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Future fuel cell and internal combustion engine automobile technologies: A 25-year life cycle and fleet impact assessment

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Abstract

Hydrogen fuel cell (FC) vehicles are receiving increasing attention as a potential powerful technology to reduce the transportation sector's dependence on petroleum and substantially decrease emissions of greenhouse gases (GHGs) at the same time. This paper projects energy use and GHG emissions from different FC vehicle configurations and compares these values to the projected characteristics of similarly sized and performing gasoline and diesel fueled automobiles on a life cycle, well to wheels and cradle to grave basis. Our analysis suggests that for the next 20 or more years, new internal combustion engine (ICE) hybrid drive train vehicles can achieve similar levels of reduction in energy use and GHG emissions compared to hydrogen FC vehicles, if the hydrogen is derived from natural gas. The fleet impact of more fuel-efficient vehicles depends on the time it takes for new technology to (i) become competitive, (ii) increase its share of the new vehicles produced, and finally (iii) penetrate significantly into the vehicle fleet. Since the lead times for bringing improved ICE vehicle technology into production are the shortest, its impact on vehicle fleet energy use and emissions could be significant in 20–30 years, about half the time required for hydrogen FC vehicles to have a similar impact. Full emission reduction potential of FC vehicles can only be achieved when hydrogen is derived from zero or very low-carbon releasing production processes on a large scale—an option that further increases the impact leadtime. Thus, a comprehensive short- and long-term strategy for reducing automobile energy use and emissions should include both the continuous improvement of ICE vehicles and simultaneous research and development of hydrogen FC cars.

Keywords: Fuel cell vehicle; Vehicle technology; Life-cycle assessment; Transportation; Greenhouse gas emusions

1. Introduction

Recent advances in fuel cell (FC) technology paired with the long-term vision of a hydrogen economy have raised widespread enthusiasm for hydrogen FC vehicles. The potential benefits of this novel technology are

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compelling, i.e., a simultaneous reduction in oil dependence and greenhouse gas (GHG) emissions, and inherently low air pollutant emissions, resulting in major benefits to society. Since FC vehicles depend on a completely new and expensive hydrogen supply infrastructure, some intermediate solutions aim at designing small-scale chemical reactors, which reform gasoline (or methanol) to hydrogen onboard the vehicle.

Largely driven by expectations of rapid technological progress, numerous studies have projected a strongly growing market for carbonaceous fuel reforming onboard or pure hydrogen storing FC vehicles. In 1997, after successfully developing a series of prototypes, one major vehicle manufacturer projected to selling 100,000 methanol FC cars by 2004 [1]. Such exaggerated enthusiasm for future technology has a long history. At the beginning of the first oil crisis in 1973/74, many analysts expected alternative engines (e.g., Stirling engine, gas turbine) to displace the internal combustion engine (ICE). Due to the substantial potential for improving the performance of the ICE and overoptimistic projections of the performance of these alternatives, these projected displacements never materialized.[1] Are we in a similar situation today? While FC vehicles seem to threaten the long-term dominance of ICE vehicles, a wide range of improved component technologies exists that promise extrapolating historical gains in fuel efficiency of ICE vehicles well into the future. A comparison of the future (20 years ahead) potential of FC vehicles to continuously improving gasoline and diesel engine technology is the purpose of this paper.

While many vehicle studies exist that have evaluated the future performance of road vehicles equipped with different fuel-saving technologies (see [2] for a summary), only recently, has substantial research focused on the comparative performance of FC and ICE vehicles. In addition to [3,4], the subject of this paper's life-cycle analysis, we have found several studies [5–9] reporting similar analyses. Common to the latter five studies, which are all important contributions to the field, are two main omissions. None of these studies takes into account the energy use associated with, and GHG emissions from the production of the vehicle itself. Our analysis shows that with rising vehicle fuel efficiency and the extra energy input for producing lighter weight and energy-intensive materials, that life-cycle component becomes increasingly important, in some cases exceeding energy use and emissions from fuel processing and distribution. In addition, neither [5–9] assess the impact of fuel-saving technologies on vehicle fleet energy use and emissions. Such impact analysis is essential in assessing which technologies to invest in, at what points in time, and to what extent in order to achieve substantial reductions of GHG emissions.

We continue by describing the life-cycle analysis that consists of three components, the fuel cycle (well-to-automobile tank), the vehicle on-the-road cycle (automobile tank-to-wheels), and the vehicle material cycle (cradle-to-grave). We then add up all life-cycle components to evaluate total energy use and emissions. In the final stage of this paper we examine the potential impact of ICE hybrid and FC technologies on total US light-duty vehicle fleet energy use and emissions. The broadening focus from an automobile based life-cycle analysis to a light-duty vehicle based fleet impact analysis is important due to the continuously increasing share of pick-up trucks, vans, and sport-utility vehicles in the US vehicle fleet, which now accounts for some 50% of all new light duty vehicles.

2. Overview of the life-cycle analysis

When conducting comparisons of different technology/fuel combinations, the choice of system boundary within which one accounts for energy use and emissions is critical. Since energy use and emissions upstream of the vehicle associated with fuel processing and distribution vary for different transportation fuels, this study considers the entire life cycle, from well-to-vehicle tank and vehicle tank-to-wheels. In addition, highly fuel-efficient vehicles typically incorporate lower resistance vehicle components, including lightweight bodies; since the amount of embodied energy in these components can be significant, such strategies may shift some of the driving related emissions to the factories producing these materials. Hence, in addition to the fuel well-to-wheels approach, we include a cradle-to-grave analysis of the vehicle itself. Together, these two life-cycle components ensure that the system boundary encompasses all significant contributors to energy use and emissions.

