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ABSTRACT

A study at MIT of the energy consumption and greenhouse gas emissions from advanced technology future automobiles has compared fuel cell powered vehicles with equivalent gasoline and diesel internal combustion engine (ICE) powered vehicles [1][2]. Current data regarding IC engine and fuel cell vehicle performance were extrapolated to 2020 to provide optimistic but plausible forecasts of how these technologies might compare. The energy consumed by the vehicle and its corresponding CO_2 emissions, the fuel production and distribution energy and CO_2 emissions, and the vehicle manufacturing process requirements were all evaluated and combined to give a well-to-wheels coupled with a cradle-to-grave assessment.

The assessment results show that significant opportunities are available for improving the efficiency of mainstream gasoline and diesel engines and transmissions, and reducing vehicle resistances. Battery parallel hybrid systems with these improved engines and vehicles are more efficient still, but are significantly more costly. Vehicles with fuel cell systems, with gaseous hydrogen as fuel, are also significantly more efficient, but when the hydrogen fuel production energy is included in the assessment, no significant advantage remains.

The impacts of several of these vehicle technologies on US light-duty vehicle fleet fuel consumption were also assessed, using an empirical data-based model of the in-use fleet as it evolves over time. Fleet impacts are delayed due to both the time required for new and improved technologies to be mass produced and spread substantially across total new vehicle production, and due to the 15 year vehicle lifetime. These fleet calculations show that extrapolating the trends of the past 15 years will likely result in a 60% increase in US light-duty vehicle fleet fuel consumption by 2030. Effective ways to offset this are through efficiency improvements where implementation can start soon, and dealing with growth in fleet size and vehicle usage.

INTRODUCTION

Automotive manufacturers and suppliers around the world are investing heavily in the development of fuel cell systems (FCSs) for light duty vehicles. We at MIT have been assessing new automobile technologies that could be commercialized by 2020 with respect to life-cycle greenhouse gas (GHG) emissions, energy efficiency, and cost. As in all comparisons of future alternatives, the results depended on the assumptions made. The assumptions and methodologies used in our studies are given in detail in [1] and [2]. One purpose was to determine how competitive FCSs would be in comparison with internal combustion engine based vehicle systems (ICESs). The primary motivation for these assessments was to evaluate new automobile technologies which might lower emissions of GHGs believed to contribute to global warming. The GHG of most concern is the carbon dioxide (CO_2) in the exhaust of vehicles burning petroleum or other carbon-containing fuels. The transportation sector accounts for about 30% of all CO_2 emissions in OECD countries, and about 20% worldwide.

Any assessment of emissions from future vehicle technologies must consider the total system over its entire life cycle. The life cycle of an 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 and including scrappage and recycling. Provision of the fuel from primary energy sources such as petroleum or natural gas must be considered from the point of resource recovery from underground reservoirs through transportation to refineries or plants where those resources are converted to fuels for vehicles. The fuel must then be distributed and deposited in the vehicle's fuel tank. The total of these steps is often called "well-to-tank". Analogously, the vehicle manufacture begins with ores or other raw and recycled 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 until the end of its lifetime when the vehicle is scrapped and recycled. Vehicle operation is often called "tank-to-wheels". "Well-to-wheels" normally means "well-to tank" plus "tank-to-wheels" but does not ordinarily include vehicle manufacture which should be included in any comprehensive life cycle analysis.

Part of our project included assessing the impact of both powertrain and vehicle improvements on total US light-duty-vehicle fleet fuel consumption and GHG emissions. Thus, this paper also compares the impact of the more promising of these future vehicle technologies on total US vehicle light-duty-vehicle fleet fuel consumption under various vehicle performance and penetration scenarios.

INDIVIDUAL VEHICLE TECHNOLOGIES AND PERFORMANCE

VEHICLE, POWERTRAIN, AND DRIVING PARAMETERS

All the vehicles examined in this study are functional equivalents of today's typical US mid-size family sedan. For the customer, this means that characteristics such as acceleration, range, passenger and trunk space, remain constant in future vehicles. All vehicles are designed to have the same ratio of peak power to vehicle mass, namely 75 W/kg, which is approximately today's average value and roughly equalizes the short-time acceleration performance of all vehicles.

The propulsion systems evaluated here consist of a) advanced spark-ignition (SI) and compression-ignition (CI) ICEs, fueled by gasoline and diesel respectively, as stand-alone engines and in parallel hybrid configurations, and b) fuel cell systems fueled by compressed hydrogen or by dilute hydrogen (about 40% by volume) in gas generated by processing gasoline on board, also in both non-hybrid and hybrid configurations. The systems are listed in Table 1. For all hybrid systems the battery and electric motor were sized to provide a ratio of peak electrical power to vehicle mass of 25 W/kg, and the power plant (ICE or FC) to provide 50 W/kg, giving the total of 75 W/kg cited above. All hybrid systems included regenerative braking.

The future advanced gasoline spark-ignition engine was assumed to have an 8% improvement in indicated efficiency (to 41%) and a 25% reduction in engine friction relative to current values, as a result of design changes, direct gasoline injection, variable valve control, and increased compression ratio. The future advanced turbocharged diesel had a 7 percent higher indicated efficiency (52%) and a 15% reduction in friction, again relative to current values, through increased boosting, improved combustion control and other design changes. Allowance was made for a loss in efficiency due to the diesel aftertreatment technology that will be required in the future.

All vehicles, except the 2001 reference and the 2020 evolutionary base case, used the same type of advanced body with reduced vehicle mass (e.g. more extensive use of aluminum) and resistances (e.g. lower drag coefficient and rolling resistance) [1]. These vehicles are compared to the typical current (2001) US mid-size family sedan, for "reference", and to a 2020 evolutionary "baseline". Both the reference and the baseline are gasoline-fueled ICE cars with similar capacity and performance; the baseline has evolutionary improvements in powertrain and vehicle technology over the next 20 years or so similar to improvements achieved during the last 20 years.

Table 1. Propulsion Systems Asssessed

Propulsion System	Description
Gasoline ICE	Advanced SI engine and auto-clutch transmission
Gasoline ICE hybrid	Gasoline ICE engine with continuously variable transmission plus battery and electric motor in parallel
Diesel ICE	Advanced CI engine and auto-clutch transmission
Diesel ICE hybrid	Diesel ICE engine with continuously variable transmission plus battery and electric motor in parallel
Hydrogen FC	Fuel cell operating on 100% compressed hydrogen with electric drive train
Hydrogen FC hybrid	Hydrogen FC with addition of a battery
Gasoline FC	Like the Hydrogen FC, but fueled by hydrogen produced by processing gasoline on board
Gasoline FC hybrid	Gasoline FC with addition of a battery

The performance of each of the vehicles we assessed was calculated using computer simulations described in [1]. Originally developed by Guzzella and Amstutz [3] at the ETH, Zurich, these simulations 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.

FUEL CELL SYSTEM PERFORMANCE

Since one focus of this study is the comparative energy consumption of advanced fuel cell vehicles, our assumptions about the future performance of fuel cell systems (FCS) are critical, and were developed as follows. We define the FCS to include a fuel processor (for gasoline fuel) which converts the fuel chemically to hydrogen, hydrogen cleanup equipment, a fuel cell "stack" which converts the hydrogen energy electrochemically to electric power, associated equipment for heat, air, and water management, and auxiliary equipment such as pumps, blowers, and controls.

The overall efficiency of an FCS is defined here as the net DC energy output of the stack (obtained from the gross output by subtracting the electrical energy needed to operate FCS auxiliaries such as pumps and compressors) divided by the lower heating value (LHV) of the fuel consumed in the FCS—whether gasoline fed to a fuel processor or hydrogen gas from a high pressure tank or other on-board hydrogen storage system. That overall efficiency will vary with the load on the fuel cell and will generally increase as load decreases except at very low loads when parasitic power losses and/or fuel processor heat losses become comparatively high and overall efficiency declines.

We assume that all these FCSs include proton exchange membrane (PEM) stacks in which hydrogen, pure or dilute, fed to the anode side of the electrolyte reacts with oxygen in air at the cathode side of the electrolyte to produce water and electric power. The anode and cathode are porous electrodes impregnated with catalytic metals, mostly platinum. We assume the stacks operate at about 80ºC and a maximum pressure (at peak power) of about 3 atmospheres.

