
Rubber	3.8	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
Wood, Felt, etc.	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9
Paint, coatings	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Nickel	0.0	0.0	0.0	0.0	1.1	1.2	1.1	1.4	1.3	1.3	10.3
Others	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Total	42.5	36.5	36.1	37.9	37.5	38.7	38.3	44.7	42.2	42.7	47.0
per kg of Vehicle Mass	32.2	32.9	35.9	35.7	36.6	36.5	36.9	33.6	33.7	36.2	40.0

Carbon Emissions from the Production of Automobile Materials

In combination with carbon emission factors per unit of primary energy, total carbon emissions can be estimated for each of the examined vehicles. As steel and aluminum continue to be the major automobile materials, accounting for about two-thirds of total vehicle mass, we have conducted more detailed estimates of CO_2 emissions from the production of these two materials. For all other materials, we use a more aggregate approach.

According to Table 4.2 and Figure 4.1, the production of primary steel parts requires about 40 GJ of thermal energy, 15% of which is being converted to electricity. The same table and Figure 4.2 suggest that the production of primary aluminum requires 200 GJ of thermal energy, 75% of which being converted to electricity. (These shares are slightly higher for secondary materials, i.e., 45% electricity for both materials). For these two materials, we apply two emission factors, one for thermal energy (by fuel) and another one for electricity. For the energy directly supplied by fossil fuels, we use the emission factor of oil (assumed to equal that of diesel fuel, i.e., 20.9 kgC/GJ); in the case of primary steel making we use an emission factor of 23.3 kgC/MJ, (the average of coal and oil), to take into account the coke-intensive iron ore reduction that accounts for roughly 50% of total thermal energy use in steel production. For electricity we use the projected U.S. 2020 fuel mix, releasing 54 kgC per GJ of electricity produced (Table 2.9).

Tables 4.5 and 4.6 report the estimated amount of CO_2 emissions from vehicle component production from primary and secondary materials. The production of the 1996 baseline vehicle parts releases nearly 1.6 tons of carbon, while this amount increases by 30-40% for the more energy-intensive aluminum-body automobiles. Mainly due to the lower energy requirements, the production of vehicle parts from recycled materials results in carbon emissions of about the original level.

While we have discussed the energy use and CO_2 emissions implications of aluminum-intensive vehicles above, the automobile industry is also pursuing a lower-cost strategy that may lead instead to a significantly larger share of plastics in the auto body. According to the energy intensities reported in Table 4.2, a plastic-intensive auto body would require only roughly a third of the primary energy and aluminum-intensive auto body does, if exclusively using virgin materials (also the CO_2 emissions should be reduced by roughly that amount). On a total vehicle basis, primary energy use would be reduced by about 25%. If using recycled materials instead, the differences in primary energy and CO_2 emissions would become negligible.

Parts Forming and Assembly

Larger vehicles require more energy for transport during assembly, represent more area to bond and paint, have larger, more massive parts to stamp or fabricate, and thus require more assembly energy. Because of the complex supply chain in the automobile industry

Table 4.5 CO_2 Emissions (kgC) Resulting from the Production of Automobile Components from Virgin Materials for all vehicles considered in this study, by material.

Power Plant	current	baseline	advanced	advanced	advanced	advanced	advanced	advanced	advanced	advanced	advanced
Fuel	SI ICE	SI ICE	SI ICE	CI ICE	SI Hybrid	CI Hybrid	SI Hybrid	FC Hybrid	FC Hybrid	FC Hybrid	Electric
Drive	gasoline	gasoline	gasoline	diesel	gasoline	diesel	CNG	gasoline	methanol	hydrogen	electricity
Body	auto	auto-cl.	auto-cl.	auto-cl.	CVT	CVT	CVT	direct	direct	direct	direct
Total Ferrous Metals	778	586	285	333	307	340	304	563	496	419	373
Aluminum	290	348	1224	1205	1193	1179	1247	1090	1088	1269	1086
Glass	22	22	22	22	22	22	22	22	22	22	22
Magnesium	57	117	117	117	117	117	117	117	117	117	117
Copper	18	18	18	18	22	22	22	43	39	37	26
Zinc	7	7	3	3	3	3	3	3	3	3	3
Lead	9	9	9	9	0	0	0	0	0	0	0
Plastics	188	182	188	203	180	190	196	135	133	185	149
Rubber	79	74	74	74	74	74	74	74	74	74	74
Wood, Felt, Carpets, etc.	120	120	120	120	120	120	120	120	120	120	120
Paint, coatings	9	9	9	9	9	9	9	9	9	9	9
Nickel	0	0	0	0	24	24	24	30	28	27	215
Others	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Total	1577	1492	2069	2113	2070	2100	2137	2206	2129	2282	2194

Table 4.6 CO_2 Emissions (kgC) Resulting from the Production of Automobile Components from Secondary Materials for all vehicles considered in this study, by material.

Power Plant	current	baseline	advanced	advanced	advanced	advanced	advanced	advanced	advanced	advanced	advanced
Fuel	SI ICE	SI ICE	SI ICE	CI ICE	SI Hybrid	CI Hybrid	SI Hybrid	FC Hybrid	FC Hybrid	FC Hybrid	Electric
Drive	gasoline	gasoline	gasoline	diesel	gasoline	diesel	CNG	gasoline	methanol	hydrogen	electricity
Body	auto	auto-cl.	auto-cl.	auto-cl.	CVT	CVT	CVT	direct	direct	direct	direct
Total Ferrous Metals	481	362	176	206	190	210	188	348	307	259	231
Aluminum	59	70	248	244	242	239	253	221	220	257	220
Glass	11	11	11	11	11	11	11	11	11	11	11
Magnesium	6	11	11	11	11	11	11	11	11	11	11
Copper	8	8	8	8	10	10	10	19	18	17	12
Zinc	2	2	1	1	1	1	1	1	1	1	1
Lead	2	2	2	2	0	0	0	0	0	0	0
Plastics	94	91	94	102	90	95	98	68	66	93	75
Rubber	79	74	74	74	74	74	74	74	74	74	74
Wood, Felt, Carpets, etc.	60	60	60	60	60	60	60	60	60	60	60
Paint, coatings	5	5	5	5	5	5	5	5	5	5	5
Nickel	0	0	0	0	24	24	24	30	28	27	215
Others	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Total	806	697	690	723	716	740	733	847	801	814	913

and the associated difficulty in estimating vehicle assembly energy requirements, assembly energy is typically estimated as a linear function of vehicle mass. According to Automotive Engineering (1996), the typical range of assembly (primary) energy is 17.4-22.1 MJ/kg. This range compares well with the numbers quoted by Röder (2000), if compared on a primary energy basis.

On a final energy basis, typically about 40-50% is consumed in terms of electricity (Röder, 2000, DaimlerChrysler, n.d.). Thus, we assume that out of the assumed 20 GJ/t of total primary energy, 10 GJ is converted to electricity (with a carbon emission factor 54 kgC per GJ of electricity produced) and the remaining energy is directly used as oil (representing about the average of the carbon emission factor of natural gas and coal).

Vehicle Distribution

The energy needed to transport a vehicle from the assembly line to the dealership depends on the energy intensity of the freight carrier and the transport distance. We assumed the average of heavy truck (1.5 MJ/tkm) and railway (0.5 MJ/tkm) transportation, i.e., 1.0 MJ/tkm, and a mean transport distance of 1600 km (about 1000 miles). The energy required for distributing the vehicle then is 1.0 • 1600 MJ/t = 1.6 MJ/kg of vehicle mass.

Vehicle Maintenance

Maintenance energy encompasses all energy that is used to replace vehicle parts or liquids, throughout the entire vehicle life. As there is virtually no information available, we have neglected this stage of energy use and emissions. However, the associated error should be small, as energy use and emissions are likely significantly smaller than material production and vehicle assembly.

Vehicle Disposal

After a vehicle's life, the automobile is shredded and its non-recycled portion sent to a landfill. Again, the disposal energy is estimated to be a linear function of vehicle mass. The disposal energy is the sum of the energy needed to move the hulk from a dismantler to a shredder (0.24 MJ per kg of material over a distance of 160 km and a truck energy intensity of 1.5 MJ/tkm) and the shredding energy (0.37 MJ per kilogram of material) [Automotive Engineering, 1997].

4.3 Total Energy Use and CO_2 Emissions

After having examined energy requirements at the different stages of the vehicle cycle, we evaluate their individual contribution, i.e., automobile materials production, vehicle assembly, distribution, maintenance, and disposal. Table 4.7 reports energy use per km driven for each of these stages, except vehicle maintenance for which data are difficult to find. (We assume a 300,000 km distance driven over the vehicle lifetime, see Chapter 1.)

Our estimated energy requirements for the production of vehicle materials and vehicle disposal are based on a recycling rate of 95% for all metals and 50% for plastics and window glass. We assume these high recycling rates because of increasing pressure on especially the automobile industry regarding the reuse of their materials to the largest possible extent[2]. The assumed metal recycling rate is already representative for automobile steels (Automotive Engineering, 1995) and is likely to be representative for other metals in the future. Due to the high economic value, this is especially plausible for aluminum and magnesium. However, we are mindful that by 2020 only a small fraction of the aluminum requirements for the advanced vehicles can be met through scrap recycling. A simple vehicle stock model shows that if advanced vehicles are first introduced in 2005 and accounted for 20% of new vehicle sales in 2020, only 17-18% of aluminum requirements can be satisfied by scrap material. Ignoring this transition (a fundamental assumption of this study) leads to slightly underestimated carbon emissions from material production.

Total vehicle cycle energy use of the 1996 baseline vehicle is 0.26 MJ/km; vehicle cycle energy use of the advanced vehicles with aluminum bodies ranges from 0.28-0.33 MJ/km. The production of vehicle materials accounts for the largest share in energy use of the vehicle cycle, ranging from two-thirds to three-fourth of total energy. The associated CO_2 emissions in grams of carbon per vehicle-km, reported in Table 4.8, reflect vehicle cycle energy use relative to the base year vehicle and the dominant share of vehicle materials production to total vehicle cycle energy use in carbon emissions.

4.4 Summary

The manufacturing of materials accounts for most of the energy use and CO_2 emissions in the vehicle cycle; the exact share mainly depends on the underlying processes and the degree of recycling, Based on our assumption of a 95% recycling rate for metals and a 50% rate for other materials, materials production accounts for roughly two-thirds of the total vehicle energy use and CO_2 emissions in the vehicle production-to-disposal cycle.

The degree of material recycling also has a strong impact on the relative energy use for vehicle material production. Under the exclusive use of virgin materials, energy use for materials production of aluminum-intensive advanced vehicles can be up to 50% higher than for the baseline; for our assumed recycling rate of 95% for metals and 50% for other materials, the energy use and emissions are roughly comparable to the baseline.

[2] Due to constrained resources and associated high costs, such a high recycling rate would be imperative for platinum group metals.

Table 4.7 Total Energy Use (in kJ/km) in the Five Life Cycle Stages: Vehicle Materials Production, Vehicle Assembly, Distribution, Maintenance, and Disposal indicated above for all examined vehicles. Energy use in materials production is based on a 95% recycling rate for all metals and a 50% recycling rate for plastics. The other materials energy use (row "Others" in Tables 4.3 and 4.4) was assumed to be identical to the average energy use per vehicle in Tables 4.3 and 4.4.

Power Plant	current	baseline	advanced	advanced	advanced	advanced	advanced	advanced	advanced	advanced	advanced
Fuel	SI ICE	SI ICE	SI ICE	CI ICE	SI Hybrid	CI Hybrid	SI Hybrid	FC Hybrid	FC Hybrid	FC Hybrid	Electric
Drive	gasoline	gasoline	gasoline	diesel	gasoline	diesel	CNG	gasoline	methanol	hydrogen	electricity
Body	auto	auto-clutch	auto-clutch	auto-clutch	CVT	CVT	CVT	direct	direct	direct	direct
Material Production	166	146	152	159	156	162	161	180	178	182	190
Vehicle Assembly	85	71	65	69	66	69	68	87	81	78	78
Vehicle Distribution	7	6	5	6	5	6	6	7	7	6	6
Vehicle Disposal	1	1	1	1	1	1	1	1	1	1	1
Total	259	225	223	233	228	238	236	275	267	267	275

Table 4.8 Total CO_2 Emissions (in gC/km) in the Five Life Cycle Stages: Vehicle Materials Production, Vehicle Assembly, Distribution, Maintenance, and Disposal indicated above for all examined vehicles. CO_2 emissions in materials production are based on a 95% recycling rate for all metals and a 50% recycling rate for plastics.

Power Plant	current	baseline	advanced	advanced	advanced	advanced	advanced	advanced	advanced	advanced	advanced
Fuel	SI ICE	SI ICE	SI ICE	CI ICE	SI Hybrid	CI Hybrid	SI Hybrid	FC Hybrid	FC Hybrid	FC Hybrid	Electric
Drive	gasoline	gasoline	gasoline	diesel	gasoline	diesel	CNG	gasoline	methanol	hydrogen	electricity
Body	auto	auto-clutch	auto-clutch	auto-clutch	CVT	CVT	CVT	direct	direct	direct	direct
Material Production	3.2	2.8	2.9	3.0	3.0	3.1	3.0	3.4	3.2	3.3	3.6
Vehicle Assembly	1.6	1.4	1.2	1.3	1.3	1.3	1.3	1.7	1.5	1.5	1.5
Vehicle Distribution	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Vehicle Disposal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	4.9	4.3	4.2	4.4	4.4	4.5	4.5	5.2	4.8	4.9	5.2

Chapter 5. Integrated Impacts and Stakeholder Views of New Technologies

5.1 Introduction

This chapter presents total life-cycle estimates of costs and environmental impacts for twelve representative passenger car vehicle/fuel options in the 2020 timeframe, integrating the results presented in Chapters 2 through 4. In addition, it identifies those characteristics of the technologies, such as risk or convenience or safety, which may be more difficult to quantify, but which may have a significant impact on one or more groups of stakeholders. Finally, it examines in a preliminary manner the impacts of each system option on each stakeholder as a result of the transition from present technology.

We have focused on a "typical" US car in our study. In the US, about 30% of our total energy consumption is associated with transportation and about half of that, with vehicles used for personal transportation. Personal transportation matches individual's desires and needs for mobility. The auto helps people achieve a desirable life style, allows them access to a wider range of jobs, and provides recreation and convenience. Although the numbers of road vehicles in the US is stabilizing, the vehicle miles traveled each year continues to increase. This, along with auto buyers demand for more amenities in their vehicles and with the increasing US sales of "light-truck-like" sport utility vehicles (SUVs), is still increasing the annual US energy use for road transportation in spite of significant improvements in the efficiency of vehicle propulsion systems.

In the past, local emissions from road vehicles created pollution and health effects that prompted increasingly stringent restrictions on tailpipe emissions of CO, NO_x, volatile hydrocarbons, particulates and other species. Such regulations have improved air quality substantially in the OECD countries, and have generated technologies that may help solve pollution problems in developing world cities. However, more recent concerns about CO_2 emissions and their potential to change climate have led to a major reexamination of our extensive use of carbon-based fuels.

As discussed earlier, the transportation sector as a whole (all modes) also generates about a third of US anthropogenic CO_2 emissions and a rapidly growing proportion of emissions globally. Opportunities for CO_2 reduction in this sector are complicated by the fact that most of the sector emissions come from widely dispersed, large numbers of individual vehicles, which are almost all dependent on petroleum-based fuels. The reduction options are basically limited to combinations of efficiency improvements, vehicle weight and drag reduction, the use of lower carbon-intensity fuels, and overall reduction in transportation demand. A global reduction in transportation demand seems unlikely between now and 2020, since developing countries are showing a rapidly growing desire for wider access to personal transportation vehicles.

Many researchers have investigated the potential of alternative fuels and new road vehicle technologies for reducing carbon emissions. However, critical comparisons of effectiveness across studies, and even within studies, are often difficult because of hidden assumptions and different system boundary assumptions. This MIT study builds on a wealth of past work, as well as on the considerable expertise of the diverse research team, to make evaluations that are intended to be consistent, reasonable, and transparent. We have chosen to compare options on a total system basis ("well-to-wheels") and for the time frame of the year 2020. We include not only the energy and emissions associated with fuel production, but also with the life-cycle of the vehicle from materials production through disposal/recycling. Our baseline vehicle is today's fleet average car (such as a 1996 Toyota Camry), evolved and improved over the next twenty years without assuming specific mandatory requirements for CO_2 emission reduction. This baseline vehicle is somewhat lighter than today's similar car (through the use of lighter weight materials like high-strength steel), and is estimated to cost about 5% more in 1997 US constant dollars. While the US vehicle fleet weight is still gradually increasing as customers seek larger vehicles, and more performance and amenities, we have arbitrarily assumed that the level of amenities, performance, and interior space will remain similar to today's fleet average car. We project that such an evolved baseline vehicle in 2020 could be developed to have about 35% less life-cycle gasoline consumption and CO_2 emissions than today's similar car. Other local emissions will be reduced significantly due to continuing regulatory pressures – we assume that all the 2020 cars will at least meet US EPA Tier 2 emission standards.

The information used in our assessments originates in recent published reports, in unpublished non-MIT studies made available to us, and in results from modeling work and other studies done at MIT. A number of outside experts, who have provided us with much helpful advice and additional information, have also reviewed the report. Our objective has been to sort through all these sources and to organize the useful results on a consistent basis for purposes of valid comparison of future technology options, based on our present state of knowledge. The preceding chapters of this report have given the details of our assessment for the system components; this chapter examines the overall system comparisons, discusses uncertainties, and then explores the impacts of alternative technology choices on different stakeholder groups within the transportation sector, both in 2020 and during the transitional period.

Our evaluation consists of a well-to-wheels analysis of major technology options for fuels, power units, drivelines, and bodies as shown in Table 5.1

Table 5.1 Component Technology Options Evaluated in this Assessment

Fuel	Power Unit	Driveline	Body
• Gasoline • Diesel • F-T diesel* • Natural gas (CNG) • Methanol • Hydrogen • Electricity	• Spark ignition ICE • Compression ignition ICE • Fuel cells • Motor	• Mechanical - Auto-clutch - CVT** • Electrical - Direct - Hybrid	• Evolutionary • Advanced (lightweight, low drag)

*Fischer-Tropsch (synthesized from natural gas); **Continuously Variable Transmission

As discussed in Chapter 3, *hybrid vehicles* incorporate two propulsion systems: a smaller size combustion engine that operates nearer peak efficiency and an electric motor with a battery supply. The engine is turned off at idle and light vehicle loads, charges the batteries when needed if there is excess power, and augments its power with motor power drawn from the batteries for acceleration. Regenerative energy recovered during braking also is used to charge the batteries. Although the two separate vehicle power systems entail added costs, weight, and complexity, the efficiency benefits are significant, especially for urban driving where starts and stops are frequent. Fuel cell vehicles operate best in a similar manner, except that the only drive required is electric. When the fuel cell vehicle is operated using a fuel other than hydrogen, a fuel-processing unit (reformer) is added to make hydrogen feed for the fuel cell. The reformer exhausts residual byproducts to the atmosphere. For more information on these technologies, a list of web sites is appended to this chapter.