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[1] An additional barrier to the large-scale introduction of methanol FC vehicles cited above is the extension and conversion of the existing oil-based fuel infrastructure.

Our fuel cycle encompasses raw material (e.g., petroleum) recovery, transport to a processing station (e.g., refinery), and distribution of the processed fuel to retail stations; in the case of hydrogen which is gaseous at standard temperature and pressure, the fuel cycle also includes a compression stage for storage and vehicle fueling. We examine each of these pathways for gasoline, diesel, and hydrogen-fueled vehicle technologies. To limit the scale of this study, we did not analyze the potential for biofuels; although, with concerted effort, biofuels could make a noticeable contribution to a reduction of petroleum use and GHG emissions within 20–25 years. The vehicle cycle comprises on-the-road vehicle usage and all other vehicle-related energy uses, i.e., vehicle manufacture, distribution, and disposal at the end of its lifetime. In that cycle we examine vehicles with mechanical, hybrid, and electric drive trains propelling a lightweight, aluminum-intensive glider (body and chassis). As a basis for comparison to today's and tomorrow's evolutionary technology, we also examine two mechanical drive train vehicles with a mild steel and high-strength steel body.

The assessment of energy use at each stage of the life-cycle analysis is a straightforward application of the first law of thermodynamics (i.e., the conservation of energy); the associated CO_2 emissions result from the conservation of mass at each conversion step, i.e., the difference in carbon between the mass flows entering and those leaving the systems-boundary of a technology step for subsequent use downstream. We also consider methane (CH_4) from natural gas leakage; total 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 CH_4 leaked. The relative importance of all other GHGs released in the transportation sector is comparatively small and below 1% of the total greenhouse forcing [10,11].

3. The fuel cycle

Consistent with the nearly one-century history of crude oil refining, we project gasoline and diesel fuel, here exclusively from refined crude petroleum, to experience continuous improvements in fuel quality over the next 20 years. However, while past improvements in fuel quality were mostly directed to improve knock resistance and reduce criteria pollutants other than sulfur dioxide, most future advances aim to comply with the mandatory reduction of the sulfur content, from currently 500 ppm to a maximum of 15 ppm for diesel fuel and to an average of 30 ppm for gasoline, in the US in 2006. In contrast to the centralized conversion of crude oil to petroleum products, hydrogen is usually projected to be produced from natural gas reforming at local filling stations—the most economic way for producing compressed hydrogen (here at 350 bar) at small and medium scale for the hydrogen transition stage [5,12–14]. The potential of hydrogen from renewable energy sources such as solar-electricity powered water electrolysis is limited by high costs, at least for the next few decades.

We used the US Energy Information Administration's forecast of US$(2001) 29.2/bbl as the reference price of crude oil for 2025 [15], which is nearly 50% higher than the long-term historical average. To take into account recent spikes and possible further increases of the crude oil price, we also examine the economics of alternative vehicle concepts based upon the two-fold and four-fold crude oil price of US$(2001) 58.4/bbl and $ 116.8/bbl, respectively. The refinery margin, i.e., the cost for plus the profit from oil refining, consists of the historical average (1982–1998) of 33 c/gal of gasoline and 22 c/gal of diesel fuel, plus 3 c/gal for sulfur reduction for either fuel [16]. All fuel costs exclude state and federal excise taxes, which in the US total about 40 c/gal.

As with the oil price projection, we use the Energy Information Administration's forecast of US$(2001) 9.3/GJ of natural gas to commercial customers. That cost is augmented by 43% due to the excess natural gas necessary to produce 1 GJ of hydrogen (corresponding to a conversion efficiency of 70%), the station charges for generating hydrogen from natural gas and fueling the vehicle, and the costs of the electric power used for compression. Table 1 summarizes major fuel cycle characteristics including energy "consumed" per unit of energy delivered to the vehicle tank, the related energy efficiency, GHG emissions per unit of energy delivered to the vehicle tank, and costs of supplied fuel. A comparison with other studies shows that our assumptions related to energy use and energy efficiency are well within one standard deviation.

Table 1
Summary of fuel cycle characteristics

	Energy use (MJ/MJ$_{Product}$)	Efficiency per stage (%)	GHG emissions (gC$_{Eq}$/MJ$_{Product}$)	Reference costs of supplied fuel (US$(2001)/GJ)
Gasoline				
Crude oil	0.04	96.2		5.7
Refining	0.16	86.2		3.0
Distribution	0.01	99.0		1.4
Other (methane leakage)			0.7	
Total	0.21	82.6	4.9	10.0
Mean $\pm 1\sigma$ of 6 studies[a]	0.18 ± 0.05	81.4 ± 3.9		
Diesel				
Crude oil	0.04	96.2		5.1
Refining	0.09	91.7		1.8
Distribution	0.01	99.0		1.2
Other (methane leakage)			0.5	
Total	0.14	87.7	3.3	8.1
Mean $\pm 1\sigma$ of 5 studies[b]	0.13 ± 0.03	87.6 ± 1.9		
Compressed H_2				
Piped natural gas	0.13	88.4		12.6[c]
Electricity input	0.21		11	1.4[d]
H_2 production & compression	0.43	69.9	23	10.3
Other (methane leakage)			2	
Total	0.77	56.5	36	24.3

[a] References include [6,10,37–40].

[b] Same references as for gasoline fuel, except [40].

[c] $ 8.1/GJ results from 1.43 GJ (to produce 1 GJ of H_2) times $ 8.8/GJ of natural gas.

[d] 18.2 kWh requirements at 7.3 c/kWh. For details see [3].