Fuel cell systems fueled by pure hydrogen iincur two types of efficiency losses: the losses in the stack (polarization loss during electrochemical conversion of the hydrogen's chemical energy to electrical energy) and the loss of generated electric power used to power the auxiliary equipment. FCSs fueled by dilute hydrogen from gasoline reformate have the same two types of losses in efficiency that pure-hydrogen FCSs suffer, but also have two additional types: 1) losses in the "fuel processor" during conversion of gasoline (by reaction with steam and air) to hydrogen and subsequent cleanup, and 2) incomplete hydrogen utilization in the stack. We assume a hydrogen utilization of 85% as in [1]. That is, 15% of the hydrogen entering the stack from the fuel processor is purged and leaves the stack unreacted (but may be used to heat the reformer).

Our objective was to identify advances in FCS technology that were plausible—but not assured—with aggressive development, but not assume advances that depended on hoped-for but not yet demonstrated technical innovation. The new stack polarization data we used correspond to the current Ballard Mark 900 80 kW stack [4] with unit cell voltage increased by 0.05 V (about 5 to 8%) at all current densities to anticipate further improvements. We also assumed that operating a stack of given area on gasoline reformate rather than pure hydrogen would reduce peak power density and cell voltage by amounts consistent with the Ballard Mark 900 experience [5]. Table 2 lists the polarization data used. For our stack conditions, the ideal unit cell voltage is 1.22-1.23 V; this ideal voltage excludes all the losses found in an operating fuel cell. We defined peak power as the power level at which unit cell voltage drops to 0.6 V for both pure hydrogen and reformate fuels.

Table 2. Stack Polarization Data

Current Density mA/cm^2	Unit Cell Voltage, V	
	100% H_2	40% H_2 (reformate)
0	1.05	1.03
25	0.94	0.92
50	0.90	0.88
100	0.87	0.84
200	0.84	0.81
400	0.79	0.75
600	0.75	0.71
800	0.72	0.67
1000	0.68	0.61
1050	--	0.60
1200	0.63	--
1300	0.60	--

For FCSs fueled by processing gasoline to hydrogen, a customary expression of efficiency of the processor (including removal of CO from the gas stream) is equal to the LHV of the hydrogen in the gas stream leaving the processor divided by the LHV of the gasoline fed to the processor. This efficiency can be increased by supplying heat to the fuel processor by burning the hydrogen in the tail gas purged from the stack. Table 3 lists the efficiencies assumed in our most recent study [2] for gasoline fuel processors feeding a stack whose peak power output is about 60 kW. At high power, the efficiency is 0.81 LHV compared to 0.725 LHV assumed in our earlier study [1]. US DOE's current 2001 "baseline" (at peak power) is 0.76 [6]. Some reformers under development are claimed to have higher efficiencies but, according to a Ford authority quoted by DeCicco [7], "Effective reformers exist only in the laboratory".

Of the energy needed to drive the FCS auxiliaries, primarily pumps and blowers for water, air, and heat management, the largest load is the air compressor which delivers air to the cathode compartments of the stack; some of the air compressor load can be offset by an expander powered by the cathode exhaust gas. Table 4 shows our assumptions about total net requirements for auxiliary power expressed as a fraction of stack gross power.

Table 3. Efficiencies of Gasoline Fuel Processors

Stack Gross Power, % of Peak	Efficiency $LHV_{H2\ Out}/LHV_{Gasoline\ In}$	
	Previous Study [1]	This Study
0	0.725	0.60
5	0.725	0.73
10	0.725	0.79
20	0.725	0.81
30	0.725	0.81
100 (Peak)	0.725	0.81

Table 4. FCS Auxiliary Power Requirements

Stack Gross Power, % of Peak	Auxiliary Power as Percent of Gross Stack Power	
	Previous Study [1]	This Study
5	15	15
10	15	12
20	15	10
30	15	10
100 (Peak)	15	10

FUEL CELL AND VEHICLE COST AND WEIGHT

In addition to projecting future advances in FCS efficiency, we considered the prospects for reduction of both FCS cost and weight. Many projections of FCS costs reflect targets rather than an analysis of specific design and manufacturing steps that would directly determine FCS costs. An example is the FreedomCAR target [8] of $30/kW by 2015 (Table 5) for FCS systems fueled by hydrogen (including fuel tank) or by gasoline. For comparison, the ADL analysis carried out for DOE [6] estimates high volume manufacturing costs in 2001 for gasoline FCS to be $249-$324/kW. In another study [9], ADL did estimate potential costs of future FCS using results from analyses done with DOE and EPRI, and concluded that "factory costs of future FCVs would likely be 40-60% higher than conventional vehicles". Typical annual ownership costs for fuel cell vehicles would therefore be about $1200 to $1800 higher than for ICE vehicles. Long-term factory costs for the FCS were estimated at about $105/kW for hydrogen and about $130/kW for gasoline fuel processor FC systems.

Table 5. Unit Cost and Weight of Future Fuel Cell Systems - *Ex fuel and storage*

Source [Reference]	100% Hydrogen Fuel		Gasoline Reformate	
	$/kW	kg/kW	$/kW	kg/kW
Previous Study [1]	60	2.9	80	4.8
ADL DOE [6]	28	1.8	45	3
FreedomCAR [8]	30*	3.1*	30	--
ADL [10]	105	--	130	3.5

* Includes hydrogen storage

The vehicle costs we used are those reported in [1]. Total vehicle costs were $18,000 for our 2020 baseline vehicle, 8 and 14% higher for advanced gasoline and diesel vehicles respectively, 17 and 23% higher for gasoline and diesel hybrids, and 23 and 30% higher for hydrogen and gasoline fuel cell hybrids. Our assumptions about fuel costs also are those developed in [1], since no new technologies have been identified that make a major change in the costs of the fuels we considered. ADL [10] notes that our fuel costs and fuel-chain energy use and GHG emissions are comparable to other studies. Our previous projections for FCS unit weights [1] still look optimistic but achievable and we have not changed them.

OVERALL FUEL CELL SYSTEM EFFICIENCY

Overall fuel cell efficiencies are listed in Table 6 under the heading “Components”. These numbers combine the efficiencies (or losses) of the individual FCS components listed in Tables 2 to 4 with no allowance for performance degradation due to design compromises needed to obtain the best combination of characteristics of the total powerplant in the vehicle. Examples of such compromises—often to reduce cost, weight, or space or to provide for warm-up or transients—would be lower stack efficiency due to smaller stack area, lower processor efficiency due to simpler but less-effective processor heat management, or lower hydrogen utilization through changed stack design and operation.

For a total integrated system, we assumed an increase of 5% in the losses in each component. The column “Integrated” in Table 6 shows overall FCS efficiencies based on the component efficiencies column but additionally assuming: a) in the stack, unit cell voltage is reduced 5% (from, say, 0.8 V to 0.76 V) at any given power density, b) auxiliary power requirements are increased 5% (from, say, 10% of net output to 10.5%) at any given power, and c) all efficiencies in the reformer are decreased 5% (from, say, an efficiency of 0.80 to 0.76). Hydrogen utilization remained at 85%. These assumed losses due to integration result in significant increases in FCV fuel consumption relative to the “component” assumption. Consumption of on-board fuel per vehicle km traveled increases about 9 to 23% depending on the driving cycle, fuel, and hybridization.

ON THE ROAD RESULTS

ON-BOARD ENERGY USE

Table A1 in the Appendix lists the assumed characteristics, and the on-the road and life-cycle energy consumptions and GHG emissions of all the ICE vehicles we assessed. Table A2, also in the Appendix, does the same for all the fuel cell vehicles. Additional details can be found in [1] and [2].

Figure 1 shows the combined 55% urban/45% highway US Federal Test Procedure driving cycle results. All of the tank-to-wheels energy consumptions are compared on a relative scale where 100 is defined as the consumption of the “baseline” car—a gasoline-engine non-hybrid car—with lower-cost evolutionary improvements in engine, transmission, weight, and drag assumed to take place by 2020. The projected on-board fuel consumption of the baseline car in this combined driving cycle is 5.4 liters of gasoline/100 km which is equivalent to 43 miles per gallon or 1.75 MJ (LHV)/km. The 2001 predecessor of the baseline car had a fuel consumption of 7.7 l/100 km (30.6 mpg) or 2.48 MJ (LHV)/km.

The bar for each of the fuel cell vehicles in Fig. 1 (and also in Figs. 4 and 5) has a shaded area and a hatched area. The shaded area indicates the fuel consumption based on assuming that each of the components of the FCS can operate as efficiently as shown in Tables 2 to 4 with an overall FCS efficiency shown in the “Components” columns of Table 6. The hatched area shows the additional fuel consumption due to efficiency losses through integration as summarized in the “Integrated” columns of Table 6. In comparing different vehicles, modest differences are not meaningful due to uncertainties in the assumptions.