It is important to remember that each of the vehicle and fuel systems we have evaluated is the result of many assumptions about the individual components and their integration. Further, when technology change is projected out twenty years, considerable uncertainty exists – especially for the rapidly evolving technologies. Thus our calculated energy efficiency results are all subject to an uncertainty range, which increases from "some" (~10%) for the more conventional technologies to "more" (~20%) for the hybrid designs and "even more" (~30%) for the fuel cell system designs. The electric car performance is strongly tied to uncertain improvements in battery technology. The cost estimates are subject to similar uncertainties; the GHG emission (carbon) estimates are also related to energy source and the efficiency of conversion and use. Thus when comparisons are made among systems with different technologies on the basis of the results presented in this chapter, it is important to recognize that these are highly dependent on the underlying assumptions which we hope we have stated clearly in Chapters 2 through 4. Although our numeric results appear to allow a ranking of the technologies evaluated against different attributes, consideration of uncertainty ranges blurs the apparent comparisons. ***Only where differences are more than these uncertainty ranges are the rankings of technologies clear.*** Our analysis does allow the effects of different options to be considered within a consistent format. We have not performed a comprehensive uncertainty analysis, so this paragraph is intended to serve as both a context and a caution about drawing too broad conclusions using technology option rankings from our representative technology system analyses.

Three groups of general characteristics were assessed for selected combinations of these technology options for vehicle capacity and performance comparable to the baseline vehicle:

- Direct economic costs (both capital and operating)
- Environmental, safety, and health effects, and
- Other characteristics, such as customer convenience and societal impacts.

In addition, each characteristic of each technology was examined for its relative impacts, both in 2020 and during the transitional period, on six major stakeholder groups:

- Vehicle Purchasers
- Fuel Manufacturers
- Fuel Distributors
- Vehicle Manufacturers (including raw materials and parts)
- Vehicle Distributors (including maintenance, repair, and recycling/scrappage)
- Government (at all levels)

A set of "templates" (attached as Appendix 5A) was developed to assess, at least on a preliminary basis, the relative impact (compared to the baseline) of each characteristic of each new technology on each stakeholder, both in the 2020 time frame and during the period of transition. These templates were developed early in the project, to assure we were covering major attributes of interest in our study. Further, the purpose of this analysis was to identify where incentives for introduction lay and where barriers might be anticipated. Future work will be needed to analyze significant opportunities or barriers to introduction for promising technologies in order to identify research needs or consider alternative implementation pathways.

5.2 Overall Integrated System Comparisons

In this section, the comparative total system performance is estimated for thirteen representative fuel/vehicle systems: today's "typical" passenger car, the evolved 2020 baseline vehicle, and eleven alternative combinations. To provide a consistent basis for comparison, all these vehicles generally have the same interior space as the 1996 Toyota Camry, the same performance characteristics (power to weight ratio, etc.), and have a driving range of around 600 km between refueling stops. The electric car has a somewhat lower range of about 400 km, because adding more batteries to extend range significantly degrades other performance attributes of the car. Further details on assumptions and uncertainties are contained in the earlier more detailed chapters of this report. While we arbitrarily assume the 2020 fleet average passenger vehicle will be similar in size and performance to today's Camry, relative rankings should remain fairly consistent even if the average size shifts up or down to some degree. [We know many other countries have smaller fleet average cars, that some US customers are eager to buy SUVs that are similar to light trucks, and that many new customers in developing countries are seeking an affordable basic car.] The values shown for 2020 are based on "optimistic realism" and represent our best estimates of potential technological advances over the next two decades. The energy usage and carbon emissions are estimated on a consistent combined US city/highway driving cycle. It is assumed that all the technologies will meet future local emission standards and the cost of the required abatement technologies is reflected in each of the cost estimates. Cost information is summarized from material in Chapters 2 and 3.

Annual operating costs are estimated for new US vehicles using fuel cost averages from Chapter 2 and the fuel consumption of the vehicle. A flat fuel tax of $0.0033 per MJ of fuel

($0.40 per gallon of gasoline equivalent) is used across all the fuel sources (this assumption is made so tax policy does not impact relative results. We recognize that taxation is a policy tool that may be used to influence economic choice between technologies. A constant maintenance/other charge of $0.036/km [we do not have a good basis for estimating differential costs for the various technologies is assumed to avoid introducing an additional bias. Capital cost is based on 20% per year on the purchase price and on 20,000 km/year of travel. Fees for license and registration of $0.02/km (scaled by purchase cost relative to the baseline to represent some excise tax and other costs)are used; and insurance costs of $0.05/km are used with half of the cost scaled by the purchase price. These assumptions are consistent with current US analysis (e.g., Davis, 1999).

Table 5.2 Comparison of US Operating Costs in $(1997)/km for Selected New Vehicle Options in 2020

	Baseline Evol. SI Gasoline	Adv. SI Gasoline	Adv. CI Diesel	Adv. SI Gasoline Hybrid	Adv. CI Diesel Hybrid	Adv SI CNG Hybrid	Adv. FC Gasoline	Adv. FC Meth-anol	Adv. FC Hydro-gen	Adv. Electric
S **Var. costs**	**0.056**	**0.053**	**0.047**	**0.049**	**0.044**	**0.049**	**0.056**	**0.050**	**0.054**	**0.045**
Fuel ex tax [% of total]	0.014 [5%]	0.012 [4%]	0.007 [2%] FT=.009	0.009 [3%]	0.005 [1%] FT=.006	0.010 [3%]	0.014 [4%]	0.010 [3%]	0.015 [4%]	0.007 [2%]
Fuel tax	0.006	0.005	0.004	0.004	0.003	0.003	0.006	0.004	0.003	0.002
Other (oil,tires, Maint.)	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036
S **Fixed costs**	**0.250**	**0.268**	**0.281**	**0.292**	**0.304**	**0.297**	**0.317**	**0.315**	**0.303**	**0.363**
Insurance	0.050	0.052	0.053	0.056	0.057	0.056	0.057	0.057	0.057	0.063
License, ex-cise tx, regist.	0.020	0.022	0.023	0.024	0.025	0.024	0.026	0.026	0.025	0.030
Capital costs	0.180	0.194	0.205	0.212	0.222	0.217	0.234	0.232	0.221	0.270
S **Total costs $/km**	**0.306**	**0.321**	**0.328**	**0.341**	**0.348**	**0.346**	**0.373**	**0.365**	**0.357**	**0.408**

*CNG = Compressed Natural Gas

In this comparison, we are focusing on new cars that would be sold in the US in 2020, so the annual operating costs reflect this assumption. We note that, as cars age, the capital value decreases and the fuel and maintenance costs become a larger fraction of the decreasing total annual operating cost. Likewise, in countries where certain fuels are heavily taxed, the ratio of capital to running costs will be less for those fuels. We have made the technology comparisons for a new vehicle in the US to provide a consistent basis. Our results could be modified if other cases were of interest. Table 5.2 shows the estimates of operating costs for the baseline 2020 vehicle and the nine alternatives (The corresponding operating cost for a 1996 Camry would be $0.309/km). Vehicle costs and energy consumption are shown in Table 5.3. All these costs are subject to uncertainties inherent in the assumptions made in this analysis. The cost differences between the baseline vehicle and the highest cost option in Table 5.2 is 22%.

It is interesting to note that, as at present, total new US vehicle annual costs in 2020 are dominated by capital cost, which is tied to the vehicle cost. Our estimates indicate that the more efficient vehicles, from an energy consumption standpoint, are more expensive, and the charges associated with increased price more than offset any fuel savings at current US tax rates. The total operating costs vary from the baseline of about 30 cents per km up to about 37 cents per km for the fuel cell vehicles. This reflects the roughly 30% greater estimated purchase price for the fuel cell vehicles. The 41 cents per km costs of the electric vehicle are mostly attributable to the increased capital costs associated with the storage batteries. We observe that only large differences in fuel costs or fuel taxes are likely to have a significant influence on annual operating costs of new cars. For example, at a UK tax rate of \$3.53/gallon of gasoline (8.8 times higher than US), the baseline vehicle fuel tax would increase to \$0.044/km and the total new baseline vehicle annual operating cost would rise to \$0.343 (about 13% higher than in the US).

Cost, Energy, and Emissions. Tables 5.3 and 5.4 present a summary of the major technical attributes for each of the technology systems evaluated. In estimating the life-cycle impacts of the technology combinations considered in Tables 5.3 and 5.4, it is important to include both the use of fuel and the use of electricity (where, based on the US mix of electrical generation projected by the EIA for 2020, each MJ of delivered electricity consumes a total of 2.16 MJ of primary energy). The EIA projections for 2020 still represent a carbon-intensive electric supply; obviously, the carbon emissions for the electric vehicle are highly dependent on the carbon intensity of electricity production. In this evaluation, the hybrid and fuel cell vehicles generate electricity to charge their batteries from the power unit and not from external recharging. Details of the fuel cycle energy use and carbon emissions are presented in Table 2.12. Figures 5.1 through 5.3 present the key information graphically.

Embodied energy. As discussed in Chapter 4, energy is also used in the manufacture, assembly, distribution and disposal of the vehicles and this energy use is shown in Table 5.3, spread evenly over the estimated 300,000 km lifetime travel distance for our typical "Camry-like" 2020 vehicle.[1] The energy associated with the life-cycle of the vehicle are shown for 95% recycling of metals and 50% recycling of plastic materials. The largest portion of the embodied energy is associated with materials production. High levels of recycling may be achieved in the future if ability to recycle is established as a design goal, perhaps driven by requirements that manufacturers accept responsibility for the disposal of scrapped vehicles. In any event, the relative impact of recycling is included in a consistent manner across all of the alternative technologies. The bulk metals, steel and aluminum, are recyclable, but there are issues of whether materials that are specialized alloys can be recycled back to the same use. The other major lightweight body panel material option is plastic, probably as a

[1] In the US, average automobile lifetimes have increased from 10.7 years in 1970 to 13.7 years in 1990 (Davis, 1999); we assume 15 years for 2020. Average annual kilometers traveled per vehicle vary with automobile age, averaging somewhat over 19,000; we assume 20,000 for 2020.

Table 5.3 Energy Use and Physical Comparison of Major Future Systems Options for Road Transportation

Summary Year Body Type Tech Fuel Power train	1996 Current SI ICE Gasoline Auto	2020 Baseline SI ICE Gasoline Auto-clutch	2020 Advanced SI ICE Gasoline Auto-clutch	2020 Advanced CI ICE Diesel Auto-clutch	2020 Advanced SI Hybrid Gasoline CVT	2020 Advanced CI Hybrid Diesel CVT	2020 Advanced SI CNG Hybrid CVT	2020 Advanced FC Hybrid Gasoline Direct	2020 Advanced FC Hybrid Methanol Direct	2020 Advanced FC Hybrid Hydrogen Direct	2020 Advanced Electric Battery Direct
Vehicle wt. Kg	1,445	1,235	1135	1,190	1,155	1,190	1,170	1,460	1,375	1,315	1,310
Veh. Range km – city **-- highway**	550 815	540 745	535 765	530 785	575 750	565 720	565 725	540 725	560 740	530 690	360 495
Veh. Price $(97)	$17,200	$18,000	$19,400	$20,500	$21,200	$22,200	$21,700	$23,400	$23,200	$22,100	$27,000
Total operating costs $/km	0.309	0.306	0.321	0.328	0.341	0.348	0.346	0.373	0.365	0.357	0.408
Gasoline equiv. consum. L/100km (mpg)	8.45 (28.0)	5.45 (43.0)	4.80 (49.0)	4.20 (56.0)	3.30 (71.0)	2.85 (82.5)	3.20 (73.5)	5.55 (42.5)	4.15 (57.0)	2.50 (94.0)	1.60 (149.0)
Energy consumption MJ/km											
Embodied energy – mfg – 95% recycled metal, 50% plastics	0.26	0.22	0.22	0.23	0.23	0.23	0.23	0.27	0.26	0.26	0.27
Fuel Cycle	0.58	0.37	0.32	0.19 [FT=1.28]	0.23	0.13 [FT=0.87]	0.19	0.38	0.73	0.62	1.10
Vehicle Fuel	2.73	1.75	1.54	1.35	1.07	0.92	1.03	1.79	1.33	0.81	(0.51e)
Total System – [System – FT diesel]	3.57	2.34	2.08	1.77 [FT=2.86]	1.53	1.28 [FT=2.02]	1.45	2.44	2.32	1.69	1.88
Energy efficiency %											
Fuel cycle	83%	83%	83%	88% [FT=52%]	83%	88% [FT=52%]	85%?	83%	65%	56%	32.0%
Veh. cycle–City/hwy	13.0/17.1%	16.9/19.4%	16.2/18.1%	19.0/21.7%	26.4/25.7%	31.8/29.8%	27.8/26.6%	17.6/17.5%	22.5/22.7%	36.2/35.8%	61.5/58.8%

Table 5.4 Carbon Emissions Comparisons of Major Future Systems Options for Road Transportation

Summary Year Body Type Tech Fuel Power train	1996 Current SI ICE Gasoline Auto	2020 Baseline SI ICE Gasoline Auto-clutch	2020 Advanced SI ICE Gasoline Auto-clutch	2020 Advanced CI ICE Diesel Auto-clutch	2020 Advanced SI Hybrid Gasoline CVT	2020 Advanced CI Hybrid Diesel CVT	2020 Advanced SI ICE CNG CVT	2020 Advanced FC Hybrid Gasoline Direct	2020 Advanced FC Hybrid Methanol Direct	2020 Advanced FC Hybrid Hydrogen Direct	2020 Advanced Electric Battery Direct
Carbon emissions gC/km											
Manufacturing Recycle 95% metals, 50% plastic	4.9	4.3	4.2	4.4	4.3	4.4	4.4	5.1	4.9	4.9	5.1
Fuel Cycle [FT diesel]	13.4	8.6	7.5	4.5 [FT=12.0]	4.5	3.0 [FT=8.2]	4.3	8.8	7.8	29.2	27.5
Vehicle Fuel [FT diesel]	53.5	34.3	30.2	28.1 [FT=27.0]	21.0	19.1 [FT=18.4]	15.5	35.1	24.9	0.0	0.0
System – [FT diesel]	**71.8**	**47.2**	**41.9**	**37.0 [FT=43.4]**	**29.8**	**26.5 [FT=31.0]**	**24.2**	**49.0**	**37.6**	**34.1**	**32.6**