4. On-the-road vehicle use

4.1. Reference conditions and vehicles examined

A consistent assessment of competing technologies requires identical reference conditions, which apply to the technology and usage characteristics of a given reference vehicle. We define all analyzed vehicles to have characteristics similar to those of the typical new US mid-size family sedan in 2001, including acceleration (approximated by the ratio of peak propulsion power to vehicle mass of 75 kW/ton), range (about 650 km), seating capacity (5), and interior space (nearly 3.1 m^3). We have examined the fuel economy of each vehicle using various driving cycles, the US FTP 75 urban cycle, the US HWFET highway cycle, the combined cycle consisting of 55% urban and 45% highway driving, and the US06, which exhibits more aggressive speed and acceleration. The characteristics of these different driving cycles are given in Table 2.

Before describing the technological characteristics of the examined vehicles, we need to stress that because of the uncertainty associated with projecting vehicle characteristics some 20 years into the future, our projections cannot indicate what future technology will be, but rather suggest what it could be. We believe all vehicles examined in this paper could be commercialized in about 20 years if the required technologies are pursued aggressively. In light of the rapidly evolving FC situation, we estimate the extent to which advances might improve FC technology by reviewing recent FC literature and by discussing the outlook for commercialization by about 2020 with FC analysts and with commercial component and vehicle developers. Our objective is to identify and include advances in FC technology that are plausible—but not assured—with aggressive development, but not include advances that depended on hoped-for technical innovation not yet demonstrated at least in bench experiments. We include only advances whose cost looked at least plausible

Table 2
Driving cycle characteristics

	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	3.2
European	1220	32.3	120	27.3	1.04
Japanese	660	22.7	70	32.4	0.77

Source: [41].

commercially, and are deliberately optimistic to be sure that advanced technologies were not ruled out prematurely.

The power trains of the vehicles examined can be classified into hybrid systems (where a battery system stores recovered braking energy and acts as an additional source of power) and non-hybrid configurations (without any energy recovery). With regard to the former, we examine a parallel hybrid ICE vehicle, where the ICE can operate in conjunction with the battery-fed electric motor and both propulsion systems can operate separately.[2] We also examine a hybrid FC vehicle, where either the FC or the battery (or both) provides electricity to the motor. Among the non-hybrid vehicles, we analyze mechanical drive train vehicles propelled with an ICE (spark ignition or diesel) and an electric power train consisting of a FC and an electric motor. In both power train configurations, the FCs can be fueled with either compressed 100% hydrogen or hydrogen (about 40% by volume) in gas generated by processing gasoline on board. These propulsion systems are then combined with different gliders (body and chassis).

As two baselines to compare with the estimated performance of the advanced vehicles, we use a 2001 reference vehicle (about the average new automobile sold in the US in that year) with a mild steel body, and a 2020 "evolving baseline" with a high-strength steel body and incremental improvements in fuel efficiency. Both vehicles are powered with a gasoline-fueled ICE. All other vehicles, more advanced, use a lightweight body and chassis (mainly because of more extensive use of aluminum) with reduced resistances (i.e., lower coefficients of aerodynamic and tire drag). Table 3 reports the major characteristics of all the vehicles examined. Compared to the average new automobile sold in the US in 2001 (first data column), vehicle mass is reduced by 6% (FC gasoline-hybrid vehicle) to 24% (advanced gasoline fueled mechanical drive train vehicle). The same table shows that the decline in mass is mainly caused by the substitution of aluminum for steel. The non-hybrid FC vehicles experience up to a 11% higher vehicle mass—a result mainly of the heavier FC (and processor).

4.2. The vehicle simulation model

To estimate the fuel efficiency of each of these vehicles, a family of Matlab Simulink programs was used. Originally developed at the Eidgenössiche Technische Hochschule (ETH) Zürich [17], these models back-calculate the fuel consumed by the propulsion system by driving the vehicle through a specified cycle. Thus, the calculation starts with the driving cycle, specified as an array of vehicle velocity versus time (at intervals of one second). From this input, vehicle acceleration is calculated; from that the instantaneous power required to operate the vehicle is obtained by adding aerodynamic drag, tire rolling resistance, and the inertial force. The total required power is converted to the torque needed to drive the wheels, which through an automatic,

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[2] Our internal sensitivity analyses indicated that the series hybrid drive train vehicle, where the ICE acts as an electricity generator and exclusively feeds an electric motor, is less energy efficient than a parallel hybrid arrangement. Another hybrid drive train arrangement are plug-in hybrids, where the vehicle's battery is not only charged from recaptured braking energy, but also from the electricity grid. Although plug-in hybrids can become important in future, the future potential of energy storage batteries is still too unclear for a thorough vehicle assessment.

manual, or continuously variable transmission is converted to the torque needed at the engine shaft (in the simplest case of a mechanical drive train). Adding the power required at engine output with the engine losses (cycle inefficiencies, engine friction, changes in rotational kinetic energy, and auxiliary component power requirements) leads to the total rate at which the fuel chemical energy is consumed. Multiplying that number by the lower heating value (LHV) results in mass of fuel used per unit distance driven, i.e., the variable of main interest in this study. Such simulations, which require performance models for each major propulsion system component and for each vehicle driving resistance, 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.

4.3. Internal combustion engines

While the fundamental principles of spark and compression ignition engines have changed little over their century long history, new and improved materials and technology, improved design, ever more sophisticated control, and better and cleaner fuels, have improved the performance of these ICEs in virtually all dimensions (increased durability and reliability, efficiency, reduced costs, emissions, and engine size and weight per unit power output). Continuing improvements in nearly all these dimensions is anticipated.