HYBRID BENEFITS FOR DIFFERENT DRIVING CYCLES

The advantage of hybrid systems relative to their non-hybrid equivalent depends on many factors: maximum power split between engine and electric motor; electrical power/ICE power transition thresholds; engine’s efficiency variation over its load and speed map; transmission characteristics; capacity of the battery system to absorb regenerative power; characteristics of the vehicle driving cycle. While we explored several of the technical issues listed above to ensure that the details of the vehicle configurations we analyzed made sense, we examined the effects of different standard driving cycles on this hybrid non-hybrid comparison more extensively [11].

The driving cycles used were the US Federal Urban and Highway Cycles, the US06 cycle, the New European Driving Cycle, and the Japanese 15-Mode Cycle. The characteristics of these different driving

Table 6. Overall Fuel Cell System Efficiencies

Net Output Energy, % of Peak	100 x Net DC Output Energy/Fuel LHV			
	100% Hydrogen Fuel		Gasoline Reformate Fuel	
	Components	Integrated	Components	Inte-grated
5	76	71	46	42
10	75	71	50	45
20	74	70	49	44
40	69	65	46	42
60	65	61	44	39
80	61	58	41	37
100	53	50	36	33

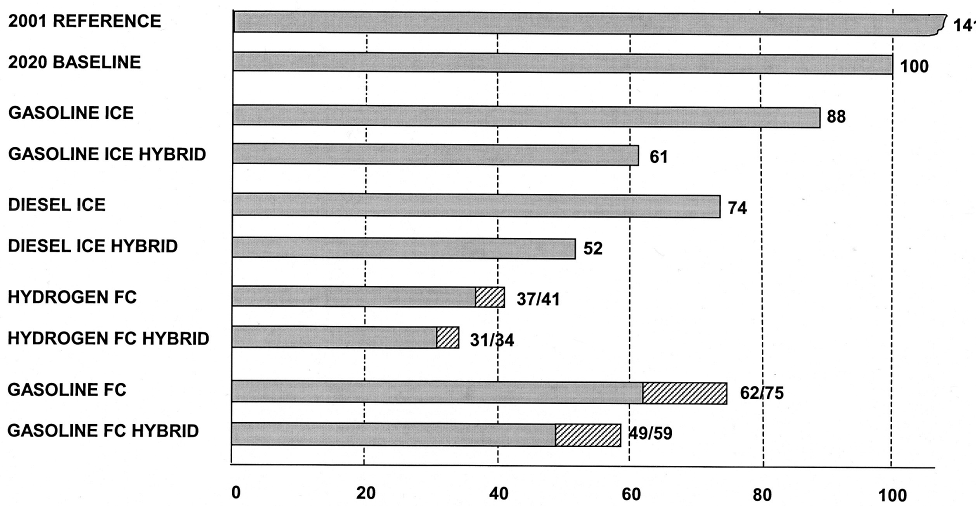

Figure 1: Relative on-board consumption of fuel energy for vehicle technology combinations. MJ(LHV)/km expressed as percentage of baseline vehicle fuel use. All vehicles (except 2001 reference and 2020 baseline) are advanced 2020 designs. Driving cycle assumed is combined Federal cycles (55% urban, 45% highway). Hatched areas for fuel cells show increase in energy use in integrated total system which requires real-world compromises in performance of individual system components.

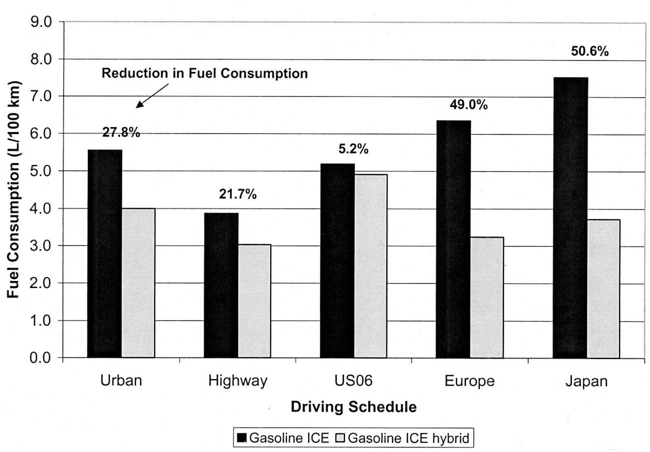

Figure 2. Effects of hybridization on gasoline SI ICE vehicles.

cycles are summarized in Table 7. The US Urban, European, and Japanese cycles are viewed as representing "urban" diriving in these three regions with low average speeds, substantial idle time, and repeated moderate acceleration and braking. The US Highway cycle represents "highway" driving, and average urban/suburban/highway fuel consumption is assumed to be 55% of the urban value added to 45% of the highway value. The US06 is a more recent high acceleration cycle intended to represent aggressive driving. Some auto companies use their own cycles (which can be roughly characterized as one-third of each of the US Urban, Highway, and US06 cycles) to represent modern light-duty vehicle driving.

Table 7. Characteristics of Driving Cycles Used

Driving Cycle	**Duration(s)**	**Average speed (km/h)**	**Maximum Speed (km/h)**	**% Time at Idle**	**Maximum Acceleration (m,s^2)**
US Urban	1877	34.1	91.2	19.2	1.6
US Highway	765	77.6	96.3	0.7	1.4
US06	601	77.2	129.2	7.5	3.24
European	1220	32.3	120	27.3	1.04
Japanese	660	22.7	70	32.4	0.77

Figure 2 shows the fuel consumption of the advanced gasoline ICE and gasoline ICE hybrid vehicles, and the reduction in fuel consumption (in %) the hybrid achieves for these five driving cycles. The greater the amount of "stop and go" driving (European and Japanese cycles) the greater the benefit (about 50% for these two cycles) from both increased average engine efficiency and regenerative braking. With higher speeds, and more aggressive accelerations, the hybrid benefit is much reduced (to 5% for the US06 cycle). (Note: modest differences in our assumptions for these technology combinations cause minor differences in calculated results. These are not significant.)

Figure 3 shows the results for the advanced fuel cell and fuel cell hybrid vehicles. The trends are similar, but the percentage hybrid fuel consumption benefits are significantly lower. Since the fuel cell is relatively more efficient at lighter loads, whereas the ICE exhibits the reverse trend, this part of the hybrid benefit (shifting the "engine" to higher loads) is much reduced.

These are specific illustrations of the impact of driving cycle characteristics on the fuel consumption advantages of the hybrid. Many other factors are important in this hybrid non-hybrid comparison, such as cost, towing capacity, performance on extended grades.

LIFE-CYCLE RESULTS

To estimate life-cycle energy consumption and GHG emissions, the energy use and GHG emissions for the fuel cycle, and the vehicle manufacturing cycle, were added to the tank-to-wheels estimates. The GHGs considered were CO_2 and methane from natural gas leakage: gC(eq) is equal to the carbon in the CO_2 released plus the carbon in a mass of CO_2 equal to 21 times the mass of methane leaked.

During the fuel cycle, gasoline and diesel fuels were assumed to be refined from crude petroleum and would have modest improvements in quality over the next 20 years. Hydrogen was assumed to be produced by the reforming of natural gas at local filling stations, and compressed to about 350 atmospheres for charging vehicle tanks. Energy consumptions during the manufacturing and distribution of these fuels were calculated to include energy from all sources required to produce and deliver the fuels to vehicle tanks. GHG emissions were calculated similarly. Results are given in Table 8 [1].

For vehicle "manufacturing" (which includes all materials, assembly, and distribution) we assumed, as in our previous report [1], intensive use of recycled

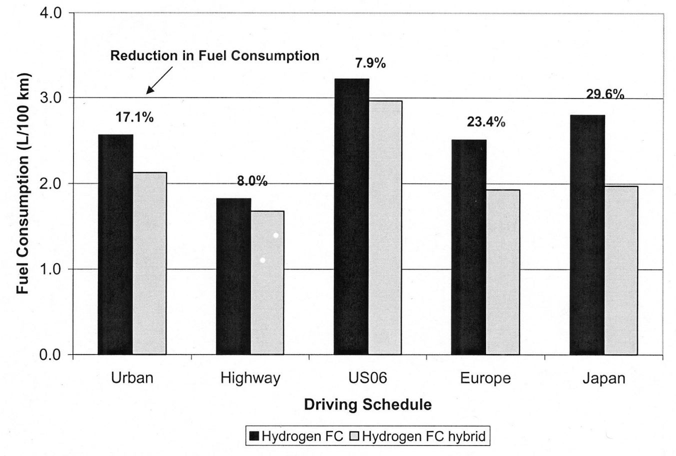

Figure 3: Effect of hybridization on fuel cell vehicles operating on direct hydrogen feed.

materials (95% of all metals and 50% of glass and plastics) and that manufacturing energy and GHGs were prorated over 300,000 km (vehicle life of 15 years driven 20,000 km/year). These manufacturing additions for the vehicles assessed ranged from 0.25 to 0.33 MJ/km in energy consumed and about 4.8 to 6.3 gC(eq)/km of GHGs released.