Figure 5.1 Life-Cycle Energy Use Comparisons

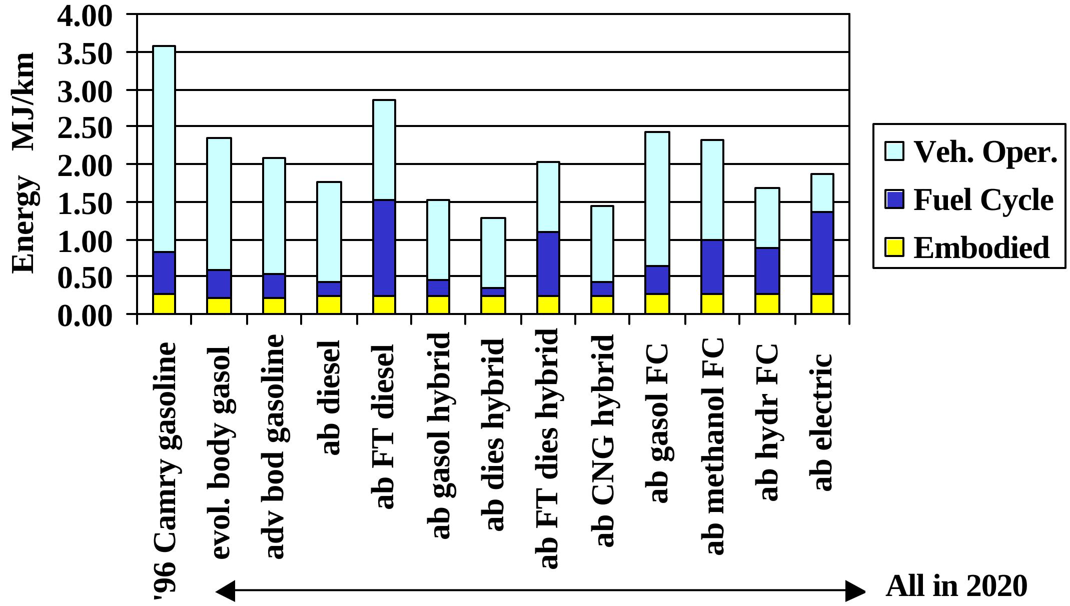


Figure 5.2 Life-Cycle Comparisons of Cost, Energy Use, and Carbon Emissions

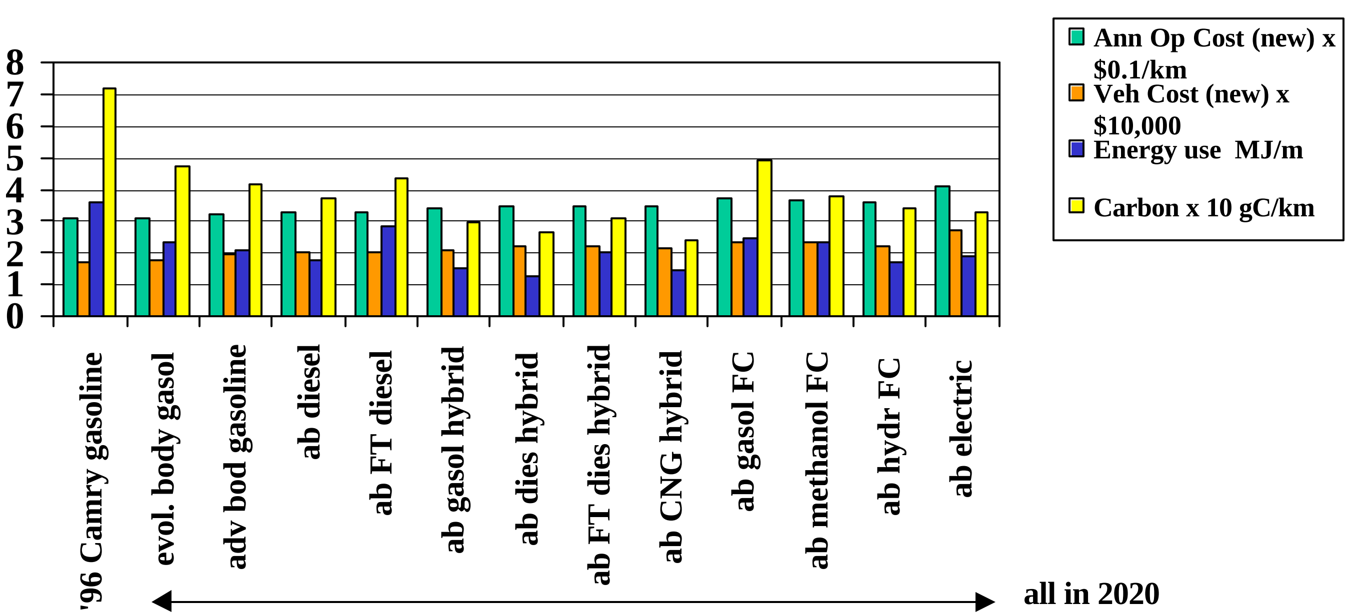
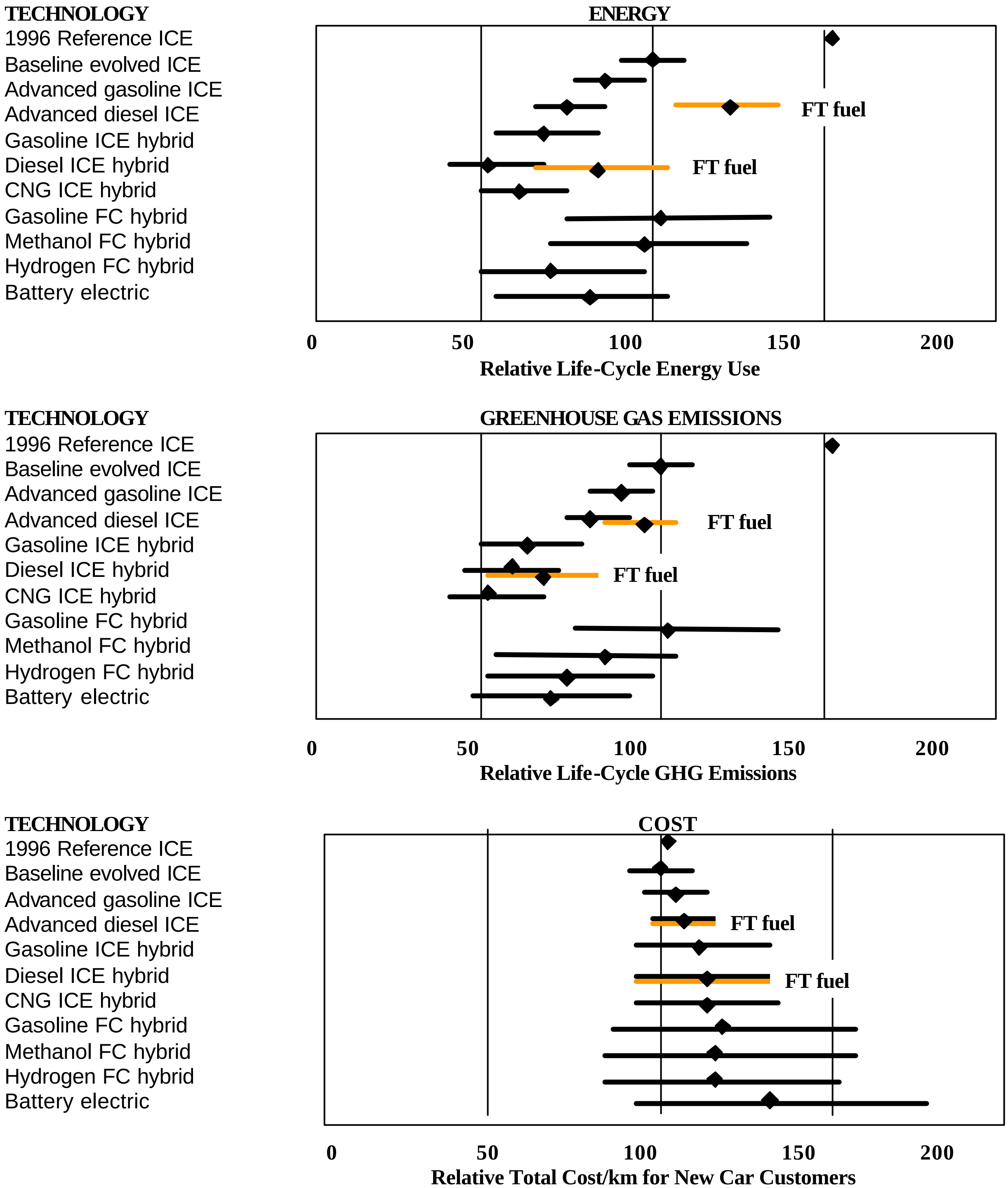


Figure 5.3 Life-Cycle Comparisons of Technologies for New Mid-Sized Passenger Cars

All cars are 2020 technology except for 1996 "Reference" car

- ICE = Internal Combustion Engine, FC = Fuel Cell
- 100 = 2020 evolutionary "baseline" gasoline ICE car
- Bars show estimated uncertainty



composite. Composites are more difficult to recycle as may be some of the components of future batteries and fuel cells. Where material properties are sensitive to alloy composition or are composites, full recycling is generally unrealistic. More analysis is needed to investigate the recycling issues properly, but this is beyond the scope of this study.

It is evident that the embodied energy in the vehicle materials is a small portion of the life-cycle energy use of the vehicle today -- about 7%. However, as future cars move to higher fuel efficiency, and incorporate more sophisticated materials to reduce vehicle weight, the embodied energy becomes a much more significant fraction of overall life-cycle energy use. For the electric car (14%); the diesel hybrid (18%); the CNG hybrid (16%); and the H_2 fuel cell (15%), it represents a more significant portion of life-cycle energy use.

Carbon emissions are reported as grams of carbon per kilometer – grams of carbon are the units that are being widely used by the climate change community. The carbon is actually emitted as carbon dioxide and the amount of carbon dioxide emitted by weight is 3.67 times larger than the carbon weight – the ratio of the molecular weights of CO_2 to C. Carbon emissions from the vehicle cycle use fuel properties data presented in Table 2.1; for the fuel production cycle, the data are shown in Table 2.12. The carbon emissions associated with energy embodied in the vehicle are shown, based on analysis presented in Chapter 4, for the same case of 95% metal and 50% plastic recycling. Carbon emissions from the vehicle cycle are dependent on both the heating value and on the carbon:hydrogen ratio for each primary fuel. Typical molecular ratios are: [coal, $CH_{0.8}$;] petroleum, $CH_{1.8}$; and natural gas (methane), CH_4. Methanol (CH_3OH) has an effective ratio of CH_3, since one hydrogen atom has already been oxidized. As shown in Table 2.1**,** *grams of carbon emitted per MJ of energy consumed* from combustion of selected vehicle fuels are: [coal (typical), 25;] petroleum fuels (typical), 20; methanol, 19; methane, 15, and hydrogen, 0. Electricity, on this same basis would also be 0.

In terms of carbon emissions, the *CNG hybrid* appears to offer the best performance – almost a 50% reduction relative to the baseline. The *diesel hybrid* is close behind with nearly 45% reduction. The *gasoline hybrid, the hydrogen fuel cell hybrid, and the electric vehicle* all offer reductions of about 30% or more. Further decarbonization of the 2020 electricity supply could reduce the emissions from the electric vehicle option further. The *gasoline fuel cell vehicle* has slightly higher carbon emissions than the baseline. The *advanced body diesel and the methanol-fueled fuel cell hybrid* offer about 20% reductions; the *advanced body gasoline ICE* offers about a 10% reduction in carbon emissions. The *FT diesel fuel vehicle* has about an 8% increase in carbon emissions; using *FT fuel in the diesel hybrid* instead of conventional diesel decreases the carbon emission reduction from –44% to –34%, because the added FT fuel production energy tends to offset the carbon reduction from the switch from petroleum to natural gas feedstock.

Local emissions. We have assumed that all the 2020 vehicles will at least meet US EPA Tier 2 standards of 43.5 mg/km for NOx and 6.2 mg/km for PM10. Gasoline or methanol fuel cell vehicles will have even lower or no NOx or particulate emissions depending on reformer performance. The hydrogen-fueled fuel cell and all-electric vehicles produce emissions only in the fuel cycle.

The diesel engine will have the most difficulty in meeting these emission challenges, but added costs for exhaust treatment and a performance penalty have been included in the diesel vehicle estimates, relative to the gasoline vehicles. The fuel cell vehicles are given a credit for not needing an exhaust treatment system.

While some local emissions are associated with production of the various fuels, there are a wide range of production technologies, with the emissions usually controlled to meet local requirements. If required, fuel production emissions could be reduced at the plants to meet future local regulatory requirements at modest cost increases.

A major implication of ultra clean vehicle technologies is that petroleum fuels in 2020 are likely to require deep sulfur removal (to very low levels), both to provide compatibility with fuel cell systems and to meet combustion engine emissions standards. The option of making sulfur-free fuels from synthesis of remote natural gas sources has also been considered, but entails significant energy penalties and, therefore gives less reduction in GHG emissions than using CNG directly.

Life-cycle comparisons. In comparing the eleven future vehicle options to the 2020 baseline, we have drawn the following general conclusions. We note that the life-cycle comparisons across technologies are based on many assumptions, so the numbers shown are subject to uncertainties that vary from technology to technology. From comparisons of our model results to actual advanced vehicle performance data, we believe that the more evolutionary technologies are subject to cost and energy uncertainties in the order of +/-10%. The hybrid vehicle predictions are more uncertain (+/-20%) and the fuel cell vehicle estimates may have uncertainties of
+/-30%. These uncertainty ranges are shown in Figure 5.3. Keeping these uncertainties in mind, we conclude from our projected results that:

- ***reducing vehicle weight*** by about 8% through use of advanced body design and materials increases estimated vehicle price by about 8% and reduces life-cycle energy consumption and GHG emissions by about 11%. Except for the evolutionary 2020 baseline vehicle, all the 2020 vehicles incorporate the advanced body design.

- ***diesel propulsion technology*** in an advanced body car offers about another 13% reduction in life-cycle energy consumption over the advanced body gasoline car, but at about a 6% added vehicle cost. Meeting future emissions standards is likely to be a greater challenge for the diesel engine and increased price and some reduction in efficiency due to emission abatement measures has been included. If clean diesel manufactured from natural gas (FT diesel) is used as the fuel to reduce emissions, the life-cycle energy consumption of the diesel becomes over 30% greater than the life-cycle energy consumption of the equivalent gasoline vehicle, and even 22% higher than the evolutionary body gasoline vehicle. The increase in fuel production energy fully offsets the GHG reduction from switching to natural gas feedstock in this case.

- ***liquid fuel hybrid vehicle*** design, in comparison to the baseline, offers a reduction in life-cycle energy consumption and GHG emissions of about 35-45% at an increased new operating cost of less than 15%. (New vehicle cost is about 20% higher.) The *diesel hybrid* is somewhat more expensive, although it offers almost a further 10% reduction in life-cycle energy consumption and GHG emissions, but with some questions about ability to meet local emissions standards. The life-cycle energy advantage of the diesel hybrid relative to a gasoline hybrid is negated if a Fischer-Tropsch clean diesel fuel is used, since the gasoline hybrid offers about 20% better life-cycle energy efficiency than the FT hybrid. GHG emissions also are about 10% higher for the FT diesel fuel than for ordinary diesel fuel, because emissions from the energy consumed in production more than offset the advantage of starting with a natural gas feedstock.

- ***CNG hybrid vehicle*** design offers energy efficiency performance between the gasoline and diesel hybrids, but does have significantly reduced CO_2 emissions (almost –50%) because of the fuel switch to natural gas. Costs are similar to the liquid-fuel hybrids.

- ***hydrogen-fueled fuel cell vehicle*** design, in comparison with the baseline, has about a 30% reduction in life-cycle energy consumption. This vehicle has no emissions of NOx and particulates, and 20% higher GHG emissions than the CNG hybrid, because of the hydrogen production cycle.

- ***electric vehicle*** design costs about 25% more then the hydrogen fuel cell car, but it has a shorter range (range is about 400 km versus 600 km for the hydrogen fuel cell car). This limitation is of some significance because recharging times are long. It has a 7% lower life-cycle energy consumption and about the same carbon emissions as the hydrogen fuel cell car. Carbon emissions could be reduced further if the electricity supply is further decarbonized. The emissions are all associated with the production of the vehicle and of electricity; the operating vehicle has essentially no local emissions. Operating costs (new) are about 33% higher than the baseline – mostly due to increased capital costs associated with battery storage. These estimates are based on our optimistic assumptions about advances in battery technology.

Role of critical assumptions. Earlier in this chapter, we used the term "optimistic realism" to describe the assumed future state of the technologies evaluated. It is worth restating here some particular assumptions that potentially can have a significant impact on the results we report.

First, we are assuming that a clean diesel engine system can be developed to meet Tier 2 emission standards at a reasonable cost. Considerable progress has been made in Europe on cleaner diesels and there are major efforts to reduce emissions from the large trucking sector where diesels are the only currently practical technology. However, if reaching these goals for cars is too costly or uses up more of the differential energy benefits of the diesel, then the diesel becomes much less attractive.

The next such assumption is that battery technology for electric vehicles will advance to the level used as a goal by the US Advanced Battery Consortium research initiative. If battery technology falls short by only reaching 2/3 of this performance goal, the performance of the electric car becomes non-competitive in most respects (over a 30% increase in energy consumption and weight for similar performance). For hybrid systems, battery specific power is the critical performance issue and acceptable levels appear attainable. Cost, however, remains a significant issue.

Another critical assumption is that on-board hydrogen storage technology will develop to allow sufficient hydrogen-fueled fuel cell vehicle range without compromising vehicle weight, performance, or capacity for passengers and luggage.

A final assumption that needs further examination is that any infrastructure change costs associated with transition to new fuels or vehicle technologies are absorbed in the normal costs of doing business. We have not added any charges to the fuel or vehicle cost estimates that are due to changes in infrastructure, since we wish to provide a comparison of the actual performance of the various options on a long term basis. Likewise, in our estimates on the availability of recycled materials, we have not included the transitional issues when a new material is added to the fleet gradually. With vehicle lifetimes of ten or more years, a stream of disposed new material in 2020 will initially be insufficient to provide a matching recycle supply for new vehicles until nearly a decade later. We have not assumed any limits on the availability of recycled materials in 2020. This assumption is of particular importance to fuel cell vehicles where virgin Pt-group metals are very costly and in somewhat limited supply and where substantial reduction in use is assumed along with aggressive recycling.

5.3 Stakeholder Viewpoints

While Tables 5.3 and 5.4 present life-cycle summaries for energy use, emissions and costs of the different future technology combinations considered, the choice of particular options may have different impacts on different stakeholders. These differences may be associated with the transition from today's technology to the new option in 2020 or with the differential characteristics of the new option in 2020. As a first cut at understanding these impacts, early in the project our research team developed and completed detailed templates to assess a large range of different economic, environmental and other attributes including those associated with the transition to each fuel/vehicle technology combination by each stakeholder group.

Table 5.5 presents an overview of the template analysis results; more details for each of the templates are provided in charts that are appended to this chapter. The full templates were completed by each research team member and then compiled for comparison. We did not separate out the transitional impacts from the on-going impacts expected in 2020 as a result of the change. Since the next phase of this project plans to focus more carefully on these issues, they are presented in this report as a first order attempt to identify impacts. The composite draft templates were presented at a working group meeting of project sponsors for critique and amplification. These templates include many interesting details that will have to be considered in the introduction of each new technology, and are summarized in Tables 5A-1 to 5A-8. Each stakeholder group table has a primary sheet which records "pluses and minuses" and two backup sheets which give the basis for the rating and provide additional

Table 5.5 Summary of Major Impacts by Stakeholder [percentages shown relative to baseline]

Stakeholder	Attribute	Baseline 2020 SI ICE Gasoline Evolut body	2020 SI ICE Gasoline Adv. body	2020 CI ICE Diesel Adv. body	2020 SI Gasoline Hybrid Adv. body	2020 CI Diesel Hybrid Adv body	2020 SI CNG Hybrid Adv body	2020 Gasoline Fuel Cell Adv body	2020 Methanol Fuel Cell Adv body	2020 Hydrogen Fuel Cell Adv body	2020 Electric Battery Grid-Power Adv body
Vehicle Purchaser	**Veh. Fuel use MJ/km**	1.75	1.54 -12%	1.35 -23%	1.07 -39%	0.92 -47%	1.03 -41%	1.79 +2%	1.33 -24%	0.81 -54%	0.51e -71%
	Ann. Op. Cost (new) 1997$	0.306	0.321 +5%	0.328 +7%	0.341 +11%	0.348 +14%	0.346 +13%	0.373 +22%	0.365 +19%	0.357 +17%	0.408 +33%
	Cost of Vehicle 1997$	$18,000	$19,400 +8%	$20,500 +14%	$21,200 +18%	$22,200 +23%	$21,700 +21%	$23,400 +30%	$23,200 +29%	$22,100 +23%	$27,000 +50%
	Other		Safety?	Safety? Particulates?	Safety? Service cost up?	Safety? Service cost up? Partic?	Safety? Slower fueling	Safety? Freeze-up?	Safety? Fuel avail? Tox? Freez?	Safety? Fuel avail? Freeze-up?	Safety? Recharge Slow?
Government	Sys.energy with recycling MJ/km	2.34	2.08 -11%	1.77, -24% FT=2.86; +22%	1.53 -35%	1.28 -45% FT=2.02; -14%	1.45 -38%	2.44 +4%	2.32 -1%	1.69 -28%	1.88 -20%
	gCeq/km with recycling	47.2	41.9 -11%	37.0, -22% FT=43.4; +8%	29.8 -37%	26.5 -44% FT=31.0; -34%	24.2 -49%	49.0 +4%	37.6 -20%	34.1 -28%	32.6 -31%
	Local: NOx emiss. Partic.	 Tier 2 Tier 2	 Tier 2 Tier 2	 Tier 2 Particulates?	 Tier 2 Tier 2	 Tier 2 Particulates?	 Tier 2 Tier 2	 Below Tier 2	 Below Tier 2 (NOx at plant)	 Vehicle zero (NOx at fuel station?)	 Vehicle zero (NOx at power plant?)
	Other		Safety?	Safety?	Safety?	Safety?	Safety?	Safety?	Safety? Methanol toxicity?	Safety? R&D needs	Safety? R&D needs Battery dispos.
Vehicle Manu-facturer			Safety?	Safety? Diesel exhaust cleanup? Cost?	Safety? New suppliers More compl? Cost?	Safety? New suppliers More complex	Cost? Safety? New suppliers More complex	Safety? Cost? New suppliers More complex Pt avail?	Cost? Safety? New suppliers More compl? Pt avail?	Cost? Safety? New suppliers, more complex H_2 storage Pt avail?	Safety? New suppliers Battery cost, performance
Vehicle Distributor/ Service					More complex	More complex	More complex New fuel Infra. Safety?	More complex	More complex New fuel Methanol tox?	More complex New fuel infra.– safety?	Battery replace/disp. Phase out fuel sales
Fuel Mfr/Distr				Diesel shift Small inv. [FT $10+B Invest.]		Diesel shift Small inv. [FT $10+B invest.]	Connect to NG grid – some new invest.		$12-15B new remote gas plants	Reform off NG grid – moderate added invest.	Elect. Sector shift

comments. The mix of pluses and minuses for the more radical technologies underlines the challenge in implementing major changes in technology.