The practical efficiency of an engine, the brake efficiency, is the product of the indicated efficiency (the ratio of gross indicated power transferred to the pistons to the input fuel chemical energy) and the mechanical efficiency (the ratio of brake or useful engine power to gross indicated power), which defines the impact of engine friction on the engine's output. The indicated efficiency can be increased by higher compression ratios,

Table 3
Characteristics of the powertain–vehicle combinations examined in this study

Abbreviation:	Reference REFV_G	Evolving EBLV_G	Advanced AV_G	Advanced HICEV_G	Advanced AV_D	Advanced HICEV_D	Advanced FCV_G	Advanced HFCV_G	Advanced FCV_{H2}	Advanced HFCV_{H2}
Fuel	Gasoline	Gasoline	Gasoline	Gasoline	Diesel	Diesel	Gasoline	Gasoline	Hydrogen	Hydrogen
Year	2001	2020	2020	2020	2020	2020	2020	2020	2020	2020
Drivetrain/engine	Mechanical	Mechanical	Mechanical	ICE-Hybrid	Mechanical	ICE-Hybrid	FC-Electric	FC-Hybrid	FC-Electric	FC-Hybrid
Displacement (L)	2.5	1.8	1.7	1.1	1.8	1.2				
No. cylinders	6	4	3	3	3	3				
Max. engine/motor power (kW)	110	93	85	86	89	89	120	103	105	95
Fuel cell system power (kW)							120	69	105	63
Transmission	Auto-Clutch	Auto-Clutch	Auto-Clutch	CVT	Auto-Clutch	CVT	Single-St.	Single-St.	Single-St.	Single-St.
Vehicle glider										
Tire rolling res. coefficient	0.009	0.008	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
Aerodynamic drag coefficient	0.33	0.27	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
Frontal area (m^2)	2.0	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Vehicle empty mass (kg)	1322	1109	998	1019	1050	1055	1462	1238	1259	1132
By component										
Body, filled	657	616	540	540	540	540	520	520	520	520
Closed body structure	418	359	282	282	282	282	282	282	282	282
Chassis	273	229	206	210	217	218	302	256	260	234
Power train	341	231	223	248	267	278	615	441	399	309
ICE/FC system & motor	164	103	95	83	139	112	597	378	379	250
Fuel system mass	51	33	29	21	26	19	25	22	80	69

By material										
Ferrous metals	834	612	328	359	357	384	819	612	604	486
Aluminum	107	125	302	283	322	289	256	254	255	253
Other metals	47	44	44	55	44	59	40	44	37	42
Plastics & rubber	160	165	164	163	171	166	150	145	147	144
Glass	35	33	33	33	33	33	33	33	33	33
Other	139	131	127	126	124	124	163	150	183	174
Energy use (MJ/km)										
US Urban	2.82	2.00	1.78	1.20	1.53	1.03	1.56	1.16	0.82	0.66
US Highway	2.06	1.45	1.25	0.91	1.04	0.78	1.03	0.88	0.57	0.51
Combined	2.48	1.75	1.54	1.07	1.30	0.92	1.32	1.04	0.71	0.59
US06	2.81	1.94	1.67	1.49	1.39	1.29	1.83	1.56	1.00	0.87
Costs (US$ 2001)										
Vehicle base price	21,600	21,600	21,600	21,600	21,600	21,600	21,600	21,600	21,600	21,600
Engine modifications		880	660	660	1650	1650	−3840	−3840	−3840	−3840
Exhaust gas cleaning		320	240	240	320	320	−300	−300	−300	−300
ICE Hybrid (battery & motor)				1930		1940				
Fuel cell system, battery, transmission & motor							12,720	11,770	11,860	11,630
Reduction of driving resistances			1550	1550	1550	1550	1550	1550	1550	1550
Total	21,600	22,800	24,050	25,980	25,120	27,060	31,730	30,780	30,870	30,640

Notes: All vehicles have a range of approximately 650 km and a similar acceleration capability, expressed by a ratio of engine/motor power to vehicle mass of 75 kW/ton. The auxiliary power of the $\mathrm{REFV_G}$ is 700 W and 1 kW for all other vehicles.

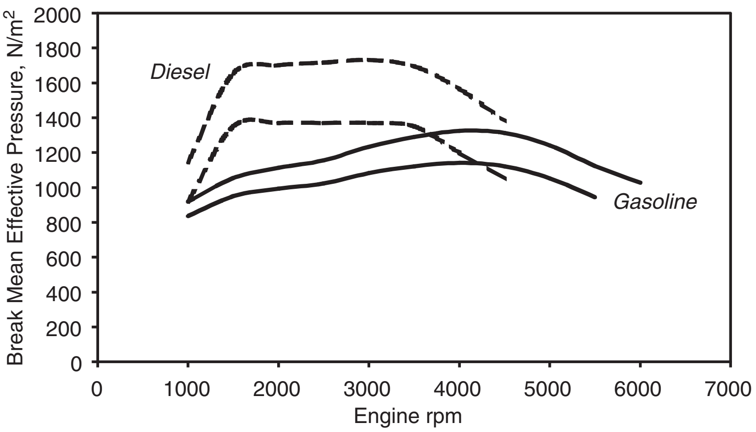

Fig. 1. Brake mean effective pressure versus engine speed for spark-ignition (continuous lines) and turbocharged direct-injection diesel (dashed lines) engines, typical current engines and projections to 2020.

historical maximum break mean effective pressure trend of 0.6%/yr, for US car and light truck production engines [18]. The increase in maximum break mean effective pressure for the diesel engine is projected to be higher, 1.2%/yr. This is because these diesels are turbocharged and the amount of intake air boost the turbocharger produces is steadily being increased.