The full life-cycle results are shown for energy in Fig. 4, and for GHGs in Fig. 5. On a life-cycle basis, both energy consumption and GHG releases for the diesel ICE and hydrogen FC hybrid vehicles are closely comparable. The gasoline ICE and gasoline FC hybrids are not as efficient but, considering the uncertainties of the results, not significantly worse than the two other hybrids. Both life-cycle energy use and

Table 8. Fuel Cycle Energy Use and CO_2*

Fuel	Energy Use	Efficiency	GHG
	MJ/MJ		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

*Per MJ of fuel energy in the tank.

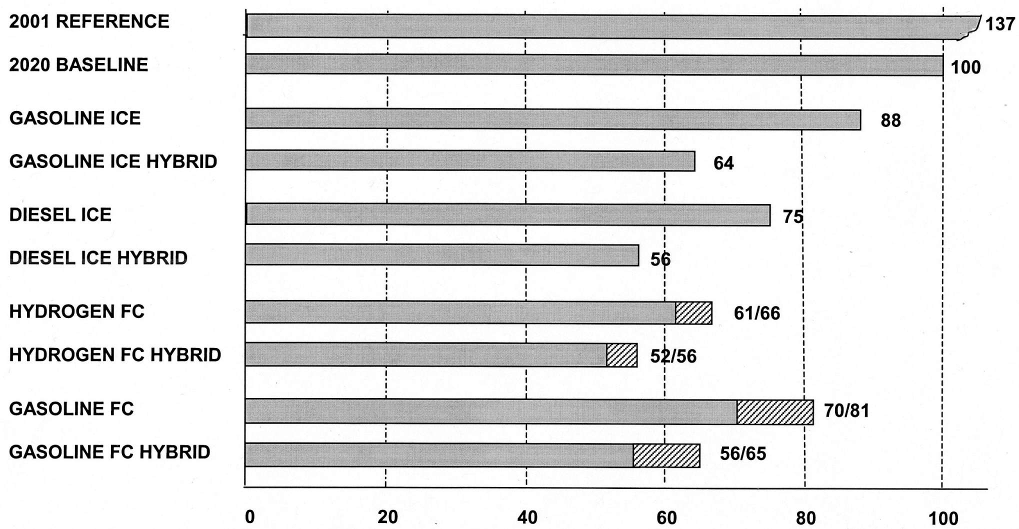

Figure 4: Relative life-cycle consumption of energy for vehicle technology combinations. Total energy (LHV) from all sources consumed during vehicle lifetime shown as percentage of baseline vehicle energy consumption. Total energy includes vehicle operation and production of both vehicle and fuel.

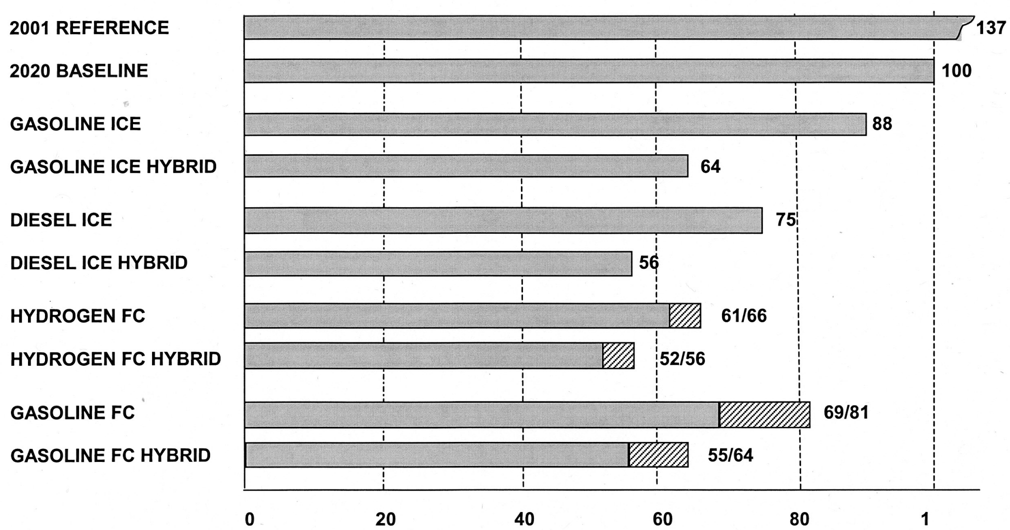

Figure 5: Relative emissions of life-cycle greenhouse gases for vehicle technology combinations. Total mass of carbon equivalent emitted during vehicle lifetime shown as percentage of baseline vehicle GHG emissions. Greenhouse gases include only CO_2 and CH_4 (assumed equivalent to 21 CO_2). Emissions include vehicle operation and production of both vehicle and fuel.

GHG releases from all four of these hybrids are between 52 and 65% of our 2020 baseline vehicle, and between 38 and 47% of our 2001 reference vehicle.

Table 9 breaks down life-cycle energy and GHG totals into the shares attributable to each of the three phases of the life cycle: operation of the vehicle on the road, production and distribution of fuel, and manufacture of the vehicle including embodied materials. The largest single share of energy, ranging from 44 to 75% of the total, results from vehicle operation. The largest single share of GHGs, from 65 to 74%, is also attributable to operation except for hydrogen fuel where the fuel cycle accounts for about 80% of the total. Vehicle manufacturing increases its share of energy and GHGs for vehicles with higher on-the-road fuel economies, up to about 21%, comparable to several of the fuel cycle shares.

Table 9. Share of Life-Cycle Energy & GHG

Vehicle	Energy, % of Total			GHG, % of Total		
	Operation	Fuel Cycle	Vehicle Mfg.	Operation	Fuel Cycle	Vehicle Mfg.
2001 Reference	75	16	9	74	18	8
2020 Baseline	74	15	11	71	18	11
Gasoline ICE	73	15	12	72	18	10
Gasoline ICE Hybrid	69	14	17	67	17	16
Diesel ICE	75	10	15	74	12	14
Diesel ICE Hybrid	70	10	20	70	11	19
Hydrogen FC	45	34	21	0	81	19
Hydrogen FC Hybrid	44	35	21	0	79	21
Gasoline FC	67	14	19	66	16	18
Gasoline FC Hybrid	66	14	20	65	16	19

Note: Percentages for FCs are averages for "Component" and "Integrated" systems. Neither system varies more than about 1% from average.

POTENTIAL US FLEET IMPACTS

OVERVIEW

To this point, we have discussed individual vehicle characteristics. However, the impact of the above vehicle improvements in fuel consumption and GHG emissions that really matter are the resulting reduction in total US vehicle fleet fuel consumed and GHGs emitted. Due to both the long penetration times required for new technologies that do make it into mass production to grow in volume so they are used in a large fraction of each years' new vehicles, and the long lifetimes of vehicles in the in-use fleet (some 15 years), fleet impacts are significantly delayed.

We have examined these fleet impacts using a model of the U.S. car and light truck vehicle fleet [12]. The model calculates the effects of introduction of more efficient technology in new vehicles on fleet fuel consumption (and hence GHG emissions) over time. Historical data were used to check the validity of the fleet turnover calculations. The model is structured in three modules as follows:

(i) Fleet vehicle number and age distribution calculations, based on new vehicle sales each year, and vehicle retirement based on age-specific scrappage and removal rates and the fleet median age.

(ii) Annual vehicle usage distributions (km/year) for each major class of vehicles as a function of model year and vehicle age.

(iii) Annual fleet fuel consumption based on the fuel consumption characteristics of each vehicle technology and type, and model year, integrated over the vehicle usage and fleet make-up distributions.