The impacts of changing fuel types are considered in terms of total system energy use per km and in the associated GHG and local emissions. While purchasers may be conscious of fuel costs, in terms of the life-cycle costs of owning and operating a new vehicle, fuel costs (ex taxes) are only a few percent of total new vehicle costs as noted in Chapter 2 and shown in Table 5.2, although fuel costs including tax can reach almost 15% of new vehicle operating costs at high ($3.53/gallon) UK tax rates. Moving to a more expensive fuel (ex tax) thus should have little impact on the total cost of transportation to a new car purchaser, though it may have some psychological impact and will be of greater importance to a used car purchaser. However, purchasers will be very conscious of fuel availability and fueling convenience when purchasing an alternative fuel vehicle. The gaseous fuels have some disadvantage because of slower energy fueling rates and larger, heavier on-board storage systems. There are differences in the safety precautions that will be required for alternative fuels. Pressurized gas transfer requires robust, leak-free couplings; experience with CNG in some existing installations shows that this challenge can be met. Additional precautions may be needed for hydrogen, but again these can be addressed by technology at some increased cost. The biggest differences associated with changing fuel impact the fuel manufacturers and distributors. Gasoline is the baseline fuel; a switch to diesel will require some modifications in refinery operations, but not a change in the petroleum feedstock. Refineries are in a continuing state of improvement to meet changes in feedstocks and product requirements, and are used to seasonal shifts in product demands.

If compressed natural gas (CNG) is used as fuel, markets will shift from the petroleum sector to the closely related natural gas sector. With a few percent of the new car fleet operating on CNG in 2020, it is likely that the existing natural gas transmission and distribution system could manage the increase in load. However, the total energy demand for road transportation in the US is roughly equal to the total demand for natural gas for all end uses. Thus, a major rapid shift to CNG in the transportation sector would cause major supply and delivery problems until infrastructure was developed.

Both methanol and hydrogen fuels would also shift the primary feedstock from petroleum to natural gas (largely methane) – which has lower carbon intensity. Synthetic (Fischer-Tropsch) diesel can also be made from natural gas. While initial production of any of these fuels might be made from domestic gas, and there may be domestic methanol capacity associated with the phase out of MTBE, any large-scale introduction of these liquid fuels would require development of new facilities sited at remote locations of large gas reserves. This switch in fuel source will require substantial investment by the fuel manufacturers and distributors, although the developments will still remain in the business area of the oil and gas industry. For this study, we have assumed that liquid fuels from natural gas, if they are required to supply a significant fraction of road transportation energy, will be produced at sites of remote gas and shipped as liquids for distribution. Clean fuels such as methanol may also require modified or new distribution infrastructure to avoid contamination from co-shipment of residual-sulfur-containing petroleum fuels.

Since there is no affordable way of shipping large quantities of hydrogen from remote sites, we have assumed that hydrogen fuel would be supplied off interconnections to the domestic natural gas distribution network. Fueling stations would be equipped with hydrogen reformers and would store the hydrogen as 5000 – 6000 psi (330 -400 bar) gas in tanks for subsequent fueling of vehicles. Since we are looking at only a modest hydrogen fleet size in the 2020 time frame, there would probably not be a capacity constraint from the natural gas distribution system. However, if hydrogen becomes the long-term energy carrier choice, there will be major additional new supply and distribution infrastructure requirements that will need to be addressed. LNG from remote sites could be imported to supplement existing gas supplies at a price similar to the existing domestic gas price.

The above assumptions result in a significant difference in the cost of the natural gas feedstocks, since the remote gas is inexpensive (~ $0.50/GJ) and the pipeline gas is at domestic market prices (~$3.00/GJ -- which is also about the price for bulk LNG imported from remote sites). However, we believe that in the 2020 time frame, any bulk manufacture of synthetic liquid fuels would probably be supplied from new facilities sited at remote locations, while both CNG and H_2 would be provided in a distributed manner off the domestic natural gas infrastructure.

A switch to electricity as a transportation energy source would shift business from the oil and gas industry to the electric sector. Again, for a modest electric car fleet, the electric transmission system will probably have adequate capacity. Longer-term major shifts to electricity as the transportation sector energy carrier of choice would have significant infrastructure development implications. In any case, none of these transitions appear to be "show stoppers" if they are phased in fairly gradually.

The impacts of changing the vehicle, including fuel in some cases, are more dramatic in scope, though they also are likely to occur in a gradual transition. Our assessment is focused on the comparative performance of the various options, assuming they have captured a few percent of the new car market in 2020.

Transitional Issues for Alternative Technologies over the Next Two Decades. The evolutionary baseline vehicle system is expected to show significant improvements over the vehicle and fuel technologies employed today. These are considered as a normal path of change, and it is assumed that local environmental emissions will continue to decrease through regulatory pressures. Because these evolutionary changes appear to involve the lowest cost among the options considered, they are a likely future path unless pressure to reduce GHG (especially carbon) emissions from the transportation sector becomes a much higher societal or governmental priority. The alternatives considered offer different levels of GHG reduction through a number of system options which have different impacts on different stakeholders.

We also note that market competition, under uncertain future regulatory constraints, also will influence technology choices. Alternative fuels will be facing a robust competitor in the petroleum industry, which has had nearly a century in optimizing its infrastructure. This competition with petroleum may inhibit or delay major private investments in alternative fuel infrastructures. In the interim, there are a number of small scale experiments with a variety of fuels and with alternative vehicle systems. There are many players in these markets today and rapid changes are likely, as experience is gained in technology and with the market performance. Major new infrastructure costs are sufficiently high that responsible investment requires the new infrastructure meet even longer term goals to avoid poor choices and wasted capital. New methodologies are needed to sort out robust strategies that meet the future needs of large groups of stakeholders in various parts of the world and also ensure environmental responsibility.

Here is a summary list by stakeholder of the major transitional issues that may be important:

- **Vehicle Purchaser**
    - Increases in costs and/or decreases in performance/amenities
    - Problems with availability and refueling convenience of new fuels (especially in early introduction, although first introduction with fleet applications would reduce this problem)
    - Safety of new vehicle in existing vehicle fleet
    - Uncertainty about technology reliability and serviceability
    - Interest in pioneering new technology?

- **Government (at all levels)**
    - International and national policy actions on GHG reduction
    - Implementation of GHG reduction mandates, if used, by locale, sector, etc.
    - Economic impacts/shifts related to new infrastructure investment
        - Major investments (offshore FT or methanol production)
        - Significant investments (debottleneck or expand natural gas or electric infrastructure, build clean methanol infrastructure)
    - Impacts on competitiveness in global markets
    - Safety management
        - Highway safety (crashworthiness, fleet size, traffic management)
        - Fuel safety (new standards for CNG, methanol, H_2)
        - New local safety and zoning requirements for fueling stations
    - Environmental stewardship and social equity issues

- **Vehicle Manufacturer**
    - Marketing challenges (cost, performance, amenities) – constrained by future government requirements?
    - Technological challenges
        - Clean diesel technology
        - Hybrid and Fuel Cell system refinements
        - Sulfur guards for FC
        - CNG, H_2, and battery energy storage improvements

        - Advanced control systems to optimize performance
    - Recycling challenges (if driven by government requirements)
        - Alloys, plastics
        - Pt group metals for fuel cells and specialized catalysts in advanced after treatment systems
    - New suppliers (more electrical systems, system integrators, fuel cell suppliers, etc.)

- **Vehicle Distributor/Servicing/Recycling/Disposal**
    - New investment (by smaller companies?)
        - New service and inspection equipment for new technologies
        - New fuel facilities for servicing
    - Component recycling (batteries, Pt group metals, etc.)
    - Hiring/training to meet different and higher skill levels for employees

- **Fuel Manufacturer**
    - Major new offshore investment (FT plants, methanol, LNG?)
    - Infrastructure expansion and debottlenecking (CNG, H_2, electricity)

- **Fuel Distributor**
    - Significant investments (by smaller companies?)
        - New distribution infrastructure for ultra clean fuels (methanol, FT diesel, etc.)
        - Fuel station storage and transfer facilities for CNG and methanol
        - Reforming, storage and transfer facilities for H_2
    - Increased safety concerns
        - H_2 facilities including pressure transfer
        - Methanol (corrosion? poisonous? environmental fate?)
        - CNG pressure transfer
    - Longer fueling times (e.g., CNG, H_2)
    - Loss of fuel business (electricity)

Continuing Impacts of Alternative Technologies in 2020. In 2020, assuming that the vehicle and fuel alternatives to support each of the technology combinations evaluated are in place, then the major residual impacts of the change rest with the vehicle purchaser and the government. It is likely that the vehicle production and service companies, as well as the fuel producers and distributors, will have incorporated the impacts of transitional changes into their cost and operational structures. Thus, the major differences that will impact car purchasers and the government appear to be:

- **Vehicle purchaser**
  - Cost of transportation per km (or cost of new vehicle)
  - Safety (crashworthiness of lighter vehicle bodies; fueling)
  - Performance (including acceleration, load and towing capacity, noise, odor, comfort, style, and level of amenities)
  - Fuel availability and refueling convenience
  - Reliability and convenience of servicing

- **Government**
  - Level of GHG reduction and economic impacts
  - Reduction in local pollution problems
  - Change in petroleum dependence
  - Changes in public safety (fueling, vehicle)

To move to most of these new technologies in 2020 will require a change in customer behavior – whether forced by the government or voluntary. It is difficult to foresee how the governments worldwide may react to climate change issues as more information emerges over the next two decades. Auto buyers may ultimately move to different purpose vehicles – perhaps a compact efficient vehicle for local errands and commuting and a larger rented vehicle for a long distance trip. While we do not include behavioral change in this study, it is important to realize that it will be a powerful factor in future choices of road vehicle alternatives.

5.4 Challenges and Opportunities for Future Road Transportation Alternatives

The evaluations and comparisons of these alternative technology combinations show that each has benefits and disadvantages.

Evolutionary changes between now and 2020 could result in the typical passenger car being lighter (about 1240 kg versus 1440 kg for a 1996 equivalent vehicle) and more efficient than today's car, and in about a 35% reduction in total energy consumption per km and carbon emissions over present vehicle usage for comparable size and performance. In the absence of any major regulatory interventions to the contrary, cars will still probably use petroleum-based gasoline, of an improved nature to meet the more stringent pollution limitations, in 2020.

> ***Challenges:*** While the GHG emissions per vehicle kilometer of the evolutionary vehicle are about 35% less in comparison to today, vehicle miles traveled worldwide will continue to increase and a still greater reduction in GHG emissions may be called for globally.
>
> ***Opportunities:*** Table 5.5 shows some of the leading options for achieving additional GHG reductions in alternative fuel and vehicle systems.

Advanced body design involves the substitution of lighter weight structural materials (e.g., aluminum, plastics), reductions in drag and rolling resistance, and other improvements that our calculations suggest could cut fuel use by about an additional 11% at about a 8% increase in cost over the baseline car. GHG and local emissions are cut proportionally. Because this is a sound way to reduce energy needs of the vehicle, it is likely that all the advanced propulsion system designs of the future will be configured with an advanced body design.

> ***Challenges:*** Auto buyers may be concerned about safety of these lighter vehicles if they are introduced into a much heavier fleet. Appearance of the vehicle may be more utilitarian and loading with heavy extras will compromise performance. Conflicts with the "SUV mentality." Vehicles will be less able to carry or tow heavy loads. Recycling of any new expensive materials will be essential; recycling of advanced specialized alloys and composites will also present challenges.

> ***Possibilities:*** Collision avoidance systems and passenger protection systems are evolving rapidly and may reduce some of the safety concerns. Car manufacturers may emphasize environmental values as a selling point and auto buyers may learn to be more receptive to this. May be able to develop an urban smaller car market?

Liquid fuel hybrid propulsion systems are particularly suited to urban driving cycles. The gasoline engine hybrid we examined would require about 25% less total energy consumption per km than is needed for the equivalent standard ICE gasoline car with a similar advanced body. Vehicle cost is higher by 8% for the advanced body and about an additional 5% for the hybrid configuration, which includes dual drives (mechanical and electrical) and special battery energy storage capacity. Carbon emissions are reduced by about 30% relative to the advanced body ICE, and 40% relative to the baseline vehicle (down about 60% from those of the typical 1996 vehicle).

> ***Challenges:*** Hybrids are more complex to service and also are subject to the energy storage limitations associated with batteries. Maximum efficiency is compromised when the vehicle is operated over widely different driving cycles since the optimum balance between the basic engine and the battery system changes, though an improvement over the combustion engine alone is always achieved. Hybrids are a good match to urban driving cycles, but are less attractive for high speed travel, carrying heavy loads, and/or over long grades, where the batteries may become drained and unavailable to supplement the lower power from the smaller engine. Cost is somewhat higher.

> ***Opportunities:*** A major change in fuel infrastructure is not needed for combustion engine hybrids. Hybrids offer a transition from today's mechanical driveline vehicles to future vehicles with electric drivelines. The major improvements in battery technology that we assume greatly benefit hybrids.

Advanced diesel engines offer, by our calculations, about a 12% energy efficiency improvement over the gasoline engine with about a 2% operating cost increase. Combined with an advanced body, the energy efficiency improvement is about 24% over the baseline gasoline ICE. Diesel technology has improved over the recent past, and could be further improved with modest investment. Many countries have or are tightening diesel emission standards, and attention is also turning toward requiring cleaner diesel trucks. In a hybrid configuration, diesel system fuel use is about 45% less than that of the baseline car (compared to about 30% less than the baseline for the hydrogen fuel cell car). Life-cycle GHG emissions are about 45% lower than the baseline (compared to about 30% lower for the hydrogen fuel cell car).

> ***Challenges:*** Diesel emissions, especially nitrogen oxides and particulates, have given this technology a bad image in the past. In the US, the EPA is tightening emissions regulations for diesels, and much research is underway to ascertain the connections between fine particulates in diesel exhaust and various respiratory ailments. If it is shown that ultrafine particulate emissions are associated with the condensation of sulfates in the diesel exhaust, deep sulfur removal in fuels will be needed. Removing most of the sulfur at the refinery seems most cost effective, though some on-board sulfur removal may also be needed. It is also unclear what level of NO_x reduction is possible with diesel technology. It will require additional R&D on fuel and engine design and on exhaust gas cleanup to make the diesel acceptably clean with respect to future regulations. Meeting these emission requirements will take additional energy and will reduce the efficiency benefit that makes the diesel technology attractive in the first place, and we have made some allowance for these factors in our assessment.

> ***Opportunities:*** "Clean" diesel vehicles can probably be developed using a combination of modified fuel, combustion conditions, and exhaust cleanup, but at some loss of the efficiency advantage that makes the technology attractive. Sulfur removal to very low levels is possible (and probably necessary); alternatively, at a considerable investment and with higher energy use and carbon emissions, synthetic clean diesel could be manufactured from remote natural gas. However, the option of cleaning up the diesel vehicle might well be less of an R&D challenge than developing the hydrogen fuel cell car and providing the necessary fuel infrastructure by 2020. Clean diesels have wider applicability in freight transportation as well as in developing countries.

CNG hybrid vehicles provide vehicle energy efficiency performance between the gasoline and diesel hybrids, but provide a substantial reduction in carbon emissions because of the switch to lower carbon intensity natural gas as the fuel. This option gives the greatest carbon emission reduction of all the options included in our study – about 50% relative to the baseline and 70% lower than today's equivalent car. The heavier and larger fuel pressurized storage tank for high pressure gas is bulky and infringes on available trunk space – and fueling times will be longer than for liquid fuel transfers.

> ***Challenges***: The storage technology on board needs substantial improvement to provide the interior and trunk space offered by liquid fuel cars. Refueling convenience will also require some innovations to be competitive. Fuel switch to

natural gas will require some substantial investments at the fueling stations – and may ultimately require expansion of the main natural gas infrastructure. The fuel switch from petroleum to natural gas can only yield up to a 25% reduction in carbon emissions (if no methane is leaked), so this option is limited in the extent to which it is able to reduce long term emissions.

Opportunities: Offers a more conventional option for major reductions in GHG emissions. Comparable to fuel cell cars using hydrogen made from natural gas in terms of energy and carbon emissions reductions.

Fuel cell vehicles offer an alternative energy conversion system that has several advantages over internal combustion engines. They avoid high combustion-generated gas temperatures and, when fueled with hydrogen, do not produce gas or particulate emissions. The fuel cell unit itself operates at higher efficiency than internal combustion engines. However, they do require hydrogen as fuel, and the emissions and inefficiencies associated with the production and
distribution of hydrogen are comparatively large. Thus, comparisons on a "well to wheels" basis are important if net system improvements are to be assessed. The fuel cell vehicles with a liquid fuel reformer on board, by our estimates, do not appear to offer any energy use benefits over the advanced body gasoline vehicle, and are inferior in performance to the similar fuel ICE hybrid options considered.

If **hydrogen** is stored on-board, a fuel plus vehicle system reduction in energy use of 30% over the baseline car is estimated. GHG emissions would then be reduced by about 30% and local emissions are virtually eliminated. In this case, the hydrogen would be manufactured at distribution/filling stations from reforming natural gas. The state of the art for hydrogen storage is still a limitation on this technology. Hydrogen can be stored as high pressure gas, a hydride, or as a liquid at ultra low temperature. Recent research suggests that carbon nanotubes may offer possibilities for hydrogen storage. The practical hydrogen storage density (weight hydrogen/total storage system weight) for all of these technologies is still well below research goals of 10%, so on board storage carries a weight and volume penalty much greater than those for liquid fuels. We have assumed a storage density of 5% in our analyses.