4.4. *Fuel cell systems*

The "heart" of the FC system is the "stack", an assembly of electrochemical cells, each with its separator, anode, cathode, and electrolyte, which converts hydrogen directly into electric power. In continuous operation the stack requires effective heat, air, hydrogen, and water management, enabled by auxiliary equipment such as pumps, blowers, and controls. An alternative, the gasoline-fueled FC system requires a fuel processor, which converts gasoline chemically to hydrogen; such systems also require hydrogen clean-up to remove any carbon monoxide and hydrocarbons before feeding the stack. All these components together form the FC system. (A FC system excludes fuel tanks and all equipment downstream of the stack's net electrical DC output.)

Suitable light duty vehicle stack utilizes a proton exchange membrane (PEM) electrolyte in which hydrogen, pure or dilute, fed to the anode is ionized and diffuses through the electrolyte to react 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. The stacks operate at about 80 °C and a maximum pressure (at peak power) of about 3 bar.

The overall efficiency of a FC system is defined here as the net DC energy output of the stack (after subtracting from the gross output the electrical energy needed to operate FC system auxiliaries such as pumps and compressors) divided by the LHV of the fuel consumed in the FC system—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 FC 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. For FC systems fueled by reforming gasoline to hydrogen, the customary expression of efficiency of the processor (including removal of carbon monoxide [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 is often increased by supplying heat to the fuel processor by burning the hydrogen in the tail gas purged from the stack.

The main loss of efficiency in a FC system fueled by pure hydrogen occurs in the stack itself where some of the fuel energy consumed is dissipated to thermal energy—through resistance losses and other types of "polarization" losses—rather than to electrical energy. The average efficiency of the FC stack over the

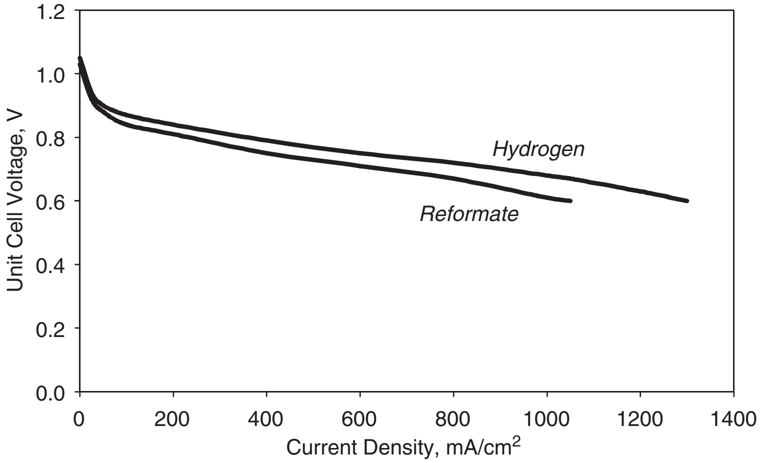

Fig. 2. Cell voltage as a function of current density of the proton exchange membrane fuel cells used in this study, 100% hydrogen use (upper curve) and gasoline reformate (lower curve).

Table 5
Overall fuel cell system efficiencies (in percent), defined as net DC output power divided by the lower heating value of fuel input

Net output energy, % of peak	100% H_2 fuel	Gasoline reformate
5	71	42
10	71	45
20	70	44
40	65	42
60	61	39
80	58	37
100	50	33

Combining these losses leads to overall FC system efficiencies, which are reported in Table 5. (Losses (and regenerative gains) downstream of the stack, in the electrical traction system and controls, are excluded.) These efficiencies take into account performance degradation of components due to design compromises needed to obtain the best combination of important characteristics of the total powerplant in the vehicle. Examples of such compromises—often to reduce cost, weight, or space or to provide for warmup 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 more practical stack design and operation. Lacking any specific way, currently, to estimate these losses for the total integrated system, we have assumed an increase of 5% in the losses in each component. These assumed losses due to integration result in significant increases in fuel consumption relative to the individual "component" losses for the FC vehicles evaluated above. Consumption of on-board fuel per vehicle km traveled increases between 9% and 23% depending on the driving cycle, fuel, and hybridization.

For all hybrid systems the battery and electric motor were sized to provide a ratio of peak battery 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. Although these hybrids provide short-time vehicle acceleration comparable to non-hybrids, they have inferior sustained performance at higher speeds while climbing long hills or towing heavy loads. We did not attempt to optimize hybrid designs by varying the relative battery and engine sizes. Choosing "optimum" designs would depend on selecting which specific characteristics (e.g., cost, fuel economy, or performance) should be given priority. Our sensitivity tests have shown that the impact of battery and engine size variations on vehicle energy use are of "second order".

4.5. Drive train and vehicle costs

Cost estimates of future technologies are necessarily rough, as they should not only reflect the research, development, and production costs (along with potential economies of scale), but also their markup in a competitive environment. Given the uncertainty associated with each of these components, the simplified approach adopted here is to add carefully reviewed costs of additional components required, to and subtract those of the components removed from the price of the reference vehicle. Table 3 (bottom) reports the projected 2020 costs of the vehicles examined. Starting from a vehicle base price of US$ 21,600, the costs of added GHG emission reduction technologies and credits for subtracted components are indicated. Engine modifications consist of the costs of variable valve lift and timing (US$ 80 per cylinder), gasoline direct injection (US$ 140 per cylinder), turbocharged, direct injection diesel engines (US$ 1,650), and exhaust gas catalysts to satisfy Tier 2 emission standards (see [3] for details). Potential credits resulting from downsizing the engine of the reference vehicle have not been taken into account, as a smaller engine requires countermeasures to reduce the higher level of vibrations and noise. The retail price increment associated with the ICE hybrid vehicles is based upon electric motor costs of US$ 16.5/kW and battery costs of US$ 440/kWh plus US$ 660 for thermal and electrical management of subsystems [22]. FC costs were assumed to be US$ 66/kW and those of processors US$ 22/kW, which are consistent with the inflation-adjusted costs given in [3]. The negative sign for FC vehicles represents the credit for the ICE and transmission (based upon US$ 35/kW) and catalytic converter. The lifetime of the FC stack is assumed to be 5000 h, which is consistent with the US Department of Energy's technical target. Given an average vehicle usage of 1 h per day, the stack lifetime translates into 14 years or about one vehicle lifetime. We also assume that high-power batteries will last for the equivalent of one vehicle life, which is consistent with recent progress in NiMH battery technology [23].