US FLEET FUEL CONSUMPTION MODEL

New Vehicle Sales, Sales Mix, and Scrappage Rates - Projections were made of new passenger cars and light-duty trucks sales for each calendar year. Historical sales data were taken from [13]. In the reference case, the total light-duty vehicle sales were estimated to grow at the same rate as the U.S. population (0.8% per year on average from 2000 to 2030, according to the medium projection of the U.S. Bureau of Census). The light-duty truck share was modeled by extrapolating the historical data to a given 2030 market share by a second order polynomial curve. The reference case assumes that the current trend of increasing percentage of light trucks will increase from its current value of 50% of new vehicles and level off at 60% market share in 2030.

Historical data on vehicle scrappage rates were taken from [14] for model years 1970, 1980 and 1990. The vehicle survival rate data for each given model year were fitted using the following equation:

$$1 - \text{Survival Rate (t)} = \frac{1}{1 + e^{-\beta(t_0)}} \quad ,$$

where, t_0 is the median age of the corresponding model year, t is the age on a given year, and β is a growth parameter defining how rapidly vehicles are retired around t_0 .

The historical survival rate data for model years 1970, 1980 and 1990 show an increase in the median age of automobiles and a small decrease in the median age of light-duty trucks: see Table 10. The intermediate median age data were linearly interpolated for both fleets (passenger cars and light duty trucks). However, extrapolating this trend would lead to excessively high values for the median lifetime, so the median age was kept constant after the model year 2000.

Table 10: Median Age (years) [14]

	Model Year 1970	Model Year 1980	Model Year 1990
Cars	10.7	12.1	13.7
Light Trucks	16.0	15.7	15.2

Thus, the number of vehicles (passenger cars and light-duty trucks) in use for each model year and for any calendar year between 1960 and 2030 can be calculated. Since the calculation starts for model year 1960, the calculated total vehicle stock composition matches the data accurately only after 10 to 15 years, when the number of vehicles from model years prior to 1960 becomes negligible relative to the total stock.

Vehicle Kilometers Traveled (VKT) - Historically, vehicles have tended to drive less each year as they age. Data show that each calendar year, the annual distance traveled per vehicle for a given model year, decreases at a rate of 4.5% per year (Greene *et al.*,[15]). Thus, the usage degradation rate is kept constant in our model at 4.5% annual decrease; however, the distance traveled per year for new vehicles is allowed to evolve for each calendar year. The average annual growth rate of new vehicle kilometers traveled depends on economic conditions and the price of fuel. This rate has been 0.5% per year during the 1970-1998 period. The reference case assumes it remains at 0.5% per year from 2000 to 2030.

Vehicle Fuel Consumption - The fuel consumption of each model year was calculated as follows. For years before 2000, the historical data for average fuel consumption for new passenger car and light-duty truck fleets were used. For future model years, the performance characteristics of each considered technology were appropriately sales weighted to obtain the average new vehicle on-road fuel consumption for these two fleets. These projected "average" vehicle fuel consumptions for each model year serve as an input to the fuel use estimates. In all the scenarios considered, the future percentage improvement in light-duty truck fuel consumption was assumed to be the same as the improvement for passenger cars. A 17% increase was applied to US fuel consumption test procedure results to adjust these new vehicle fuel consumptions to on-the-road values. The 17% adjustment factor was also applied to ICE-hybrid vehicles since little data are yet available to calibrate on-road fuel consumption for this type of vehicle [12].

TECHNOLOGY PENETRATION SCENARIOS

In all the technology scenarios, the following input parameters remain constant: the average annual growth rate of new vehicle sales (0.8% per year); the annual growth rate of the average per-vehicle kilometers travelled (0.5% per year); the evolution of the share of light trucks in new light-duty vehicle sales (currently 50%, and rising to 60% market share in 2030). The five technology scenarios considered are following:

Reference Scenario (No Change) - The average new car and light-duty truck fuel consumptions remain at their 2000 levels until 2030 (on-road fuel consumption of 9.8 L/100 km for cars and 13.7 L/100 km for light trucks).

Baseline - The baseline scenario assumes a steadily decreasing fuel consumption for new vehicles as technologies for reducing vehicle fuel consumption are progressively rolled out by automakers into the light-duty fleet: see Fig. 6. Note this baseline inherently assumes that most of the realizable efficiency increase is not traded for larger heavier vehicles, higher performance, and other amenities. During the past decade or so, efficiency increases were fully traded for these attributes. Thus fuel consumption in all new 2005 vehicles decreases by 5% relative to new 2000 vehicles, and in new 2020 vehicles reaches the 35% reduction calculated in our technology assessment study "On the Road in 2020" [1] and reevaluated here. Further decreases in fuel consumption are assumed, to 50% of 2000 fuel consumption levels in new 2030 vehicles. These relative improvements are assumed to be the same for all light-duty vehicles.

Advanced Vehicles with Internal Combustion Engine Hybrids - To further reduce fuel consumption, more advanced technologies relative to those included in the baseline projection must come into production. In these fleet calculations, we considered ICE-hybrid vehicles as the incoming advanced technology. Again, the relative fuel consumption improvement for light-duty trucks is assumed to be the same as for cars. The current average fuel consumption of ICE hybrids was determined by scaling the fuel consumption of the Toyota Prius to a vehicle with the average mass of new passenger cars. The 2020 fuel consumption for the advanced gasoline ICE-hybrid vehicle is that calculated by our assessment here. Between these two levels, we assume a linear decrease. Beyond 2020, we assumed a less steep slope, leading to a 66% fuel consumption improvement in new 2030 hybrid vehicles (5% better than the 2020 value) relative to the 2000 baseline fuel consumption. These relative ICE hybrid fuel consumption improvements are also shown in Fig. 6.

The baseline fuel consumption assumptions (solid line in Fig. 6) apply to all the vehicles produced in a given model year. For hybrids, a production penetration scenario is needed. Three cases were considered (see Table 11):

- Low penetration scenario with a 2030 market share of 25%,
- Medium penetration scenario with a 2030 market share of 50%,
- High penetration scenario with a 2030 market share of 75%.

With these parameters, the sales-weighted fuel consumption was calculated for each calendar year, for both passenger car and light-duty truck fleets. These data are the input to the total fleet fuel use calculations.

FLEET SCENARIO RESULTS

Reference Scenario - This scenario assumes that light-duty vehicle fuel consumption is not reduced over the next 30 years, continuing the trend witnessed during the last 10-15 years, when improved vehicle efficiency was traded for performance, power, size, weight and other amenities while the CAFE standards remained unchanged. This scenario can be thought of as "business as usual." Table 12 shows this reference scenario light-duty vehicle fleet fuel use. Total fuel use grows steadily because of the fleet and vehicle kilometers traveled growth. The 2030 level (774 billion liters of gasoline per year) is 63% higher than the 2000 level. Light trucks account for about two thirds of the total fuel use in 2030.

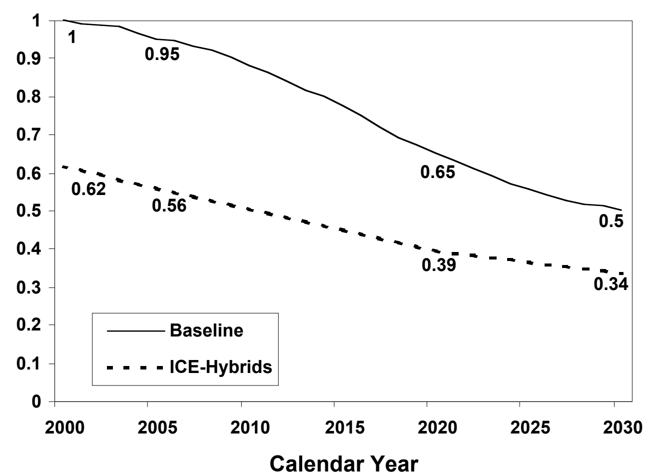

Figure 6: Relative Improvement in fuel consumption (vertical axis) relative to the 2000 new car average fuel consumption.