Challenges: On-board hydrogen storage is a major limitation on the use of fuel cells. Building a hydrogen production and storage infrastructure will take significant investment and will start to shift the transportation sector from petroleum to natural gas. [Initially, the natural gas distribution pipeline infrastructure will have capacity to support limited hydrogen production, but eventually additional infrastructure will require major investments]. Since fuel cells produce water, provisions must be made to prevent freezing problems in cold climates when cars are not in use. Present fuel cells require significant amounts of platinum grade metals which make them costly. We have made quite optimistic assumptions about future costs, recycling, and performance. Fuel cell technology is still in the prototype stage, and major improvements in cost, weight, volume, and performance will be required to compete with ICE based technology.

Opportunities: Longer term, research may find better hydrogen storage technologies. Work is also progressing on fuel cells that might use pure methanol as fuel – to date direct methanol fuel cells, i.e., systems without reformers to convert methanol to hydrogen, have had very low efficiency. If hydrogen for fuel cells is produced from carbon-free electricity or from carbon fuels with carbon sequestration, this has the potential to be a near zero GHG emission technology.

Electric cars are considered zero emission vehicles, but on a "well to wheels" basis, the emissions depend on the emissions associated with electricity and vehicle production. Large power plants can be more efficient than individual vehicle engines, so some GHG reduction is gained for the same fuel. Nuclear power and electricity from renewable energy can reduce associated GHG emissions to near zero, however, fossil fuels are projected to remain the predominant fuel for power generation in the 2020 timeframe. Using the electric sector supply mix for 2020 as forecast by the EIA, life-cycle carbon emissions for the electric vehicle option are 30% lower than those for the baseline gasoline vehicle, and the life-cycle energy consumption is lower by about 20%. Costs for electric vehicles are higher, mainly because of the cost of batteries – a major limitation in performance is due to the energy storage limitations of batteries.

Challenges: Improved energy and power density batteries with affordable cost and recyclability are major needs; the likelihood of having commercializable batteries with competitive characteristics by 2020 is not large.

Opportunities: If carbon dioxide capture and sequestration are applied to large fossil-fueled power plants, this could be a way (at increased cost and energy use) to continue to use fossil fuel in the transportation sector without major GHG emissions.

Other possibilities:

- **Synthetic fuels:** Fischer Tropsch and similar processes for converting natural gas to liquid fuels offer the potential for using "inexpensive" remote natural gas reserves and for producing a fuel without sulfur and other contaminants associated with petroleum-based fuels. Of course, if implemented on a scale to provide a significant fraction of transportation fuel, this option will require major offshore investment in construction of production plants and a distribution infrastructure. The fuel cycle analyses indicate that the Fischer Tropsch technology imposes significant fuel cycle energy penalties that are counter to goals of improved life-cycle efficiency and reduced life-cycle carbon emissions. All fuels (without carbon sequestration) produced from natural gas have a maximum theoretical carbon emission reduction of 25% per unit of energy, which reflects the lower carbon intensity of methane relative to petroleum fuels.

- **Behavioral changes: C**hanges in auto buyer behavior are likely to be slow – and will require that new options are at least as attractive as the old. While we have not addressed behavioral changes in this assessment, we recognize that they may come about in response to, or perhaps independently of, the new technologies. Increased use of public transportation, more carpooling, less use of cars for short trips, etc. can be encouraged through pricing mechanisms, convenience and education. If major reductions in GHG emissions are needed, more attention will have to be paid to land use planning, integrated with efficient transportation systems. The present market structure and the interests of car manufacturers encourage the acquisitive instincts of many auto buyers to upgrade to larger, more luxurious vehicles, that also are larger consumers of energy. Behavioral changes seem unlikely without government interventions or a major change in the environmental consciousness of customers.

5.5 Some Generalizations and Broader Implications:

In today's world, we see a spectrum of technology choices, which are largely influenced by local government policies and economic conditions, along with consumer wants. In broad terms:

- US has low taxes on vehicles and fuels. There are about as many vehicles as there are licensed drivers, so personal vehicle fleet size is stabilizing. But drivers are traveling more, and choosing larger, more powerful vehicles with more amenities. Good highway and fuel infrastructures facilitate increased vehicle use and encourage higher speed (lower efficiency) operation. Local pollution is a concern in some areas; GHG concerns are not a high priority in general.
- Europe and Japan have larger taxes in general on both vehicles and fuels. Differential tax policy in some countries has resulted in greater use of diesels and clean diesel technology has advanced in these areas. Travel distances are somewhat shorter in these more compact countries and urban congestion is considerable. Good road and fuel infrastructure exist. Alternative public transportation is convenient and available. SUVs appear to be much less attractive in these regions. A higher level of environmental consciousness and awareness of GHG issues seems to exist.
- Developing countries have limited infrastructure, and some actually subsidize fuel for agricultural uses. As these countries industrialize, road and fuel infrastructure investments are being made, but they usually lag demand because of limitations on available capital. Rising standards of living are making personal transportation a rapidly increasing priority, but for low cost vehicles. Some countries become the market for old "dirtier" vehicles that are retired from the OECD sphere of nations. Interim transportation is provided by mini-buses (similar in size to SUVs, but with no pollution control in many cases) or by dirty two-cycle motor bikes. Air pollution problems are severe in urban areas, along with noise and congestion. GHG issues are a low priority compared to economic development, but are recognized when in synergy with energy efficiency or pollution abatement goals. These countries could be a prime market for small and cleaner SI or diesel ICE cars. Infrastructure needs

and costs, along with vehicle costs, for the hybrid and FC vehicles make these less likely choices. It is easy for the developed world to suggest a new view of mobility to developing countries, but our arguments lack credibility if we continue to demand the sorts of personal transportation amenities to which we are accustomed.

- If major reductions in GHG emissions are required globally, the developing nations will need to be engaged. However, the costs entailed in GHG reduction in developing countries will have to be shared by the developed world. Where the opportunities lie in the transportation sector will be an issue for ongoing examination over the next decades.

5.6 Framework for Robust, Multi-stakeholder Choices

In the prior section, we provided our first cut at what the key transitional and end-point issues would be for the immediate group of stakeholders involved in the auto/fuel component of our society. These issues tie into a much broader set of economic, environmental, and societal issues. The second phase of this project will focus on trying to elucidate these issues by actual involvement of stakeholder representatives to address the following issues along a time line extending out, say, fifty years. We have planned a meeting at MIT in October 2000 to engage representative stakeholders in a first cut at defining the issues and developing a methodology.

First it is important to define a **general long-term objective**, which might be along the following lines:

Finding robust pathways to future personal transportation options that are:

- **Widely acceptable and affordable to the public (locally and globally)**
- **Environmentally responsible (toward zero emissions – and with minimal depletion of non-renewable –or non-substitutable – resources, including land)**
- **Without unduly disruptive transient economic and institutional impacts (both in the transport sector and more broadly)**
- **On a path to a sustainable global communication and transportation architecture**

Subsequent meetings with stakeholder groups would be used to further modify or refine the general objective and the major bounding constraints. We would start with US stakeholder groups and then apply the methodology, if feasible, to other parts of the world.

- What are the particular issues of concern and how are they ranked in importance to each representative stakeholder group?
    - Essential factors
    - Desired factors
    - Adverse factors
    - Unacceptable factors
- What are the interactions and interconnections with the other major stakeholder groups?

- How do the major technology pathways fit the particular stakeholder concerns?
- How does the stakeholder value short term economic benefits and longer term environmental or societal gains? (This provides a measure similar to risk taking or risk aversion in decision models.)
- How does the stakeholder value (monetize?) new technology?

Next we would explore potential methodologies for a strategic framework. Perhaps a decision analytical or systems dynamics model could be used to describe the interactions and feedbacks. Perhaps some techniques from game theory could be used to explore the interactions. Of course, all the alternatives are subject to growing uncertainty in cost and performance as technologies are projected out into the future. Therefore, some measures of probability of technological success and costs that incorporate uncertainty will be needed.

At this point, a clear methodology is not apparent since this is a non-linear, complex problem fraught with uncertainty and behavioral variables that are perhaps even more uncertain than the technological predictions. However, we see Phase 2 of this project as the start of the exploration of an important issue that may spawn additional research and creative thinking about this challenge.

If the world decides that we need to reduce GHG emissions significantly, there are many alternatives that could be considered. Uncertainties in our knowledge about the consequences of our emissions on climate make it difficult to know how major an action is needed and on what time scale. Some reductions can be achieved now at fairly low cost, but it is important to keep a longer-range view in mind before making major infrastructure investments that are inconsistent with longer-term goals and options. Figure 5.4 presents a preliminary cartoon of what future options may be from a Year 2000 perspective. As you look at this figure, imagine what someone in 1900 might have sketched in guessing at our technologies and life style today. There will be many surprises over the next century; this is a first guess. However, a framework of this sort may be useful in making short term decisions about major changes that will establish transportation sector infrastructure lasting many decades.

In the developed world, we have become accustomed to a life style that is largely fueled by our relatively inexpensive and plentiful fossil reserves. Developing countries also have considerable reserves of fossil fuel and plan to use these to facilitate their development. In the absence of GHG concerns, it is likely that fossil fuel use would continue to grow along with global development. Local pollution problems would be resolved as living standards increased globally. Eventually, depletion of reserves might become an issue, but the rate at which new reserves are being accessed through technological improvements puts depletion concerns at least decades in the future.

However, GHG concerns are causing a reexamination of our unlimited use of fossil fuels. The Framework Convention on Climate Change (FCCC) was ratified by the UN members in 1994 and included a commitment to:

"stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. "

While the Kyoto Protocol sets target reductions in GHG emissions for Annex 1 countries (the developed countries), it remains unratified. Some industries and governments are trying to meet goals voluntarily, but so far the only significant GHG reductions since 1990 have been associated with areas that have undergone economic collapse. There still is much uncertainty about the issues of climate change and the appropriate timing and extent of mitigating actions. However, the options that seem available to reduce emissions in a world of growing energy demand, include efficiency improvements, decarbonization of the fuel supply, and changes in our usage of energy. If required, the least costly and disruptive of these options will be applied first – then options that involve more change in infrastructure and technology – and finally those that are very expensive or require major changes in life style.

With increasing global population and a growing number of megacities, mobility and personal transportation demands will continue to grow. Urban population densities will require the availability of concentrated fuel sources – if they are to be met by renewable energy sources, the footprint of energy collection outside the urban area will need to be greatly larger than the urban area itself.

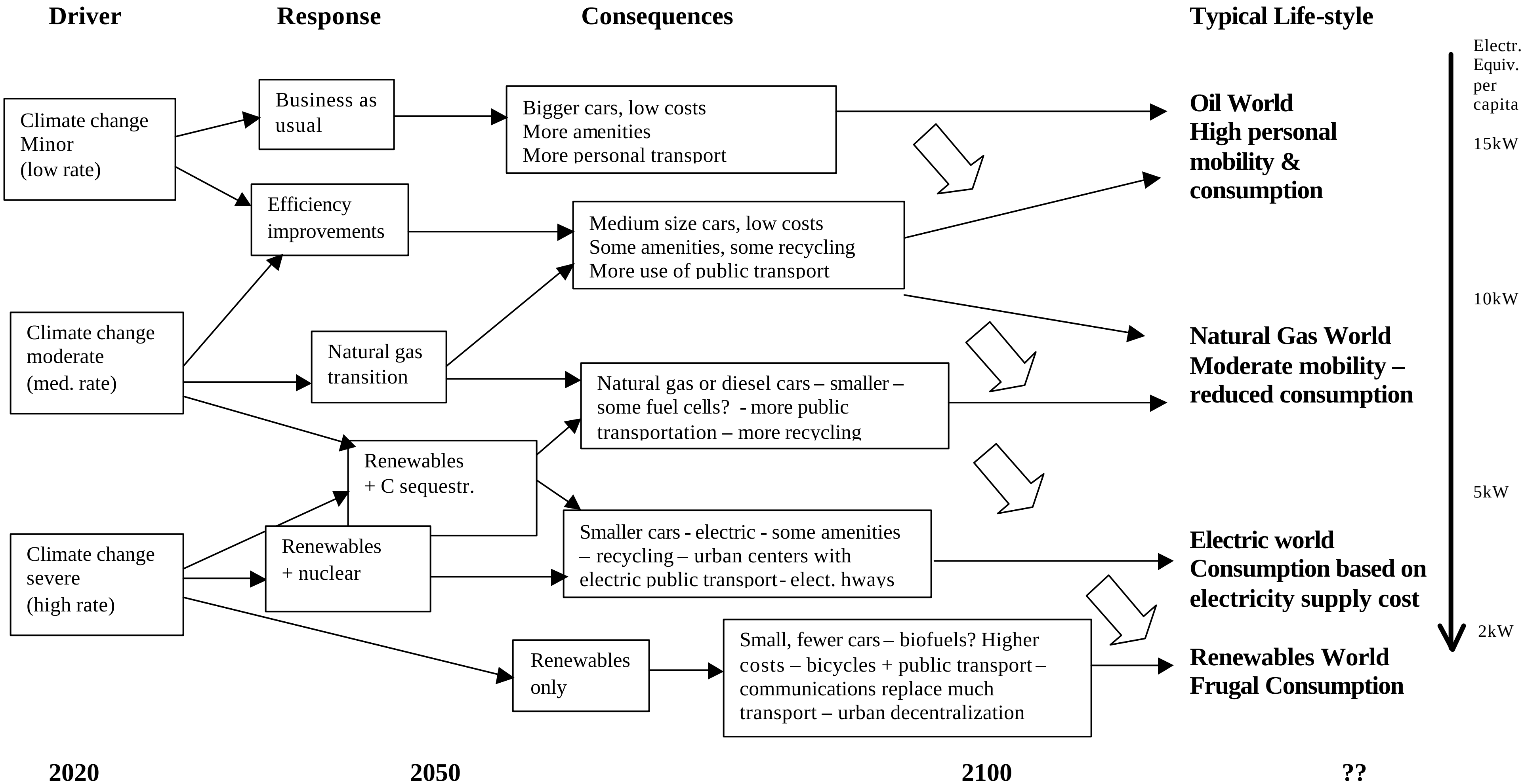
Figure 5.4 examines some of the possibilities and their implications for the future. Over the next century, there will be technological and environmental surprises that will modify this picture. However, it is important to start thinking about the possibilities and challenges ahead and their implications for the future of transportation as we know it today. In the next phase of this project, we hope to expand our understanding of frameworks and options for the future.

5.7 Conclusions

The results of this study depend importantly on the methodologies and assumptions we chose. The following broad conclusions apply to specific combinations of technology as used in mid-size passenger cars operated over traditional urban/highway driving cycles. All our quantitative results are subject to the uncertainties expected in projecting 20 years into the future, and those uncertainties are larger for rapidly developing technologies like fuel cells and new batteries.

- A valid comparison of future technologies for passenger cars must be based on life cycle analysis for the total system, which includes assessment of fuel and vehicle manufacture and distribution in addition to assessment of vehicle performance on the road.

Figure 5.4 Decision Options for a Sustainable Mobility Future: Some Preliminary Thoughts



Notes: **1.Time line for action shortens with faster climate change** **2. New environmental or social issues (e.g., depletion, social equity) can cause down shift**
3. New technology can cause new options – changes up or down in consumption? **4. Equity for developing countries increases rate of change**
4. Ultimate zero emissions transport fuels seem to be electricity or hydrogen. Making hydrogen from emission free electricity involves some energy loss; only justified if hydrogen storage system energy density gets to be substantially better than battery storage energy density.

- Successful development and penetration of new technologies requires acceptance by all major stakeholder groups: private-sector fuel and vehicle suppliers, government bodies at many levels, and ultimate customers for the products and services. Therefore, the economic, environmental, and other characteristics of each technology must be assessed for their potential impacts on each of the stakeholder groups.

- Continued evolution of the traditional gasoline car technology could result in 2020 vehicles that reduce energy consumption and GHG emissions by about one third from comparable current vehicles and at a roughly 5% increase in car cost. This evolved "baseline" vehicle system is the one against which new 2020 technologies should be compared.

- More advanced technologies for propulsion systems and other vehicle components could yield additional reductions in life cycle GHG emissions (up to about 50% lower than the evolved baseline vehicle) at increased vehicle purchase and use costs (up to about 20% greater than the evolved baseline vehicle).

- Vehicles with hybrid propulsion systems using either ICE or fuel cell power plants are the most efficient and lowest-emitting technologies assessed. In general, ICE hybrids appear to have advantages over fuel cell hybrids with respect to life cycle GHG emissions, energy efficiency, and vehicle cost, but the differences are within the uncertainties of our results and depend on the source of fuel energy.

- If automobile systems with drastically lower GHG emissions are required in the very long run future (perhaps in 30 to 50 years or more), hydrogen and electrical energy are the only identified options for "fuels", but only if both are produced from non-fossil sources of primary energy (such as nuclear or solar) or from fossil primary energy with carbon sequestration.

Again, these conclusions are based on individual average-vehicle calculations, with vehicle attributes held at today's levels. The expectations and choices of customers may change over the next twenty years and such changes can affect the extent to which potential reductions in GHG emissions are realized.