As that section of Table 3 shows, fuel efficiency improvements come at a cost. While the 20-year ahead evolving vehicle is about 6% more expensive than the 2001 reference car, the projected retail price of the advanced vehicles is between 11% (advanced gasoline fueled vehicle with mechanical drive train) and 47% (advanced gasoline-fueled FC electric vehicle) higher. The capital costs of the most fuel-efficient vehicle, the hybrid hydrogen FC vehicle, are 43% higher than that of today's average car and 35% higher than those of the evolving car 20 years ahead.

It has to be stressed that the projected retail prices are for new vehicles sold about 20 years from now. Using that time horizon, the automobile industry should have sufficient time to change production plans, at least for improvements and changes in mainstream IC engines, transmissions, and vehicle technology, without early retirement of unamortized equipment and tooling, which would result in additional costs.

5. Vehicle manufacturing, distribution, and disposal

This second part of the vehicle cycle includes materials processing and forming, parts assembly, distribution of the assembled vehicle, and vehicle scrappage and disposal at the end of the vehicle's lifetime. Although vehicle maintenance and repair are also integral components of the vehicle cycle, there is virtually no information available on their energy impact, and thus we had to neglect this stage of energy use and emissions.

Accounting for about two-thirds of the primary energy used, materials production is by far the most energy-intensive stage within this part of the vehicle cycle. Based on a literature survey we have tabulated material compositions of all major vehicle components. For example, the reference vehicle spark-ignition engine consists of roughly 70% ferrous metals, 20% aluminum, and 10% plastics. These shares were then multiplied by the engine weight and subsequently added to the respective material categories. (Because of the lack of a detailed model that estimates the structural characteristics of vehicle bodies using different materials, this rough material life-cycle analysis neglects all materials with a share smaller than one percent of vehicle weight.) Table 3 reports the resulting aggregated material composition of all the vehicles examined. While ferrous metals account for about two-thirds of today's automobiles, a shift to an aluminum body along with enhanced aluminum use in other vehicle components reduces that share to about 40%. At the same time, the aluminum content rises from below 10% to 20–30%.

The associated energy use was initially estimated by multiplying the mass of individual materials with the approximate primary energy use required for producing these materials, neglecting the different types of manufactured parts and thus levels of energy use. The averaged primary energy intensities range from 30 MJ/kg of window glass to 220 MJ/kg of virgin aluminum. We next examined the energy use resulting from an aggressive recycling-based strategy; in that case, the primary energy intensities are significantly reduced and account for only 15 and 40 MJ/kg of window glass and aluminum, respectively. See [3] for details. Multiplying these numbers by the mass of the individual materials results in total energy use. We assumed intensive use of recycled materials (95% of all metals and 50% of glass and plastics) in vehicle manufacturing. Prorating material processing energy use and GHGs over 300,000 km (vehicle life of 15 years driven 20,000 km/year), results in an energy use of 0.15–0.19 MJ/km, depending on the powertain/glider combination. Note that these high recycling fractions are "steady-state" values. During the transition "build-up" phase, due to the delays in recycling resulting from the 15 year lifetime of the light-duty vehicles, energy use and GHG emissions would initially be the "zero recycle" values and only gradually transition to the "steady-state" values. Thus initial per vehicle impacts would be higher (see also Fig. 7 below and related text).

Vehicle assembly accounts for the second largest share in energy use and GHG emissions in this part of the vehicle cycle. Since larger vehicles require more energy for transport during assembly, represent more area to bond and paint, and have larger, more massive parts to stamp or fabricate, they require more assembly energy. Because of the complex supply chain in the automobile industry and the associated difficulty in estimating vehicle assembly energy requirements, assembly energy is typically estimated as a linear function of vehicle mass. The typical range of assembly (primary) energy is 17–22 MJ/kg [24,25]. On a final energy basis, typically about 40–50% is consumed in terms of electricity [25,26]. Thus, we assume that 13 GJ of primary energy is converted to electricity (with a carbon emission factor 54 kgC/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).

According to the 1997 US Commodity Flow Survey, the average distribution distance of a light duty vehicle is about 750 km [27]. Although the total weight of the shipped vehicles is roughly split equally between trucks and railways, the longer average distribution distance of the latter causes three times as many ton km (tkm) to be generated by rail compared to trucks. Given average energy intensities of 0.23 MJ/tkm for rail [28] and around 1.7 MJ/tkm for tractor–trailer combinations [29], the average energy use needed to transport a vehicle from the assembly line to the dealership is about 0.60 MJ/kg of vehicle; if taking into account a fuel cycle efficiency for diesel fuel of 87.8% (Table 1), the related primary energy equivalent corresponds to 0.68 MJ/kg of vehicle.[4] After a vehicle's life, energy is consumed in shredding the automobile and sending its non-recycled portion to a landfill. Again, the disposal energy is estimated to be a linear function of vehicle mass. The disposal energy consists of the energy needed to move the hulk from a dismantler to a shredder (0.31 MJ/kg of material, assuming a truck energy intensity of 1.7 MJ/tkm, a diesel fuel cycle efficiency of 87.7%, and an average transport distance of 160 km) and the shredding energy (0.37 MJ/kg of material) [30].