Table 11: Market Penetration Scenarios for New ICE-Hybrid Vehicles

Year	LOW		MEDIUM		HIGH	
	%	Thousand Vehicles	%	Thousand Vehicles	%	Thousand Vehicles
2005	0.5%	82	1.0%	163	1.5%	245
2010	2.1%	357	4.2%	713	6.2%	1,053
2015	7.2%	1,273	14.5%	2,563	22%	3,836
2020	16%	2,962	32%	5,942	48%	8,904
2030	24%	4,841	48%	9,702	73%	14,543

Table 12. Fleet Fuel Use for the Reference Case

	Billion Liters	Million Barrels per Day (Mbd)
1990	390	6.7
2000	475	8.2
2010	580	10.0
2020	680	11.7
2030	774	13.3

Baseline Scenario - This scenario assumes that fuel economy is no longer largely traded for increased performance, vehicle size/weight, and amenities, and the technologies progressively rolled out into the fleets result in significant vehicle fuel consumption improvements. As a result, average new car fuel consumption decreases steadily as defined by the solid curve in Fig. 6. This same percentage improvement in fuel consumption is assumed for new light trucks. In 2020, the average estimated new car and new light truck on-road fuel consumptions are 6.4 L/100 km and 8.9 L/100 km, respectively, as compared to the 2000 values of 9.8 L/100 km and 13.7 L/100 km.

The cumulative effect of these less-fuel-consuming vehicles results in significant fleet fuel savings compared to the reference case. Around 2015, the fuel consumption reduction offsets the growth in the fleet size and VKT, and total fuel use begins to decrease. The maximum fleet fuel use under the baseline scenario is 562 billion liters of gasoline per year in 2015, a 20% reduction over the reference case (in 2030 a 40% reduction is projected). Figure 7 shows the total fleet fuel use for these two cases.

Baseline + Advanced ICE-Hybrids - Here, ICE-hybrid vehicles, with the advanced body design, are substituted progressively for the baseline vehicles defined above. According to the three penetration rates, Low, Medium and High, the hybrid vehicles' market share gradually increases to 25%, 50% and 75% of the light-duty vehicle market share by 2030. Again, light trucks are assumed to gain the same percentage improvement in fuel consumption, and the fraction of hybrids in new light-duty vehicles is assumed to be identical for cars and light trucks. The fleet fuel consumption, and average vehicle fuel consumption, are shown in Fig. 7 and Fig. 8. Until about 2013, the impact of hybrids is negligibly small due to low (though growing) production numbers. Beyond about 2015, these hybrid fuel consumption improvements decrease baseline fleet fuel use by 2.6%, 5.2%, and 7.9% for the low, medium and high market share cases in 2020, and by 6.2%, 12.4% and 18.6% in 2030.

Note that to continue the decrease in the fleet energy use requires a continuing fuel consumption reduction for new vehicles to counterbalance the effects of growth in vehicle fleet size and increasing VKT.

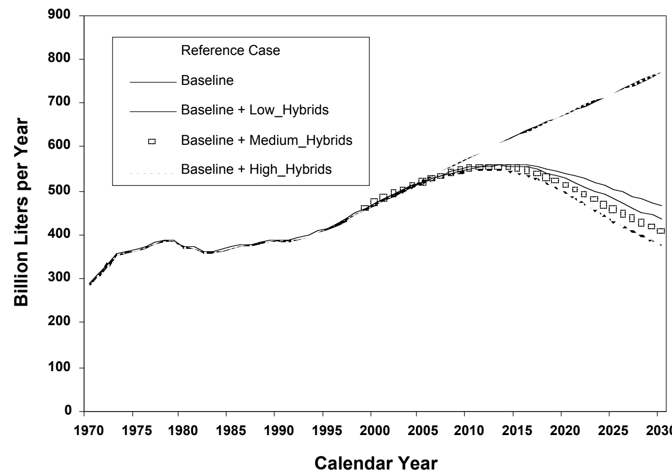

Figure 7: Light-duty fleet fuel use for various technology scenarios.

Sensitivity to Fleet Growth and VKT - We also examined the effects of changes in (1) sales mix, (2) new vehicles sales growth rate, and (3) average annual VKT growth rate. The reference case assumption of 60% market share of light trucks in 2030, was changed to 50%, 40% and 30% of the 2030 light-duty vehicle market. The results are presented in Table 13.

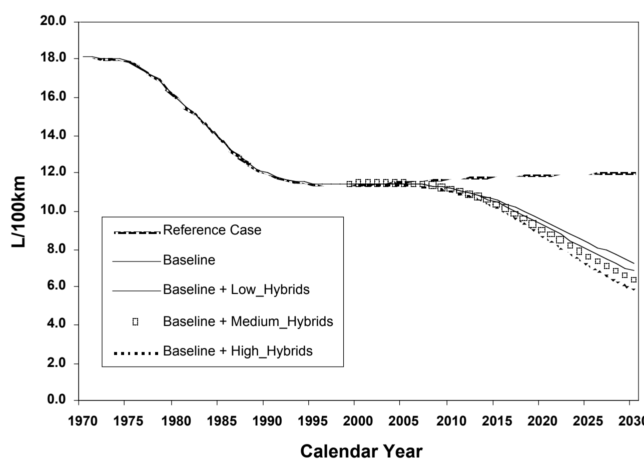

Figure 8: Average light-duty vehicle fuel consumption for various technology scenarios.

Table 13: Sensitivity Analysis of Light Truck Share of New Vehicle Sales

	2030 Light Truck Market Share			
	60%*	50%	40%	30%
	Fuel Use (billion liters)	Percent fuel use change		
Reference				
2020	679	-0.7%	-1.3%	-2.0%
2030	774	-1.6%	-3.3%	-4.9%
Baseline				
2020	541	-0.6%	-1.2%	-1.8%
2030	467	-1.5%	-3.1%	-4.6%

*Reference case

The maximum reduction in fleet energy use due to changes in light truck market share, relative to the reference case, is 2% in 2020 and 5% in 2030 for a decrease in the share of light trucks to 30% of new sales in 2030. This percentage reduction, relative to the baseline fuel use level, is less.

The reference case assumes a 0.8% annual growth rate for the new light-duty vehicle sales. We analyzed the case where this average annual growth rate is halved to 0.4%. The effects are surprisingly significant. Half the reference case growth rate leads to an additional 6% fleet fuel savings in 2020, and 9% in 2030. It is plausible that a slow down in new light-duty vehicle sales might occur, due to approaching saturation in vehicles per licensed driver.

In the reference case, the average annual per-vehicle kilometers traveled grows at an annual rate of 0.5% from 2000 to 2030. The effect of reducing this increase was examined. The results show that a 0% growth of annual per-vehicle travel can lead to fuel savings of 8% of the baseline case level in 2020 and nearly 12% in 2030. Thus, successful travel reduction strategies can have a significant impact on the fleet energy use.

All these individual fuel conserving strategies are illustrated in Fig. 9, relative to the baseline technology scenario. A composite scenario was then examined. Relative to the baseline, this considers the introduction of advanced ICE-hybrids under the medium market share assumption (50% market share in 2030), concurrently with the improving baseline vehicles. In addition, the annual new vehicle sales growth rate is halved to (0.4%), while the annual per-vehicle kilometers traveled is assumed to remain constant (0% growth). This scenario also assumes a decline in the market share of light trucks to 40% in 2030. Such a composite scenario illustrates the potential impacts that a series of measures can have on the fleet fuel consumption. The composite scenario is also shown in Fig. 9, and the quantitative benefits of each individual strategy and the composite strategy added to the baseline, are quantified in Table 14.

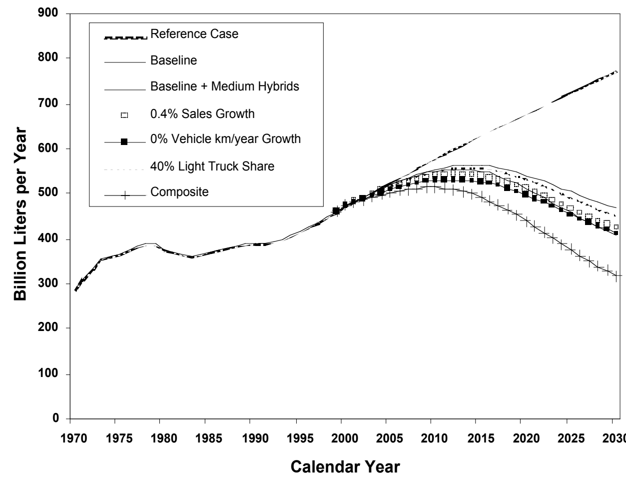

Figure 9: Light Duty Fleet Fuel Use for Various Scenarios

DISCUSSION

Several conclusions can be derived form the above fleet impact analysis. First, the projected reduction of new vehicle fuel consumption through improvements in mainstream technology (the baseline) provides the most significant savings in fleet energy use over the next 20 or so years because these improvements are substantial, and can be implemented in large volume most rapidly. This underlines the benefits of early action to improve vehicle fuel consumption. Changes in the share of light trucks in the new vehicle sales mix will have only a modest effect on fleet energy use. Measures like travel reduction and slowing down of the growth in fleet size, over many years, could have a significant impact on fleetwide fuel savings due to compounding. Considering the baseline scenario as a reference, the effect of the latter measures is comparable in magnitude to the introduction of advanced ICE-hybrids vehicles into the fleet. Also, travel and fleet growth reduction strategies have a more immediate effect on fleet fuel consumption.