Chapter 5A: Appendices

5A.1 Detailed Stakeholder Templates

Note: Each has several pages – the first page shows a summary of whether the category is much better (++), better (+), the same (=), worse (-) or much worse (--) than the baseline mid-size sedan in 2020. Backup pages with a brief rationale for the rating follow. (Note: We added the CNG hybrid after this analysis was completed)

Table 5A-1 TEMPLATE: VEHICLE PURCHASER									
Vehicle Description: POWERTRAIN	SI	SI	CI	SI	CI	Fuel Cell	Fuel Cell	Fuel Cell	Batteries
FUEL	gasoline	gasoline	diesel	gasoline	diesel	methanol	gasoline	hydrogen	electricity
DRIVE	mechanical	mechanical	mechanical	hybrid	hybrid	electric	electric	electric	electric
BODY	evolution	advanced	advanced	advanced	advanced	advanced	advanced	advanced	advanced
1. Direct Financial Costs									
1.1 Purchase price of vehicle		– ?	–	– –	– –	– –	– –	– –	– –
1.2 Home fueling/charging facility		=	=	– ?	– ?	?	?	?	–
1.3 Vehicle financing		=	=	=	=	=	=	?	?
1.4 Insurance		=	=	=	=	–	–	–	–
1.5 Maintenance and repair		=	=	–	–	–	–	–	–
1.6 Fuel (excluding excise tax)		+	?	+	?	+	+	=	?
1.7 Scrappage requirements		=	=	–	–	–	–	–	– –
2. Environment, Safety, Health									
2.1 Vehicle collision safety		–	–	–	–	–	–	– – ?	–
2.2 Fuel safety/toxicity issues		=	=	=	=	–	=	–	–
2.3 Emission inspection requirements		=	=	=	=	=	=	+	+ +
3. Other									
3.1 Refueling ease: locations, duration, convenience		=	=	+	+	–	+	–	–
3.2 Vehicle road performance		=	=	=	=	=	=	=	–
3.3 Vehicle capacity (people, goods)		=	=	=	=	?	?	– ?	?
3.4 Vehicle reliability		=	=	–	–	?	?	?	=
3.5 Vehicle range		=	=	=	=	=	=	=	– –
3.6 Vehicle starting ease		=	=	=	=	?	?	?	+
3.7 Vehicle appearance and style		–	–	–	–	–	–	–	–
3.8 Maintenance and repair convenience		=	=	=	=	–	–	–	=

TEMPLATE: VEHICLE PURCHASER, cont'd.					
Vehicle Description:	**POWERTRAIN**	SI	CI	SI	CI
	FUEL	gasoline	diesel	gasoline	diesel
	DRIVE	mechanical	mechanical	hybrid	hybrid
	BODY	advanced	advanced	advanced	advanced
1. Direct Financial Costs					
1.1 Purchase price of vehicle					
1.2 Home fueling/charging facility		none	none	home charging, optional for hybrids	home charging, optional for hybrids
1.3 Vehicle financing		same	same	same	same
1.4 Insurance		same	same	same	same
1.5 Maintenance and repair		same	same	more complexity with hybrid drive	more complexity with hybrid drive
1.6 Fuel (excluding excise tax)					
1.7 Scrappage requirements		same	same	batteries	batteries
2. Environment, Safety, Health					
2.1 Vehicle collision safety		less mass	less mass	less mass	less mass
2.2 Fuel safety/toxicity issues		same	same	same	same
2.3 Emission inspection requirements		same	same	same	same
3. Other					
3.1 Refueling ease: locations, duration, convenience		same	same	duel power source, more efficient	duel power source, more efficient
3.2 Vehicle road performance		same	same	same	same
3.3 Vehicle capacity (people, goods)		same	same	same	same
3.4 Vehicle reliability		same	same	additional complexity	additional complexity
3.5 Vehicle range		same	same	same	same
3.6 Vehicle starting ease		same	same	same	same
3.7 Vehicle appearance and style		aerodynamic constraints	aerodynamic constraints	aerodynamic constraints	aerodynamic constraints
3.8 Maintenance and repair convenience		same	same	same	same

TEMPLATE: VEHICLE PURCHASER, cont'd.					
Vehicle Description:	**POWERTRAIN**	Fuel Cell	Fuel Cell	Fuel Cell	Batteries
	FUEL	methanol	gasoline	hydrogen	electricity
	DRIVE	electric	electric	electric	electric
	BODY	advanced	advanced	advanced	advanced
1. Direct Financial Costs					
1.1 Purchase price of vehicle					
1.2 Home fueling/charging facility		optional recharge at home?	optional recharge at home?	optional recharge at home?	home charging is only fueling option
1.3 Vehicle financing		same	same	is hydrogen an issue?	resale value? limited battery life-cycle
1.4 Insurance		is reformer an issue?	is reformer an issue?	is hydrogen an issue?	?
1.5 Maintenance and repair		less complex, but new technology	less complex, but new technology	less complex, but new technology	less complex, but limited battery life
1.6 Fuel (excluding excise tax)					
1.7 Scrappage requirements		battery, fuel cells	battery, fuel cells	battery, fuel cells	lots of batteries
2. Environment, Safety, Health					
2.1 Vehicle collision safety		less mass, heated reformers	less mass, heated reformers	less mass, hydrogen containment	less mass; battery leakage
2.2 Fuel safety/toxicity issues		methanol transfer/leakage	same	hydrogen transfer	battery dependent, electric shock
2.3 Emission inspection requirements		same or less frequent	same	minimal tailpipe emissions	zero tailpipe emissions
3. Other					
3.1 Refueling ease: locations, duration, convenience		methanol has lower energy content	more efficient	hydrogen transfer	long recharging time
3.2 Vehicle road performance		same	same	same	compromised power for range
3.3 Vehicle capacity (people, goods)		reformer, battery, fuel cell size	reformer, battery, fuel cell size	hydrogen storage, battery, fuel cell	battery/motor size dependent
3.4 Vehicle reliability		unknown	unknown	unknown	electric drive reliable
3.5 Vehicle range		same	same	same	reduced range from battery limits
3.6 Vehicle starting ease		unknown	unknown	unknown	no start up necessary
3.7 Vehicle appearance and style		aerodynamic constraints	aerodynamic constraints	aerodynamic constraints	aerodynamic constraints
3.8 Maintenance and repair convenience		less complex, but new technology	less complex, but new technology	less complex, but new technology	little maintenance except battery life

Table 5A-2 TEMPLATE: GOVERNMENT										
Vehicle Description:	**POWERTRAIN**	SI	SI	CI	SI	CI	Fuel Cell	Fuel Cell	Fuel Cell	Batteries
	FUEL	gasoline	gasoline	diesel	gasoline	diesel	methanol	gasoline	hydrogen	electricity
	DRIVE	mechanical	mechanical	mechanical	hybrid	hybrid	electric	electric	electric	electric
	BODY	evolution	advanced	advanced	advanced	advanced	advanced	advanced	advanced	advanced
1. Direct Financial Costs										
1.1 Federal R&D costs			–	–	–	–	–	–	– –	– –
1.2 Incentive/subsidy programs			–	=	–	–	–	–	– –	– –
1.3 Costs/revenues from taxes/fines/fees/license			–	=	–	–	–	–	–	– –
1.4 Legal suit costs			=	=	=	=	=	=	=/–	=
1.5 Cost of emission and safety monitoring/inspection			=	–	=	–	–	=	–	+
1.6 Costs/credits for future GHG quotas			+	+	+	+	+	+	+	?
2. Environment, Safety, Health										
2.1 Standard setting and regulatory demands			=	=	=	=	–	–	– –	–
2.2 Local/regional emission and health impacts			+	–	+	–	+	+	+ +	+ +
2.3 National GHG emissions			+	+	+	+	+	+	+	?
2.4 Waste disposal			=/ –	=/ –	=/ –	=/ –	–	–	–	– –
2.5 Transportation safety			–	–	–	–	–	–	– –	–
3. Other										
3.1 International credibility and leadership			=	–	=	–	+	=/ +	+	?
3.2 Political and legal pressures from special interest groups			=	–	=	–	+	=/ +	+	+
3.3 Infrastructure changes to accommodate new technologies			=	=	=	=	–	=	– –	=

TEMPLATE: GOVERNMENT, cont'd.					
Vehicle Description:	**POWERTRAIN**	SI	CI	SI	CI
	FUEL	gasoline	diesel	gasoline	diesel
	DRIVE	mechanical	mechanical	hybrid	hybrid
	BODY	advanced	advanced	advanced	advanced
1. Direct Financial Costs					
1.1 Federal R&D costs		need R&D push	need R&D push	need R&D push	need R&D push
1.2 Incentive/subsidy programs		higher costs	higher costs	higher costs	higher costs
1.3 Costs/revenues from taxes/fines/fees/license		higher costs	higher costs	higher costs	higher costs
1.4 Legal suit costs		no change	no change	no change	no change
1.5 Cost of emission and safety monitoring/inspection		no change	more sophisticated particulate sampling	no change	particulate monitoring
1.6 Costs/credits for future GHG quotas		minimum action	efficiency	efficiency	efficiency
2. Environment, Safety, Health					
2.1 Standard setting and regulatory demands		no change	no change	no change	no change
2.2 Local/regional emission and health impacts		efficiency lowers emissions	particulates?	efficiency	particulates ?
2.3 National GHG emissions		efficiency lowers emissions	efficiency	efficiency	efficiency
2.4 Waste disposal		less mass, more complex/less recyclable	less mass, more complex/less recyclable	less mass, more complex/less recyclable	less mass, more complex/less recyclable
2.5 Transportation safety		lighter weight	lighter weight	lighter weight	lighter weight
3. Other					
3.1 International credibility and leadership		minimum action	seen as inaction	minimum action	seen as inaction
3.2 Political and legal pressures from special interest groups		minimum action	seen as inaction	minimum action	seen as inaction
3.3 Infrastructure changes to accommodate new technologies		no change	no change	same	no change

TEMPLATE: GOVERNMENT, cont'd					
Vehicle Description:	**POWERTRAIN**	Fuel Cell	Fuel Cell	Fuel Cell	Batteries
	FUEL	methanol	gasoline	hydrogen	electricity
	DRIVE	electric	electric	electric	electric
	BODY	advanced	advanced	advanced	advanced
1. Direct Financial Costs					
1.1 Federal R&D costs		some R&D	some R&D	major R&D/H2 stor.	major R&D
1.2 Incentive/subsidy programs		some higher cost	some higher cost	much higher cost	much higher cost
1.3 Costs/revenues from taxes/fines/fees/license		some higher cost	some higher cost	higher cost	much higher cost
1.4 Legal suit costs		no change ?	no change ?	H2? No change?	no change ?
1.5 Cost of emission and safety monitoring/inspection		methanol monitoring?	reformer ?	new systems -H2 leakage	minimum monitoring for car
1.6 Costs/credits for future GHG quotas		minor efficiency improvement	efficiency	efficiency and fuel source	electric source ?
2. Environment, Safety, Health					
2.1 Standard setting and regulatory demands		new regulations to be developed	new regulations to be developed	new regulations to be developed	new regulations to be developed
2.2 Local/regional emission and health impacts		reformer performance/ efficiency?	reformer performance/ efficiency?	clean automobiles in urban areas	clean automobiles in urban areas
2.3 National GHG emissions		CH4 source	efficiency	CH4 fuel source?	electric source?
2.4 Waste disposal		methanol spills? also, recyclability	no change	?	less mass, more complex/less recyclable; also battery disposal
2.5 Transportation safety		lighter weight	lighter weight	light weight and H2	lighter weight
3. Other					
3.1 International credibility and leadership		proactive	minimum action	proactive	Depends on electric source
3.2 Political and legal pressures from special interest groups		proactive	minimum action	proactive	politically correct
3.3 Infrastructure changes to accommodate new technologies		shift to gas/methanol	fuel same; vehicle different	shift to gas/new infrastructure	electricity infrastructure

Notes: Baseline is taken as the first column – an evolutionary body with a mechanical drive and gasoline ICE. All other cases have lightweight body, which helps efficiency and degrades safety. Federal R&D cost differences represent small portions of the total government budget

Items 1.2 and 1.3 are linked – if subsidies are needed, it is unlikely that revenues can be generated for the government

Assume that by 2020, the market penetration is about 10%, so existing electric and gas infrastructures can handle shifted load.

Development of new regulations is not a major issue as this is an ongoing process anyway

For electric cars, the present electric mix contains a large fossil fuel component – have not yet calculated the net emissions relative to the baseline

Table 5A-3 TEMPLATE: VEHICLE MANUFACTURER										
Vehicle Description:	**POWERTRAIN**	SI	SI	CI	SI	CI	Fuel Cell	Fuel Cell	Fuel Cell	Batteries
	FUEL	gasoline	gasoline	diesel	gasoline	diesel	methanol	gasoline	hydrogen	electricity
	DRIVE	mechanical	mechanical	mechanical	hybrid	hybrid	electric	electric	electric	electric
	BODY	evolution	advanced	advanced	advanced	advanced	advanced	advanced	advanced	advanced
1. Direct Financial Costs										
1.1 Manufacturing plant (incl. parts) and equipment investment			=	–	– –	– –	?	?	?	?
1.2 Rate of return on new investment			?	?	?	?	?	?	?	?
1.3 Cost of raw materials, utilities			–	–	–	–	– ?	– ?	– ?	– ?
1.4 Labor and other direct personnel costs			=	=	–	–	+	+	+	+
1.5 New R&D costs			–	–	–	–	– –	– –	– –	– –
1.6 New marketing and advertising			=	=	=	=	=	=	=	=
1.7 Training			=	=	–	–	–	–	–	–
1.8 Warranty costs			=	=	–	–	– –	– –	– –	– –
2. Environment, Safety, Health										
2.1 Employee exposure to new materials and unfamiliar safety issues			=	=	=	=	–	=	–	–
2.2 Raw material production emissions			–	–	–	–	– – ?	– – ?	– – ?	– – ?
2.3 Manufacturing plant emissions			=	=	=	=	+	+	+	?
2.4 Conformance to vehicle emission requirements, incl. potential GHG			=	–	+	–	+ +	+ +	+ +	+ +
3. Other										
3.1 Need for new personnel skills			=	=	–	–	–	–	–	–
3.2 Relationship among vehicle and parts manufacturers and materials suppliers			=	=	–	–	–	–	–	–
3.3 Potential responsibility for scrapped vehicles										
3.4 Public image			+	+	+	+	+ +	+ +	+ +	+ +
3.5 Availability of scarce materials			=	=	=	=	?	?	?	=

TEMPLATE: VEHICLE MANUFACTURER, ct'd.					
Vehicle Description:	**POWERTRAIN**	SI	CI	SI	CI
	FUEL	gasoline	diesel	gasoline	diesel
	DRIVE	mechanical	mechanical	hybrid	hybrid
	BODY	advanced	advanced	advanced	advanced
1. Direct Financial Costs					
1.1 Manufacturing plant (incl. parts) and equipment investment		Large volumes: prod. process only slightly slower comp. to St. Small volumes: ASF requires less investment	In addition to shift St-Al: more expens. injection system and more engine material	In addition to shift St-Al: investments associated with electric motor, control electronics, and energy storage	In addition to shift St-Al: investments associated with elec. motor, control electronics, energy storage, injection system, and engine material
1.2 Rate of return on new investment					
1.3 Cost of raw materials, utilities		Al more expensive than St	Al more expensive than St	Al more expensive than St	Al more expensive than St
1.4 Labor and other direct personnel costs		Minor change	Minor change	More parts	More parts
1.5 New R&D costs		Somewhat more development for Al-body	Somewhat more development for Al-body	Somewhat more development for Al-body	Somewhat more development for Al-body
1.6 New marketing and advertising		Different, but not more marketing	Different, but not more marketing	Different, but not more marketing	Different, but not more marketing
1.7 Training		Minor change	Minor change	New drive train	New drive train
1.8 Warranty costs		No major change	No major change	Larger risk since new drive train	Larger risk since new drive train
2. Environment, Safety, Health					
2.1 Employee exposure to new matls and safety issues		None	None	None	None
2.2 Raw material production emissions		higher energy intensity: Al production ca. 50 GJ(el) per ton, St ca.14 GJ(coal) per ton; also: aluminum production releases PFCs with a GWP of several 1000 times larger than CO_2	higher energy intensity: Al production ca. 50 GJ(el) per ton, St ca.14 GJ(coal) per ton; also: aluminum production releases PFCs with a GWP of several 1000 times larger than CO_2	higher energy intensity: Al production ca. 50 GJ(el) per ton, St ca.14 GJ(coal) per ton; also: aluminum production releases PFCs with a GWP of several 1000 times larger than CO_2	higher energy intensity: Al production ca. 50 GJ(el) per ton, St ca.14 GJ(coal) per ton; also: aluminum production releases PFCs with a GWP of several 1000 times larger than CO_2
2.3 Manufacturing plant emissions		No change	No change	No change	No change
2.4 Conformance to vehicle emission requirements, incl. potential GHG		Slightly better opportunity for emission reduction due to light weight	Slightly better opportunity for emission reduction due to light weight, NOx and Part. more difficult to reduce	Slightly better opportunity for emission reduction due to light weight and more continuous engine operation	Slightly better opportunity for emission reduction due to light weight and more continuous engine operation. NOx? Part?
3. Other					
3.1 Need for new personnel skills		Minor change	Minor change	New drive train needs new skills	New drive train needs new skills
3.2 Relationship among vehicle and parts manufacturers and materials suppliers		New suppliers, more opportunities since global Al market, but perhaps capacity constraints	New suppliers, more opportunities since global Al market, but perhaps capacity constraints	Radically new suppliers are inherently a cost	Radically new suppliers are inherently a cost
3.3 Potential responsibility for scrapped vehicles		?	?	?	?
3.4 Public image		High-tech image	High-tech image	High-tech image	High-tech image
3.5 Availability of scarce materials		No problem	No problem	No problem	No problem

TEMPLATE: VEHICLE MANUFACTURER, ct'd.					
Vehicle Description:	**POWERTRAIN**	Fuel Cell	Fuel Cell	Fuel Cell	Batteries
	FUEL	methanol	gasoline	hydrogen	electricity
	DRIVE	electric	electric	electric	electric
	BODY	advanced	advanced	advanced	advanced
1. Direct Financial Costs					
1.1 Manufacturing plant (incl. parts) and equipment investment		In addition to shift St-Al: no ICE production plant but additional investments associated with FC and reformer, future FC costs uncertain	In addition to shift St-Al: no ICE production plant but additional investments associated with FC and reformer, future FC costs uncertain	In addition to shift St-Al: no ICE production plant but additional investments associated with FC, more expensive fuel tank; future FC costs uncertain	In addition to shift St-Al: no ICE production plant but additional investments associated with electric motor, battery, control electronics, uncertain costs
1.2 Rate of return on new investment					
1.3 Cost of raw materials, utilities		Al more expensive than St; amount and price of Pt. un-certain for FC	Al more expensive than St; amount and price of Pt. un-certain for FC	Al more expensive than St; amount and price of Pt. un-certain for FC	Al more expensive than St; future battery costs uncertain
1.4 Labor and other direct personnel costs		No labor-intensive engine plant	No labor-intensive engine plant	No labor-intensive engine plant	No labor-intensive engine plant
1.5 New R&D costs		Somewhat more development for Al-body; R&D for FC system, incl. reformer	Somewhat more development for Al-body; R&D for FC system, incl. reformer	Somewhat more development for Al-body; R&D for FC system	Somewhat more development for Al-body; R&D for battery
1.6 New marketing and advertising		Different but not more marketing	Different but not more marketing	Different but not more marketing	Different but not more marketing
1.7 Training		New power train	New drive train	New power train	New power train
1.8 Warranty costs		Larger risk since new powertrain	Larger risk since new drive train	Larger risk since new powertrain	Larger risk since new powertrain
2. Environment, Safety, Health					
2.1 Employee exposure to new matls and safety issues		Methanol fuel toxic	None	Hydrogen fuel explosive	Battery hazardous materials
2.2 Raw material production emissions		higher energy intensity: Al production ca. 50 GJ(el) per ton, St ca.14 GJ(coal) per ton; also: aluminum production releases PFCs with a GWP of several 1000 times more than CO_2; emiss. due to FC production?	higher energy intensity: Al production ca. 50 GJ(el) per ton, St ca.14 GJ(coal) per ton; also: aluminum production releases PFCs with a GWP of several 1000 times larger than CO_2; emiss. due to FC production?	higher energy intensity: Al production ca. 50 GJ(el) per ton, St ca.14 GJ(coal) per ton; also: aluminum production releases PFCs with a GWP of several 1000 times larger than CO_2; emiss. due to FC production?	higher energy intensity: Al production ca. 50 GJ(el) per ton, St ca.14 GJ(coal) per ton; also: aluminum production releases PFCs with a GWP of several 1000 times larger than CO_2; emiss. depend on battery type
2.3 Manufacturing plant emissions		Rather less control required, since no engine production	Rather less control required, since no engine production	Rather less control required, since no engine production	Rather less control required, since no engine production; but also battery dependent
2.4 Conformance to vehicle emission requirements, incl. potential GHG		Virtually zero tailpipe emission vehicle	Virtually zero tailpipe emission vehicle	Virtually zero tailpipe emission vehicle	Zero tailpipe emission vehicle
OTHER					
3.1 Need for new personnel skills		New power train, new skills	New drive train, new skills	New power train, new skills	New power train, new skills
3.2 Relationship among vehicle and parts manufacturers and materials suppliers		Radically new suppliers are inherently a cost	Radically new suppliers are inherently a cost	Radically new suppliers are inherently a cost	Radically new suppliers are inherently a cost
3.3 Potential responsibility for scrapped vehicles		?	?	?	?
3.4 Public image		Even stronger high-tech image	Even stronger high-tech image	Even stronger high-tech image	Even stronger high-tech image
3.5 Availability of scarce materials		depending on Pt requirements	depending on Pt requirements	depending on Pt requirements	No problem