Table 6 summarizes the resulting GHG emissions of material production, vehicle assembly, vehicle distribution, and scrappage of the retired car. The emission levels are about 5 gC_{eq}/km, with a spread of up to ±10% in nearly all cases. The only exception is the gasoline FC vehicle, where the comparatively high emissions from materials production (that result from the fuel processor and larger FC) cause total vehicle cycle GHG emissions to be 20% above the average.

6. On-the-road and life-cycle analysis results

The bottom part of Table 3 reports the on-board fuel energy use in all the vehicles examined for all the driving cycles considered. For the combined US driving cycle, fuel use for the current 2001 vehicle is 2.48 MJ/km (7.7 L/100 km, 30.6 mpg). Over the course of the next 20 years, low-cost evolutionary improvements in engine, transmission, weight, and drag can reduce vehicle energy consumption by nearly 30% to 1.75 MJ/km (5.4 L/100 km, 43 mpg)—the gasoline-fueled, evolving baseline vehicle. The associated retail price increase is

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[4] As shown in Table 6, energy and greenhouse gas emissions from vehicle distribution account for only 1% of those from vehicle manufacturing, distribution, and disposal. Thus, their sensitivity with regard to the distribution distance and mode is very small.

Table 6
Greenhouse gas emissions (gC_{eq}) per kilometer driven in the vehicle cycle, consisting of materials production, vehicle assembly, vehicle distribution, and scrappage of the retired vehicle

	$REFV_G$	$EBLV_G$	AV_G	$HICEV_G$	AV_D	$HICEV_D$	FCV_G	$HFCV_G$	FCV_{H2}	$HFCV_{H2}$
Materials	3.28	2.90	2.86	2.96	2.99	3.05	3.71	3.32	3.34	3.14
Assembly	1.63	1.38	1.24	1.27	1.31	1.32	1.83	1.55	1.59	1.43
Distribution	0.06	0.05	0.05	0.05	0.05	0.05	0.07	0.06	0.06	0.05
Scrappage	0.04	0.03	0.03	0.03	0.03	0.03	0.04	0.03	0.03	0.03
Total	5.00	4.35	4.17	4.32	4.38	4.45	5.65	4.97	5.03	4.66

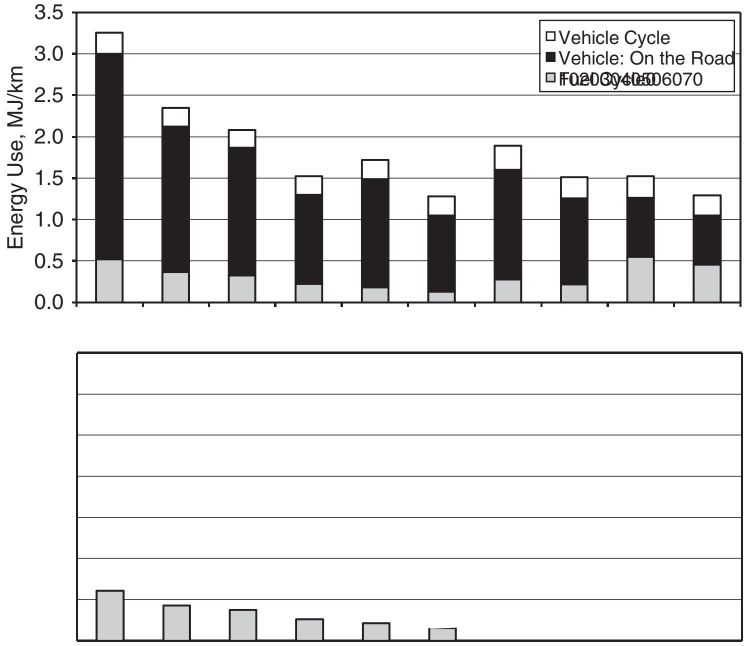
about 6%. Significant further reductions are possible up to about 0.6 MJ/km in the case of the hybrid, hydrogen-fueled FC vehicle. However, these additional reductions in tank-to-wheels energy use also result in a more significant increase in the retail price; that of the hybrid, hydrogen-fueled FC vehicle rises by 34% compared to the evolving baseline vehicle.

The extent of the fuel consumption reduction depends importantly on the way in which the vehicle is driven. The greatest fuel consumption benefit of hybrid vehicles occurs in urban driving, where ICE hybrids offer about a 33% lower fuel consumption than their mechanical drive train counterparts. That reduction in fuel use declines to 25% in highway driving and about 10% in the high acceleration US06 cycle. Due to the inherently more energy-efficient part-load performance of FCs, the additional energy-consumption benefit of hybrid drive trains is smaller.

While the energy consumption values in Table 3 are “on-the-road” numbers, Figs. 3a–c include energy consumption, GHG emissions, and costs of all the life-cycle components—fuel and vehicle production and distribution, and vehicle use. Both life-cycle energy use and GHG releases from all four of the hybrid vehicles considered are between 54% and 65% of our 2020 baseline vehicle, and between 39% and 47% of our current 2001 reference vehicle. In contrast to the on-the-road numbers, the least amount of life-cycle energy use and GHG releases is now provided by two hybrid vehicles: the diesel ICE and the hydrogen FC automobile. (The gasoline ICE and FC hybrids appear to be not quite as fuel-efficient but considering the uncertainties of the results, not significantly different from the two other hybrids.) Note that the hydrogen for the hybrid FC vehicle is obtained from natural gas, the currently cheapest and most practical means of production. However, this approach, as Fig. 3b indicates, does not reduce GHG emissions compared to the diesel ICE hybrid vehicle. Whether or not FC vehicles can reach the levels of performance assumed here, several different propulsion system and vehicle technology opportunities exist to develop light-duty vehicles capable of major reductions in energy and GHGs from personal travel.