As shown in Fig. 9, the total fleet energy use for the composite scenario peaks in 2020, five years earlier than what would be achieved if only technology improvements were implemented.

It is important to note that, with the assumptions of the reference scenario (on sales mix, sales and VKT growth), the model predicts that a minimum annual rate of reduction of average new vehicle fuel consumption of 1.3% is needed to offset the effects of stock and VKT growth and stabilize the total light duty vehicle fleet fuel use as shown in Fig. 10. This number is sensitive to new vehicle sales growth rate and per-vehicle annual VKT growth rate. A continuing decrease in new vehicle fuel consumption is needed to limit the growth of light-duty vehicle fleet fuel use and GHG emissions.

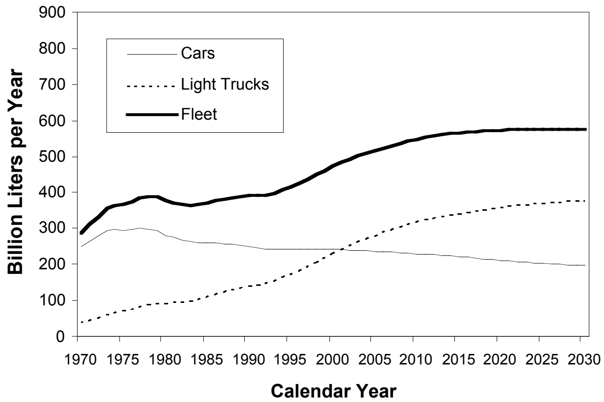

Fig. 10: Stabilization in light-duty vehicle fleet fuel use due to a steady 1.3% annual decrease in average new vehicle fuel consumption.

ICE hybrids (see Fig. 7) have limited impact relative to the baseline before about 2015 because production volumes have not become substantial enough. However, beyond that point their beneficial impact steadily increases as their relative production volume grows. Beyond about 2030, their increasing penetration into the in-use vehicle fleet steadily drops the total fleet fuel consumption below the baseline vehicle technology fleet consumption levels.

We have not examined the impact of fuel cell vehicles on fleet energy consumption. One reason is that with hydrogen as the fuel-cell fuel, how that hydrogen is produced and the energy consumed and GHG emissions released in its production and distribution are critical questions. With all vehicles using petroleum-derived fuels, the fuel production and distribution energy consumption is smaller (about 15%) and the relative penalty that is added to fuel use on the vehicle is constant. Note also that the lead times for fuel cell technology to enter large scale mass production and penetrate across a significant fraction of new car production will, at best, be much longer than ICE-hybrid technology which is already in limited mass production.

Fuel cell technologies and hydrogen are not likely to be available at acceptable cost, scale, and robustness to make significant contributions to petroleum reduction within this 20 or so year timescale. In any case their estimated well-to-wheels benefits are not significantly better than those achieved through ICE-based technology improvements unless the hydrogen used is produced without releasing significant CO_2.

CONCLUSIONS

Our assessment shows that substantial reductions in energy use and GHG emissions over the next 20 years can be achieved through improvements in mainstream vehicle technologies (ICEs, transmissions, and vehicles). Use of ICE hybrids would increase these reductions, but at significantly higher cost. However, judging solely by lowest life-cycle energy use and greenhouse gas releases, there is no current basis for preferring either fuel cell (FC) or internal combustion engine (ICE) hybrid powerplants for mid-size automobiles over the next 20 years or so using fuels derived from petroleum or natural gas. That conclusion applies even with optimistic assumptions about the pace of future fuel cell development.

All hybrid vehicles are superior to their non-hybrid counterparts, but their relative benefits are greater for ICE than for FC powertrains. Hybrids can reduce both life-cycle energy use and GHGs to between about 37 to 47% of current comparable vehicles, and to between about 52 to 65% of what might be expected in 2020 as a result of normal evolution of conventional technology.

These reductions in energy use and GHG releases result from not only advances in powertrains but also from reduction of both vehicle weight and the driving resistances of aerodynamic drag and tire rolling resistance.

If automobile systems with GHG emissions much lower than the lowest estimated here are required in the very long run future (perhaps in 30 to 50 years or more), hydrogen appears the most promising fuel option identified to date. But the hydrogen must be produced from non-fossil sources of primary energy (such as nuclear or renewables) or from fossil primary energy with effective carbon sequestration. Biofuels may also increase their currently limited role. A comparison of the on-the-road and life-cycle energy and GHG results for hydrogen—superior in the former but about the same in the latter—illustrates why a valid comparison of future technologies for light-duty vehicles must be based on life-cycle analysis for the total fuel and vehicle system.

The effects of new vehicle technologies such as hybrids on US fleet fuel consumption are significantly delayed due to both the time for these new technologies to achieve large-scale mass production and the 15 year in-use vehicle lifetime. Growth in total vehicle fleet size and annual kilometers traveled, and increasing percentage of light trucks in the new vehicle sales mix, all counter these individual vehicle improvements. About a 1.3% annual decrease in average new vehicle fuel consumption is required to offset these growth

Table 14: Savings in Light-Duty Vehicle Fleet Fuel Use for Chosen Actions

Fuel Use: Billion Liters or Percent Change							
Year	Reference Case	Baseline	Medium Hybrids	0.4% Sales Growth	0% VKT Growth	40% Light Truck	Composite
2020	679	-20.3%	-24.5%	-24.8%	-26.8%	-21.3%	-35.2%
2030	774	-39.6%	-47.1%	-45.1%	-46.7%	-41.5%	-58.8%
2020		541	-5.2%	-5.6%	-8.1%	-1.2%	-18.7%
2030		467	-12.4%	-9.1%	-11.7%	-3.1%	-31.7%

trends and stabilize the total US light-duty vehicle fleet fuel consumption around 2015 and beyond. Implementing the baseline technology improvements discussed in this paper would produce fleet fuel savings of 20% in 2020 relative to the no-change reference scenario. ICE-hybrid vehicle penetration into the market relative to this baseline case, even with their much lower than baseline vehicle fuel consumption, has limited impact before 2015 but does usefully improve fleet performance beyond about 2020.

A sobering overall conclusion is that it requires combining all potentially plausible technology, growth, and sales mix options together—clearly tasks requiring a major national commitment—to reduce US light-duty vehicle fleet annual fuel consumption over the next 20 years to levels below today's value of about 500 billion liters per year.

REFERENCES

1. Weiss, M. A., Heywood, J.B., Drake, E., Schafer, A., and AuYeung, F., "On the Road in 2020: A life-cycle analysis of new automobile technologies". Energy Laboratory Report # MIT EL-00-003, Massachusetts Institute of Technology, October 2000. http://lfee.mit.edu/publications/reports
2. Weiss, M.A., Heywood, J.B., Schafer, A., and Natarajan, V.K., "Comparative Assessment of Fuel Cell Cars," MIT LFEE 2003-001 RP, February 2003. http://lfee.mit.edu/publications/reports
3. Guzzella, L., and A. Amstutz. "Quasi-Stationaren-Simulations". Matlab programs and text Benutzeranleitung, Laboratorium fur Motorsysteme, Institute fur Energietechnik, ETH-Zurich, 1998.
4. Ballard Power Systems. "Ballard Fuel Cell Power Module, Mark 900 Series, Mk 900 Polarization". Burnaby, BC, Canada, November 2001.
5. Barbir, Frano, et al. "Design and Operational Characteristics of Automotive PEM Fuel Cell Stacks". Energy Partners, LC, West Palm Beach, FL. SAE 2000-01-0011.
6. Arthur D. Little, Inc. "Cost Analysis of Fuel Cell System for Transportation, 2001 System Cost Estimate, Task 3 Report to: Department of Energy", Ref. 49739 SFAA No. DE-SCO2-98EE50526, August 2001.
7. DeCicco, John M. "Fuel Cell Vehicles: Technology, Market, and Policy Issues". SAE Research Report RR-010, November 2001.
8. US Department of Energy. "FreedomCAR Goals". Office of Advanced Automotive Technologies.
9. Arthur D. Little, Inc. "Guidance for Transportation Technologies: Fuel Choice for Fuel Cell Vehicles, Main Report, Phase II Final Report to DOE", 35340-00, December 14, 2001.
10. Arthur D. Little, Inc. "Guidance for Transportation Technologies: Fuel Choice for Fuel Cell Vehicles, ADL Phase II Results Comparison to MIT Study, Revised Phase 3 Deliverable to DOE", 75111-00, February 26, 2002.
11. Natarajan, V.K., "The Performance of IC Engine and Fuel Cell Hybrid Propulsion Systems in Light-Duty Vehicles," MIT Mech. Eng. S.M. Thesis, February 2002.
12. Bassene, S.A., "Potential for Reducing Fuel Consumption and Greenhouse Gas Emissions from the US Light-Duty Vehicle Fleet," MIT S.M. in Technology and Policy Thesis, September, 2001.
13. Davis, S.C., Transportation Energy Data book: Edition 20. Center for Transportation Analysis, Oak Ridge National Laboratory, Oak Ridge, TN, 2000.