Table 5A – 4.TEMPLATE: VEHICLE DISTRIBUTOR										
Vehicle Description:	**POWERTRAIN**	SI	SI	CI	SI	CI	Fuel Cell	Fuel Cell	Fuel Cell	Batteries
	FUEL	gasoline	gasoline	diesel	gasoline	diesel	methanol	gasoline	hydrogen	electricity
	DRIVE	mechanical	mechanical	mechanical	hybrid	hybrid	electric	electric	electric	electric
	BODY	evolution	advanced	advanced	advanced	advanced	advanced	advanced	advanced	advanced
1. Direct Financial Costs										
1.1 Vehicle cost to dealer			–	–	– –	– –	?	?	?	– –
1.2 Investment in new facilities including maintenance and repair			=	=	=	=	–	–	–	=
1.3 Parts inventory costs			=	=	–	–	–	–	–	–
1.4 Rate of return on investments including investors			=	=	=	=	–	–	–	–
1.5 Vehicle preparation and delivery costs			=	=	=	=	=	=	=	=
1.6 Labor costs and training, incl. sales and personnel			=	=	–	–	–	–	–	–
1.7 Insurance			–	–	– –	– –	?	?	?	– –
1.8 Warranty costs born by distributor			=	=	?	?	?	?	?	?
2. Environment, Safety, Health										
2.1 Hazards during servicing and repair			=	=	=	=	=	=	–	=
2.2 Service emissions and wastes			=	=	=	=	=	=	=	– ?
3. Other										
3.1 Availability of skilled labor			=	=	–	–	–	–	–	–
3.2 Compatibility with existing facilities			=	=	=	=	–	–	–	–
3.3 Issues of purchase and resale of used vehicles, e.g. rapid obsolescence			=	=	=	=	?	?	?	?

TEMPLATE: VEHICLE DISTRIBUTOR, cont'd.					
Vehicle Description:	**POWERTRAIN**	SI	CI	SI	CI
	FUEL	gasoline	diesel	gasoline	diesel
	DRIVE	mechanical	mechanical	hybrid	hybrid
	BODY	advanced	advanced	advanced	advanced
1. Direct Financial Costs					
1.1 Vehicle cost to dealer		somewhat higher due to Al. body	somewhat higher mainly due to Al. body	significantly higher due to Al. body and drive train	significantly higher due to Al. body and drive train
1.2 Investment in new facilities including maintenance and repair		Negligible	Negligible	Negligible	Negligible
1.3 Parts inventory costs		Negligible	Negligible	More parts in addition to ICE vehicles	More parts in addition to ICE vehicles
1.4 Rate of return on investments including investors		Comparatively small risk	Comparatively small risk	Comparatively small risk	Comparatively small risk
1.5 Vehicle preparation and delivery costs		No change	No change	No change	No change
1.6 Labor costs and training, incl. sales and personnel		No change	No change	New drive train	New drive train
1.7 Insurance		such as 1.1	such as 1.1	such as 1.1	such as 1.1
1.8 Warranty costs born by distributor		No change	No change	?	?
2. Environment, Safety, Health					
2.1 Hazards during servicing and repair		No change	No change	No change	No change
2.2 Service emissions and wastes		No change	No change	No change	No change
3. Other					
3.1 Availability of skilled labor		No change	No change	Some more training required	Some more training required
3.2 Compatibility with existing facilities		Practically no change	Practically no change	Practically no change	Practically no change
3.3 Issues of purchase and resale of used vehicles, e.g. rapid obsolescence		No major change in vehicle	No major change in vehicle	No major change in vehicle	No major change in vehicle

TEMPLATE: VEHICLE DISTRIBUTOR, cont'd.					
Vehicle Description:	**POWERTRAIN**	Fuel Cell	Fuel Cell	Fuel Cell	Batteries
	FUEL	methanol	gasoline	hydrogen	electricity
	DRIVE	electric	electric	electric	electric
	BODY	advanced	advanced	advanced	advanced
1. Direct Financial Costs					
1.1 Vehicle cost to dealer		FC costs uncertain	FC costs uncertain	FC costs uncertain	significantly higher due to Al. body and power train
1.2 Investment in new facilities including maintenance and repair		New facilities for FC system	New facilities for FC system	New facilities for FC system	Negligible
1.3 Parts inventory costs		More parts in addition to ICE vehicles	More parts in addition to ICE vehicles	More parts in addition to ICE vehicles	More parts in addition to ICE vehicles
1.4 Rate of return on investments including investors		Higher risk since new technology	Higher risk since new technology	Higher risk since new technology	Higher risk since new technology
1.5 Vehicle preparation and delivery costs		No change	No change	No change	No change
1.6 Labor costs and training, incl. sales and personnel		New power train	New drive train	New power train	New power train
1.7 Insurance		such as 1.1	such as 1.1	such as 1.1	such as 1.1
1.8 Warranty costs born by distributor		?	?	?	?
2. Environment, Safety, Health					
2.1 Hazards during servicing and repair		No change	No change	Need for extra safety measures for hydrogen fuel	No change
2.2 Service emissions and wastes		No change	No change	No change	Battery likely toxic
3. Other					
3.1 Availability of skilled labor		Some more training required	Some more training required	Some more training required	Some more training required
3.2 Compatibility with existing facilities		Some change due to FC system	Some change due to FC system	Some change due to FC system	Some change due to electric drive
3.3 Issues of purchase and resale of used vehicles, e.g. rapid obsolescence		?	?	?	?

Table 5A-5. TEMPLATE: FUEL MANUFACTURER									
Vehicle Description: POWERTRAIN	SI	SI	CI	SI	CI	Fuel Cell	Fuel Cell	Fuel Cell	Batteries
FUEL	gasoline	gasoline	diesel/F-T	gasoline	diesel/F-T	methanol	gasoline	hydrogen	electricity
DRIVE	mechanical	mechanical	mechanical	hybrid	hybrid	electric	electric	electric	electric
BODY	evolution	advanced	advanced	advanced	Advanced	advanced	advanced	advanced	advanced
1. Direct Financial Costs									
1.1 Manufacturing plant investment including offsites		**=**	**–/ – –**	**=**	**–/ – –**	**– –**	**=**	**– –**	**=**
1.2 Feedstock investment and/or transportation investment for delivery to plant		**=**	**=/ –**	**=**	**=/ –**	**=**	**=**	**?**	**= ?**
1.3 Interest/Rate of return on investment		**=**	**=/ –**	**=**	**=/ –**	**–**	**=**	**–**	**=**
1.4 Operating costs, including labor		**=**	**+/ ?**	**=**	**+/ ?**	**?**	**=**	**–**	**=**
1.5 Overhead including insurance rent, taxes		**=**	**=/ ?**	**=**	**=/ ?**	**?**	**=**	**?**	**?**
1.6 Purchased feedstock		**=**	**=/ + +**	**=**	**=/ + +**	**+ +**	**=**	**?**	**+**
1.7 Overhead, materials and services		**=**	**=/ ?**	**=**	**=/ ?**	**?**	**=**	**?**	**=**
1.8 New R&D costs		**=**	**=/ –**	**=**	**=/ –**	**–**	**=**	**–**	**=**
2. Environment, Safety, Health									
2.1 Extraction, manufacturing GHG emissions, including leaks		**=**	**=/ – –**	**=**	**=/ – –**	**– –**	**=**	**– –**	**– –**
2.2 Other air emissions		**=**	**+/ ?**	**=**	**+/ ?**	**– ?**	**=**	**=**	**– –**
2.3 Liquid emissions		**=**	**=/ =**	**=**	**=/ =**	**=**	**=**	**?**	**–**
2.4 Solid Wastes		**=**	**=/ =**	**=**	**=/ =**	**=**	**=**	**?**	**–**
2.5 Safety and toxicity of new fuels/feedstocks		**=**	**=/ =**	**=**	**=/ =**	**–**	**=**	**–**	**=**
3. Other									
3.1 Need for new personnel skills		**=**	**=/ –**	**=**	**=/ –**	**–**	**=**	**–**	**=**
3.2 Certainty of demand		**=**	**=/ =**	**=**	**=/ =**	**– –**	**=**	**– –**	**=**
3.3 Compatibility with existing infrastructure		**=**	**=/ =**	**=**	**=/ =**	**–**	**=**	**– –**	**=**
3.4 Setting and maintaining product specifications		**=**	**=/ =**	**=**	**=/ =**	**–**	**–**	**?**	**=**

Notes: "diesel / F-T" represents diesel from petroleum on the left of the slash and Fischer-Tropsch diesel on the right of the slash.
The distinction between these two types of diesel represents itself only on the Fuel Manufacturers part of the template.

TEMPLATE: FUEL MANUFACTURER, cont'd.				
Vehicle Description: POWERTRAIN	SI	CI	SI	CI
FUEL	gasoline	diesel/F-T	gasoline	diesel/F-T
DRIVE	mechanical	mechanical	hybrid	hybrid
BODY	advanced	advanced	advanced	advanced
1. Direct Financial Costs				
1.1 Manufacturing plant investment including offsites	No major change	Conversion of gasoline refineries to increased diesel production slightly costly, F-T manufacture expensive	No major change	Conversion of gasoline refineries to increased diesel production slightly costly, F-T manufacture expensive
1.2 Feedstock investment and/or transportation investment for delivery to plant	No major change	No major change for petroleum, but gas preparation investment necessary for F-T	No major change	No major change for petroleum, but gas preparation investment necessary for F-T
1.3 Interest/Rate of return on investment	No major change	No major change for petroleum, but F-T plant would involve more risk and higher ROI	No major change	No major change for petroleum, but F-T plant would involve more risk and higher ROI
1.4 Operating costs, including labor	No major change	Petroleum refining costs less, but F-T refinery costs unclear	No major change	Petroleum refining costs less, but F-T refinery costs unclear
1.5 Overhead including insurance rent, taxes	No major change	No major change for petr. diesel	No major change	No major change for petr. diesel
1.6 Purchased feedstock	No major change	No major change for petroleum diesel, but remote natural gas for F-T is cheap	No major change	No major change for petroleum diesel, but remote natural gas for F-T is cheap
1.7 Overhead, materials and services	No major change	No major change for petroleum diesel	No major change	No major change for petroleum diesel
1.8 New R&D costs	No major change	No major change for petroleum diesel, but F-T would require R&D	No major change	No major change for petroleum diesel, but F-T would require R&D
2. Environment, Safety, Health				
2.1 Extraction, manufacturing GHG emissions, including leaks	No major change	No major change for diesel, but F-T CO2 emissions are higher	No major change	No major change for diesel, but F-T CO2 emissions are higher
2.2 Other air emissions	No major change	Petroleum diesel refining uses less energy and emits less; F-T balance uncertain	No major change	Petroleum diesel refining uses less energy and emits less; F-T balance uncertain
2.3 Liquid emissions	No major change	No major change	No major change	No major change
2.4 Solid Wastes	No major change	No major change	No major change	No major change
2.5 Safety and toxicity of new fuels/feedstocks	No major change	No major change or new issues	No major change	No major change or new issues
3. Other				
3.1 Need for new personnel skills	No major change	No major change for petroleum, but slight increase for F-T	No major change	No major change for petroleum, but slight increase for F-T
3.2 Certainty of demand	No major change	No major change	No major change	No major change
3.3 Compatibility with existing infrastructure	No major change	No major change	No major change	No major change
3.4 Setting and maintaining product specifications	No major change	No major change	No major change	No major change

TEMPLATE: FUEL MANUFACTURER, cont'd					
Vehicle Description:	**POWERTRAIN**	Fuel Cell	Fuel Cell	Fuel Cell	Batteries
	FUEL	methanol	gasoline	hydrogen	electricity
	DRIVE	electric	electric	electric	electric
	BODY	advanced	advanced	advanced	advanced
1. Direct Financial Costs					
1.1 Manufacturing plant investment including offsites		Major investment for new methanol plants (from fossil)	No major change	Major investment required	No new generation capacity needed by 2020
1.2 Feedstock investment and/or transportation investment for delivery to plant		No major change	No major change	? May need new gas supply to stations	Incomplete penetration prevents significant change
1.3 Interest/Rate of return on investment		Higher risk in remote methanol plant	No major change	Higher risk would require higher ROI	Incomplete penetration prevents significant change
1.4 Operating costs, including labor		? Relative cost of methanol manufacturing	No major change	Increased costs for higher skills needed	Incomplete penetration prevents significant change
1.5 Overhead including insurance rent, taxes		? Might depend on relative rates of insurance and taxes.	No major change	?	Incomplete penetration prevents significant change
1.6 Purchased feedstock		Cost of gas feedstock lower than crude oil	No major change	?	Incomplete penetration prevents significant change
1.7 Overhead, materials and services		? Further R&D expected.	No major change	?	Incomplete penetration prevents significant change
1.8 New R&D costs		No major change	No major change	New H2 production technology would require some R&D	Incomplete penetration prevents significant change
2. Environment, Safety, Health					
2.1 Extraction, manufacturing GHG emissions, including leaks		Large increase in CO2 emissions; possible methane leakage.	No major change	Major increases in CO2 and possible methane leaks	Emissions from added power generation
2.2 Other air emissions		? No major change in NOx production, but expected increase in particulates from methanol production	No major change	More NOx but fewer particulates	Emissions from added power generation
2.3 Liquid emissions		No major change	No major change	?	Cooling water
2.4 Solid Wastes		No major change	No major change	?	Ash, scrubber wastes, spent fuel
2.5 Safety and toxicity of new fuels/feedstocks		Methanol is volatile and toxic relative to "base" gasoline or diesel.	No major change	Higher pressure H2 fuel presents increased safety risk	No major change
3. Other					
3.1 Need for new personnel skills		Some retraining required for major methanol refineries	No major change	Some new skills would be needed to handle new process	No major change
3.2 Certainty of demand		Higher uncertainty of demand	No major change	Demand highly uncertain	No major change
3.3 Compatibility with existing infrastructure		Some changes required for alternative methanol tanks at existing facilities.	No major change	High-pressure H2 very different from current liquid fuel setup	No major change
3.4 Setting and maintaining product specifications		Fuel cells more sensitive to fuel contaminants	Fuel cells more sensitive to fuel contaminants	?	No major change

Table 5A-6. TEMPLATE: FUEL DISTRIBUTOR									
Vehicle Description: POWERTRAIN	SI	SI	CI	SI	CI	Fuel Cell	Fuel Cell	Fuel Cell	Batteries
FUEL	gasoline	gasoline	diesel	gasoline	diesel	methanol	gasoline	hydrogen	electricity
DRIVE	mechanical	mechanical	mechanical	hybrid	hybrid	electric	electric	electric	electric
BODY	evolution	advanced	advanced	advanced	advanced	advanced	advanced	advanced	advanced
1. Direct Financial Costs									
1.1 Station, terminal, and truck/pipeline investments		=	=	=	=	–	=	– –	– –
1.2 Interest/Rate of return on investment		=	=	=	=	=	=	–	=
1.3 Labor		=	=	=	=	=	=	–	+
1.4 Overhead including insurance rent, taxes		=	=	=	=	=	=	–	+
1.5 Fuel cost (working capital)		=	+	=	+	=	=	+	+
2. Environment, Safety, Health									
2.1 Environmental: Evaporation and leaks during storage, transport, and disposing		=	=	=	=	–	=	– –	+
2.2 Local zoning and code compliance		=	=	=	=	?	=	–	?
2.3 Safety: Hazards in handling toxic, flammable, or high pressure fuels		=	=	=	=	?	=	–	=
3. Other									
3.1 Supply reliability		=	=	=	=	–	=	–	=
3.2 Special skill needs for refueling		=	=	=	=	=	=	–	–
3.3 Maintaining fuel quality		=	=	=	=	?	=	?	=
3.4 Fueling time and convenience		=	=	=	=	–	=	–	– –

TEMPLATE: FUEL DISTRIBUTOR, cont'd.					
Vehicle Description:	**POWERTRAIN**	SI	CI	SI	CI
	FUEL	gasoline	diesel	gasoline	diesel
	DRIVE	mechanical	mechanical	hybrid	hybrid
	BODY	advanced	advanced	advanced	advanced
1. Direct Financial Costs					
1.1 Station, terminal, and truck/pipeline investments		No major change	No major change	No major change	No major change
1.2 Interest/Rate of return on investment		No major change	No major change	No major change	No major change
1.3 Labor		No major change	No major change	No major change	No major change
1.4 Overhead including insurance rent, taxes		No major change	No major change	No major change	No major change
1.5 Fuel cost (working capital)		No major change	Diesel is about 20% cheaper than gasoline	No major change	Diesel is about 20% cheaper than gasoline
2. Environment, Safety, Health					
2.1 Environmental: Evaporation and leaks during storage, transport, and disposing		No major change	No major change	No major change	No major change
2.2 Local zoning and code compliance		No major change	No major change	No major change	No major change
2.3 Safety: Hazards in handling toxic, flammable, or high pressure fuels		No major change	No major change	No major change	No major change
3. Other					
3.1 Supply reliability		No major change	No major change	No major change	No major change
3.2 Special skill needs for refueling		No major change	No major change	No major change	No major change
3.3 Maintaining fuel quality		No major change	No major change	No major change	No major change
3.4 Fueling time and convenience		No major change	No major change	No major change	No major change