14. Davis, S.C., Transportation Energy Data Book: Edition 19. Center for Transportation Analysis, Oak Ridge National Laboratory, Oak Ridge, TN, 1990.

15. Greene, D.L., and Hu, P.S., "Influence of the Price of Gasoline on Vehicle Use in Multivehicle Households," Transportation Research Record, pp. 19-24, 1984.

APPENDIX

Table A1: Vehicles Using Internal Combustion Engines [2]

	Gasoline				Diesel	
	2001 Reference	2020 Baseline	2020 Advanced	2020 Hybrid	2020 Advanced	2020 Hybrid
Mass (kg)						
Body & Chassis	930	845	746	750	757	758
Propulsion System (3)	392	264	252	269	293	297
Total (Incl. 136 kg payload)	1458	1245	1134	1155	1186	1191
Vehicle Characteristics						
Rolling Res. Coeff	0.009	0.008	0.006	0.006	0.006	0.006
Drag Coeff.	0.33	0.27	0.22	0.22	0.22	0.22
Frontal Area (m^2)	2.0	1.8	1.8	1.8	1.8	1.8
Power for Auxiliaries (W)	700	1000	1000	1000	1000	1000
Engine						
Displacement (L)	2.50	1.79	1.65	1.11	1.75	1.16
Indicated Eff. (%)	38	41	41	41	51	51
Frictional ME Pressure (kPa)	165	124	124	124	153	153
Max. Engine Power (kW)	110	93	85	58	89	59
Max. Motor Power (kW)				29		30
Use of On-Board Fuel						
Driving Cycle						
US Urban (MJ/km)	2.82	2.00	1.78	1.20	1.53	1.03
US Highway (MJ/km)	2.06	1.45	1.25	0.91	1.04	0.78
US06 (MJ/km)	2.81	1.94	1.67	1.49	1.39	1.29
Combined (MJ/km) (4)	2.48	1.75	1.54	1.07	1.30	0.92
Combined (mpg) (8)	30.6	43.2	49.2	70.7	58.1	82.5
Combined as % Baseline	141	100	88	61	74	52
Life-Cycle Combined Energy						
Vehicle Operation (MJ/km)	2.47	1.75	1.55	1.07	1.31	0.92
Fuel Cycle (MJ/km) (5)	0.52	0.37	0.32	0.22	0.18	0.13
Vehicle Manufacturing (MJ/km)	0.29	0.25	0.25	0.26	0.26	0.26
Total (MJ/km)	3.28	2.37	2.12	1.55	1.75	1.31
Total as % Baseline	138	100	89	65	74	55
Life-Cycle Combined GHG Emissions						
Vehicle Operation (gC/km) (7)	48.5	34.4	30.2	21.0	27.1	19.1
Fuel Cycle (gC/km) (6)	12.1	8.6	7.6	5.2	4.3	3.0
Vehicle Manufacturing (gC/km)	5.5	4.8	4.8	5.0	5.0	5.1
Total (gC/km) (9)	66.1	47.8	42.6	31.2	36.4	27.2
Total as % of Baseline	138	100	89	65	76	57

Notes:
(1) 1 liter (0.737 kg) gasoline = 32.2 MJ (LHV)
(2) 1 liter (0.856 kg) diesel = 35.8 MJ (LHV)
(3) Propulsion system mass includes ICE, drive train, motors, battery, fuel (2/3 full), and tank
(4) Combined cycle is 55% urban/45% highway
(5) Fuel cycle energy, MJ per MJ fuel in tank: gasoline 0.21, diesel 0.14
(6) Fuel cycle gC per MJ fuel in tank = gasoline 4.9, diesel 3.3
(7) Vehicle operation gC per MJ burned = gasoline 19.6, diesel 20.8
(8) Gasoline equivalent miles per gallon calculated as equal fuel LHV
(9) gC of GHG calculated as C in CO_2 released plus carbon in CO_2 equal to 21 times mass of methane leaked

Table A2: Vehicles Using Fuel Cell Systems [2]

	Hydrogen				Gasoline			
	Non-hybrid	**Non-hybrid**	**Hybrid**	**Hybrid**	**Non-hybrid**	**Non-hybrid**	**Hybrid**	**Hybrid**
	Comp.	Integrated	Comp.	Integrated	Comp.	Integrated	Comp.	Integrated
Mass (kg)								
Body & Chassis	776	780	752	754	821	822	775	776
Propulsion System (3)	465	479	372	378	638	640	460	463
Total (Incl. 136 kg payload)	1377	1395	1260	1268	1595	1598	1371	1375
Vehicle Characteristics								
Rolling Res. Coeff	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
Drag Coeff.	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
Frontal Area (m^2)	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Power for Auxiliaries (W)	1000	1000	1000	1000	1000	1000	1000	1000
Propulsion System								
Max. Net Stack Power (kW)	103	105	63	63	120	120	69	69
Max. Motor Power (kW)	103	105	95	95	120	120	103	103
Use of On-Board Fuel								
Driving Cycle								
US Urban (MJ/km)	0.75	0.82	0.60	0.66	1.29	1.56	0.96	1.16
US Highway (MJ/km)	0.52	0.57	0.47	0.51	0.85	1.03	0.73	0.88
US06 (MJ/km)	0.92	1.00	0.78	0.87	1.51	1.83	1.27	1.56
Combined (MJ/km) (4)	0.65	0.71	0.54	0.59	1.10	1.32	0.86	1.04
Combined (mpg) (8)	117.3	106.5	140.3	128.1	69.2	57.4	88.4	73.1
Combined as % Baseline	37	41	31	34	62	75	49	59
Life-Cycle Combined Energy								
Vehicle Operation (MJ/km)	0.65	0.71	0.54	0.59	1.10	1.32	0.86	1.04
Fuel Cycle (MJ/km) (5)	0.50	0.55	0.42	0.46	0.23	0.28	0.18	0.22
Vehicle Mfg. (MJ/km)	0.31	0.32	0.28	0.28	0.33	0.33	0.28	0.28
Total (MJ/km)	1.46	1.58	1.24	1.33	1.66	1.93	1.32	1.54
Total as % Baseline	61	66	52	56	70	81	56	65
Life-Cycle Combined GHG Emissions								
Vehicle Operation (gC/km) (7)	0	0	0	0	21.5	26.0	16.8	20.3
Fuel Cycle (gC/km) (6)	23.3	25.6	19.4	21.3	5.4	6.5	4.2	5.1
Vehicle Mfg. (gC/km)	5.8	5.9	5.3	5.3	6.2	6.3	5.4	5.4
Total (gC/km) (9)	29.1	31.5	24.7	26.6	33.1	38.6	26.4	30.8
Total as % of Baseline	61	66	52	56	69	81	55	64

Notes: (1) 1 liter (0.737 kg) gasoline = 32.2 MJ (LHV)
(2) 1 kg hydrogen = 120.0 MJ (LHV)
(3) Propulsion system mass includes fuel cell system, drive train, motors, battery, fuel (2/3 full), and tank
(4) Combined cycle is 55% urban/45% highway
(5) Fuel cycle energy, MJ per MJ fuel in tank: gasoline 0.21, hydrogen 0.77
(6) Fuel cycle gC per MJ fuel in tank = gasoline 4.9, hydrogen 36
(7) Vehicle operation gC per MJ burned = gasoline 19.6, hydrogen 0
(8) Gasoline equivalent miles per gallon calculated as equal fuel LHV
(9) gC of GHG calculated as C in CO_2 released plus carbon in CO_2 equal to 21 times mass of methane leaked