TEMPLATE: FUEL DISTRIBUTOR, cont'd.					
Vehicle Description:	**POWERTRAIN**	Fuel Cell	Fuel Cell	Fuel Cell	Batteries
	FUEL	methanol	gasoline	hydrogen	electricity
	DRIVE	electric	electric	electric	electric
	BODY	advanced	advanced	advanced	advanced
1. Direct Financial Costs					
1.1 Station, terminal, and truck/pipeline investments		Distribution and storage changes required to carry methanol	No major change	Station and gas pipeline costs could fall on manufacturer/distributor	Charging facilities required at home or elsewhere
1.2 Interest/Rate of return on investment		No major change	No major change	Higher risk would require higher ROI	No major change
1.3 Labor		No major change	No major change	More (skilled) labor at station, but no truck drivers	No service station or distributor labor
1.4 Overhead including insurance rent, taxes		No major change	No major change	Insurance probably higher	No costs
1.5 Fuel cost (working capital)		Negligible difference	No major change	Fuel storage minimal	No working capital
2. Environment, Safety, Health					
2.1 Environmental: Evaporation and leaks during storage, transport, and disposing		More toxic than gasoline	No major change	GHG and other emissions and leaks from reformer	No environmental impact of distribution
2.2 Local zoning and code compliance		?	No major change	Local problems are likely	
2.3 Safety: Hazards in handling toxic, flammable, or high pressure fuels		?	No major change	High pressure a problem, plus easy ignition of leaking gas	Possible hazards in recharging
3. Other					
3.1 Supply reliability		Fewer supply sources likely	No major change	Reliability of all station equipment uncertain	No major change
3.2 Special skill needs for refueling		No major change	No major change	Reformer and compressor equipment require skills	Some learning likely required
3.3 Maintaining fuel quality		?	No major change	?	No major change
3.4 Fueling time and convenience		Takes longer due to lower energy density of methanol	No major change	Self service not likely	Long charging times and perhaps limited locations for charging

5A.2 Some Web Sites for Further Information

Hybrid vehicle technology:	http://www.hybrid-cars.com/ http://www.hev.doe.gov/
Specific car models:	http://www.autoweb.com/
Hydrogen & FC Letter: US Dept. of Energy:	
Energy Information Agency	http://www.eia.doe.gov/
Transportation:	http://www.ott.doe.gov/technologies.shtml
Argonne NL	http://www.transportation.anl.gov/
NREL:	http://www.ctts.nrel.gov/programs.html
ORNL:	http://www.ntrc.com/
PNGV: Industry	http://www.uscar.org
Government	http://www.ta.doc.gov/pngv
International Energy Agency	http://www.iea.org/
US Environmental Protection Agency	http://www.epa.gov

References

ACEA (European Automobile Manufacturers Association). "CO2perate." <www.acea.be/eucarinternet/CO2perate.html>. December 15, 1999.

Affenzeller J., 1995, **personal communication**, AVL Graz, Austria in course of Ph.D. thesis: ***A. Schafer, 2000, Reduction of Greenhouse Gas Emissions in the Global Transportation Sector***, Institute for Energy Economics and Rationale Use of Energy, University of Stuttgart, German, 1995.

Agee, M.A**. Economic Gas to Liquids Technologies, A New Paradigm for the Energy Industry**. Montreux, Switzerland Energy Roundtable VII. May 13, 1997.

Allard, M. **" Issues Associated with Widespread Utilization of Methanol."** SAE Paper No. 2000-01-0005. In ***Fuel Cell Power for Transportation 2000 (SP-1505)***, Society of Automotive Engineers, Inc., Warrendale, PA, March 2000.

American Iron and Steel Institute. <http://www.autosteel.org>. 2000.

Anderman, M., F. R. Kalhammer, and D. MacArthur. ***Advanced Batteries for Electric Vehicles: An Assessment of Performance, Cost, and Availability.*** Draft manuscript prepared for State of California Air Resources Board, Sacramento, CA. June 22, 2000.

Arthur D. Little, Inc. ***Integrated Fuel Chain Analysis Model (IFCAM). User Instructions for Version 3.1 (filename IFCAMV31.xls***). Report to Ford Motor Company. February 27, 1996.

Atkins, P., H. J. Hittner, and D. Willoughby. **"Some Energy and Environmental Impacts of Aluminum Usage."** In J. Tester, D. Wood and N. Ferrari (eds.) *Energy and the Environment in the 21st Century, Proceedings of the Conference held at the Massachusetts Institute of Technology, Cambridge, MA, March 26-28, 1990,* pp. 383-387, 1990.

Automotive Engineering. **"Life Cycle Analysis: Getting the Total Picture on Vehicle Engineering Alternatives."** Pages 49-52, March 1996.

Automotive Engineering. **"Progress in Recycling Specific Materials from Automobiles."** Pages 51-53, August 1997.

Automotive Engineering. **"Recycling Processes and Products: A Quick Read."** Page 43, August 1995.

AuYeung, F. ***Future Light-Duty Vehicles: Predicting Their Fuel Consumption and Assessing Their Potential.*** MS thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts, June 2000.

AuYeung, F., J. B. Heywood, and A. Schafer. **"Future Light-Duty Vehicles: Predicting Their Fuel Consumption and Carbon-Reductions Potential."** SAE Paper to be published at Society of Automotive Engineers World Congress, Detroit, Michigan, March 2001.

Berlowitz, P., and C. Darnell. **"Fuel Choices for Fuel Cell Powered Vehicles."** SAE Paper No. 2000-01-0003. In ***Fuel Cell Power for Transportation 2000 (SP-1505)***, Society of Automotive Engineers, Inc., Warrendale, PA, March 2000.

Birch S. "**Tire Life.**" *Automotive Engineering*, No. 4/5, January 1996.

Casten, S., P. Teagan, and R. Stobart. **"Fuels for Fuel-Cell-Powered Vehicles."** SAE Paper No. 2000-01-0001. In ***Fuel Cell Power for Transportation 2000 (SP-1505)***, Society of Automotive Engineers, Inc., Warrendale, PA, March 2000.

Chon, D., and J. Heywood. "**Performance Scaling of Spark-Ignition Engines: Correlation and Historical Analysis of Production Engine Data."** SAE Paper 2000-01-0565, 2000.

Contadini, J. F., R. M. Moore, D. Sperling, and M. Sundaresan. "Life-Cycle Emissions of Alternative Fuels for Transportation: Dealing with Uncertainties." SAE Paper No. 2000-01-0597. In ***Environmental Concepts for the Automotive Industry (SP-1542),*** SAE 2000 World Congress, Detroit, MI, March 6-9, 2000.

DaimlerChrysler. **Environmental Report 200, Facts and Figures.** Stuttgart. 2000

Davis, B. H. (1999a**) "Indirect Coal Liquefaction—Where Do We Stand."** Presented before the Division of Petroleum Chemistry, Inc., at the Symposium on Syngas Conversion to Fuels and Chemicals, 217th National Meeting, American Chemical Society, Anaheim, CA, March 21-25, 1999.

Davis, S. C. ***Transportation Energy Data Book: Edition 19.*** Prepared by Oak Ridge National Laboratory, Center for Transportation Analysis, Energy Division for US DOE. ORNL-6958 (Edition 19 of ORNL-5198). September 1999. c. 325 pages.

DeLuchi, M. A. (1989a) **"Hydrogen Vehicles." Chapter 6 of *Alternative Transportation Fuels; An Environmental and Energy Solution*,** Daniel Sperling, ed. Quorum Books: Westport, Connecticut, 1989.

DeLuchi, M. A., Quanlu Wang, and Daniel Sperling. (1989b) **"Electric vehicles: performance, life-cycle costs, emissions, and recharging requirements."** *Transportation Research-A*, v. 23A, no. 3, 1989.

Dietrich, P., A. Amstutz, and A. Schafer. ***Low Greenhouse Gas Emission Automobiles--Technology and Costs.*** Discussion Paper 98-6-1. The Cooperative Mobility Program; Center for Technology, Policy and Industrial Development; MIT. June 1998. 49 pages

Dietrich, P., J. Heywood, A. Schafer, F. AuYeung. ***Low-Greenhouse Gas Emission Automobiles: Technology and Costs***. Manuscript in preparation, 2000.

Energy Information Administration, US DOE (1999a). ***Annual Energy Outlook 2000.*** DOE/EIA-0383(2000). December 1999.

Energy Information Administration, US DOE (1999b). ***Annual Energy Review 1998.*** DOE/EIA-0384(1998). July 1999.

Energy Information Administration, US DOE. ***Emissions of Greenhouse Gases in the United States 1996.*** DOE/EIA-0573(96). October 1997.

Environmental Protection Agency (1999). ***Carbon Dioxide Emissions from the Generation of Electric Power in the United States.*** <http://www.epa.gov/oppeoee1/globalwarming/ publications/emissions/CO2emiss.pdf>. 1999.

Foster Wheeler Corp. **"Foster Wheeler Starchem Methanol Process."** <www.fwc.com/publications/tech_papers>. August 1999.

Friedman, D. J. **"Maximising Direct-Hydrogen PEM Fuel Cell Vehicle Efficiency—Is Hybridization Necessary?"** SAE Paper No. 1999-01-0539. Society of Automotive Engineers. 1999.

General Motors Corporation**.** **"GM EVI-Specifications." <**www.gm.com> . 2000.

Guzzella, L., and A. Amstutz. **"Quasi-Stationaren-Simulations."** Matlab programs and text Benutzeranleitung, Laboratorium fur Motorsysteme, Institute fur Energietechnik, ETH-Zurich, 1998.

Hansen, R., and O. Olsvik. **"Norwegian methanol plant outlines operations, expansion plans**." *Oil & Gas Journal*, p. 46, Feb. 7, 2000.

Hoehlein, B., et al. ***Brennstoffzelen-Studie (Fuel Cell Studies): Ganzheitliche Systemuntersuchung zur Energiewandlung durch Brennstoffzellen.*** Forschungsvereinigung Verbrennungskraftmaschinen e.V., Frankfurt am Main, 1998.

IEA (International Energy Agency). **"Monthly Price Statistics." <**www.iea.org/stat.html> March 2000.

IEA (International Energy Agency). ***Automotive Fuels for the Future: The Search for Alternatives*****.** IEA-AFIS, Paris. August 1999. 92 pages. ISBN: 92-64-16960-1.

International Iron and Steel Institute and United Nations Environment Program. ***Steel Industry and the Environment: Technical and Management Issues.*** Technical Report No. 38, 1997.

International Petroleum Encyclopedia (IPE). **"Gas-to-liquids technology breakthroughs: Is overhaul of energy equation at hand?"** Penn Well, 1998.

Joshi, S., L. Lave, H. Maclean, and R. Lankey. ***A Life Cycle Comparison of Alternative Transportation Fuels.*** Society of Automotive Engineers paper. 2000.

Kalhammer, F. Personal communication. 2000.

Kalhammer, F. R., P. R. Prokopius, V. P. Roan, and G. E. Voecks. ***Status and Prospects of Fuel Cells as Automobile Engines, A Report of the Fuel Cell Technical Advisory Panel.*** Prepared for State of California Air Resources Board, Sacramento, CA. July 1998.

Kluger, M., and D. Long. **"An Overview of Current Automatic, Manual and Continuously Variable Transmission Efficiencies and their Projected Future Improvements."** SAE Paper 1999-01-1259, 1999.

Knott, D. **"Gas-to-liquids projects gaining momentum as process list grows."** *Oil and Gas Journal*, June 23, 1997.

Lange, J.-P. **"Perspectives for Manufacturing Methanol at Fuel Value."** *Industrial and Engineering Chemistry Research*, vol. 36, pp. 4282-4290, 1997.

Mathijs, M., G. Sendan, and D. Punt. **"Status and Prospects of Gas-to-Liquids Processes."** Presented before the Division of Petroleum Chemistry, Inc., at the Symposium on Syngas Conversion to Fuels and Chemicals, 217th National Meeting, American Chemical Society, Anaheim, CA, March 21-25, 1999. 3 pages.

MathPro Inc. ***Effects of 10 PPM Sulfur Standard for Gasoline and Diesel Fuel on CO_2 Emissions of the EU Refining Sector. Final Report (Revised).*** Prepared for Ford Motor Co., June 8, 2000.

Maclean, H. L., and L. B. Lave. **"A life-cycle model of an automobile."** *Environmental Science & Technology*, July 1, 1998, p. 322-330.

National Research Council, Standing Committee to Review the Research Program of the Partnership for a New Generation of Vehicles. ***Review of the Research Program of the Partnership for a New Generation of Vehicles***. Sixth Report. 2000.

Nimocks, R. M. **"Potential for GTL as a Gas-Conversion Alternative in Low-Oil-Price Environment."** Presented before the Division of Petroleum Chemistry, Inc., at the Symposium on Syngas Conversion to Fuels and Chemicals, 217th National Meeting, American Chemical Society, Anaheim, CA, March 21-25, 1999. 2 pages.

Ogden, J. M., T. G. Kreutz, and M. Steinbugler. ***Fuels for Fuel Cell Vehicles: Vehicle Design and Infrastructure Issues***. Report No. 982500. Presented at Society of Automotive Engineers International Fall Fuels and Lubricants Meeting and Exposition, San Francisco, California, October 19-22, 1998. 25 pages.

Ogden, J. M., M. M. Steinbugler, and T. G. Kreutz. **"A comparison of hydrogen, methanol and gasoline as fuels for fuel cell vehicles: implications for vehicle design and infrastructure development."** *Journal of Power Sources,* vol. 79, pp. 143-168, 1999.

Office of Technology Assessment. ***Advanced Automotive Technologies: Visions of a Super-Efficient Family Car.*** OTA-ETI-638. US Government Printing Office: Washington, DC. September 1995. 304 pages.

Renault. **Press Kit: MOSAIC Program**. Renault Presse, 34, Quai Du Point du Jour, 92019 Billancourt, France. 1995.

Röder, A. ***Life-Cycle Inventory of Different Car Powertrains—Final Report.*** Paul Scherrer Institute, Villigen, Switzerland, 2000.

Sathaye, J., B. Atkinson, and S. Meyers. ***Alternative Fuels Assessment: The International Experience***. LBL-24736. Lawrence Berkeley Laboratory, U. of California. March 1988.

Schweimer, G.W., and M. Schuckert. ***Life Cycle Analysis of a Golf***, Forschungsbericht Nr. K-EFVT 9604 V/5, Volkswagen Konzernforschung, 1996.

Sierra Research Inc. **"Automotive Fuel Economy Potential Using Cost-Effective Design Changes."** Unpublished. 1997.

Singh, et al. ***Total Energy Cycle Assessment of Electric and Conventional Vehicles: An Energy and Environmental Analysis***, Argonne National Laboratory, ANL/ES/RP—96387, 1998.

Singleton, A. H**. "Advances make gas-to-liquids process competitive for remote locations."** *Oil and Gas Journal*, p. 68, August 4, 1997.

Sinor, J.E. Consultants Inc**. "Mossgas and Syntroleum Economics Compared."** <http://edj.net/sinor/sfr1-98arti.html>, February 1999.

Stark, H. A. (ed.). ***Wards Automotive Yearbook.*** Detroit, MI. 1997.

Stodolsky F., A. Vyas, R. Cuenca, L Gaines. ***Life-Cycle Energy Savings Potential from Aluminum-Intensive Vehicles*** Transportation Technology R&D Center, Argonne National Laboratory, Argonne, IL, 1995.

Thomas, C. E., B. D. James, F. D. Lomax, and I. F. Kuhn (1998a). ***Fuel Options for the Fuel Cell Vehicle: Hydrogen, Methanol or Gasoline?*** Presented at the Fuel Cell Reformer Conference, South Coast Air Quality Management District, Diamond Bar, CA, November 1998. 24 pages.

Thomas, C. E., B. D. James, F. D. Lomax, and I. F. Kuhn (1998b). ***Societal Impacts of Fuel Options for Fuel Cell Vehicles.*** SAE Paper No. 982496. Presented at Society of Automotive Engineers International Fall Fuels and Lubricants Meeting and Exposition, San Francisco, California, October 19-22, 1998. 22 pages.

Thomas, C. P. ***Economics of Alaska North Slope Gas Utilization Options***. Report INEL—96/0322. Idaho National Engineering Laboratory. August 1996.

Tillmann, A-M., H. Baumann, E. Eriksson, and T. Rydberg. ***Life-Cycle Analyses of Selected Packaging Materials—Quantification of Environmental Loadings***, Chalmers Industriteknik, Göteborg, Sweden, 1991.

US ABC. **"United States Advanced Battery Consortium Battery Criteria: Commercialization."** <www.USCAR.org>. May 2000.

US DOE. **"Hybrid Electric Vehicle Component Information."** <http://www.hev.doe.gov/components/batteries.html>. August 1999/

US DOE, Office of Policy, Planning and Analysis; Office of Policy Integration. ***Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector. Technical Report Three: Methanol Production and Transportation Costs.*** DOE/PE-0093. November 1989. 46 pages.

US GAO. **"Testimony: Alternative Fuels: Experiences of Countries Using Alternative Motor Fuels."** GAO/T-RCED-91-85. Statement of Victor S. Rezendes before Subcommittee on Environment, Energy, and Natural Resources, Committee on Government Operations, House of Representatives, July 29, 1991.

Wall Street Journal. "Oil Prices Generate Political Heat." *Wall Street Journal*, page A18, September 30, 2000.

Wang, M., and H.-S. Huang (1999a). ***A Full Fuel-Cycle Analysis of energy and Emissions Impacts of Transportation Fuels Produced from Natural Gas***. Report ANL/EDSs-40. Prepared by Argonne National Laboratory, The Center for Transportation Research, Energy Systems Division for US DOE. December 1999. 114 pages.

Wang, M. Q. (1999c) ***GREET 1.5—Transportation Fuel-Cycle Model, Volume 1: Methodology, Development, Use, and Results***. Argonne National Laboratory Report No. ANL/ESD-39, Vol. 1. August 1999.

Wang, M., M. Mintz, M. Singh, K. Stork, A. Vyas, and L. Johnson. ***Assessment of PNGV Fuels Infrastructure. Phase 2 Report: Additional Capital Needs and Fuel-Cycle Energy and Emissions Impacts***. Report ANL/ESD-37. Prepared by Argonne National Laboratory, The Center for Transportation Research, Energy Systems Division for US DOE. August 1998. 171 pages.

World Fuels Today, page 1. October 12, 2000. Hart Publications, Potomac, MD. 2000.