The largest single share of life-cycle energy use, ranging from 46% to 76% of the total, results from vehicle operation. Similarly, the largest single share of GHGs, from 67% to 74%, can be attributed to vehicle operation except for hydrogen fuel where the fuel production and distribution cycle accounts for about 80% of the total. With higher on-the-road fuel economies and shift toward lighter and more energy-intensive materials, vehicle manufacturing increases its share of energy and GHGs up to about 20%, corresponding to the fuel cycle share in about half of these 2020 vehicles.

Finally, Fig. 3c reports the life-cycle costs of all vehicles examined. The vehicle retail price is annualized over 15 years using a consumer discount rate of 12%/yr. The underlying crude oil price is US$(2001) 29.2/bbl, which translates into fuel cost of US$ 10.0/GJ ($ 0.32/L), when a refinery margin and fuel distribution costs of US$ 4.3/GJ is added. Since fuel costs account for only 13.5% of the total costs for owning and operating the 2001 reference vehicle, none of the more fuel-efficient vehicles is economically more attractive to US consumers. Increasing the projected 2025 oil price to US$(2001) 58.4/bbl (fuel costs of $ 15.7/GJ at the retail station) would make the evolving baseline vehicle the lowest-cost vehicle option. Another doubling of the crude oil price would be required to make the next expensive alternative cost-competitive, i.e., the advanced diesel vehicle with a mechanical drive train. Remember, however, that the price to the consumer associated with these oil prices excludes profit margins and gasoline taxes. For comparison, a “European” fuel price level of about US$ 1.5/L or US$ 46.5/GJ would make all non-FC vehicles competitive to both the 2001 reference vehicle and the 2020 evolving baseline vehicle, if amortizing low GHG-emission technology over the full vehicle lifetime.



Increased vehicle use can compensate for some of the higher capital costs of alternative vehicles, but that usage would need to be implausibly high at low fuel prices. At the reference oil price of US$ 29.2/bbl (or a fuel price of $ 10.0/GJ), the next cost-effective alternative to the evolving baseline vehicle, i.e., the advanced diesel mechanical drive train vehicle, would require an annual distance driven of 50,000 km to become cost effective. That break-even distance would decline to 33,000 km in the scenario with two-fold crude oil prices, i.e., US$ 58.4/bbl (or a fuel price of $ 15.7/GJ). Due to their higher retail price, the break-even distance of all other alternative vehicles would be larger.

7. The fleet impact of fuel-saving vehicle technology

Given the substantial potential through technologies for reducing new automobile GHG emissions over the next 20 years and beyond, we now examine the extent to and timeframe within which such advanced technologies can contribute to reducing GHG emissions of the total automobile fleet. The timespan from a technically viable concept to achieving a significant impact from use of that technology on vehicle fleet energy consumption and emissions can be separated into three stages: the time required to achieve market competitiveness, the penetration of such fuel saving technology across new vehicle production, and the penetration of these produced and sold new vehicles into the total vehicle fleet. We discuss and apply this framework to two of the projected vehicles, i.e., the hybrid, gasoline fueled internal combustion engine vehicle ($HICEV_G$) and the hybrid, hydrogen-fueled fuel cell vehicle ($HFCV_{H2}$). Since automobiles account for a continuously declining share of the light duty vehicle fleet, we also simulate the fleet impact of the examined technologies on the light truck fleet. To obtain the fuel efficiency improvement potentials for that vehicle segment, as a rough approximation, we scale those of related automobile technologies using the current average light truck fuel consumption as a base point.

7.1. Achieving market competitiveness

The dimensions of market competitiveness include overall vehicle performance (acceleration, fuel consumption, emissions, durability and reliability, safety, quality), convenience, and costs. While the first two characteristics are necessary prerequisites for any vehicle sale, costs will determine whether the new vehicle will ultimately penetrate beyond niche market levels. Unfortunately, short amortization periods leave little room for cost-effective fuel efficiency improvements. Several studies suggest that consumers may be willing to amortize extra costs associated with the purchase of fuel-saving technology over only 3 years [31]. When applying that short amortization period to the projected 2020 vehicles, none of them would be cost-competitive to the 2001 reference vehicle in the US today, even in a world with crude oil prices of US$ 58/bbl.

However, two reasons exist why many of the projected vehicles can become cost-competitive during the next 5–10 years or so. First, cost-competitiveness increases with income. As evidenced by historical US data, the average price of an automobile has approximately grown in proportion to GDP/cap[5] [28,30]. If GDP/cap continues to grow at the historical (1970–2000) rate (resulting in a 46% increase through 2020) and consumers no longer trade off improved fuel consumption for ever increasing levels of driving performance and comfort, all projected "advanced" automobiles would become cost-competitive to the 2001 reference vehicle by 2020. Due to their comparatively low retail price increase, most non-FC vehicles would become cost-competitive within a few years only. Second, while the projected income figures are based upon mean values, the skewed income distribution causes the time horizon to be even shorter for higher income groups.

Thus, when combining these affordability considerations with the anticipated state of technology characteristics (performance, convenience), we estimate that slightly less fuel-efficient versions of the $HICEV_G$ vehicle will become market competitive in about 5 years. Due to the significantly less mature stage of on-board FC technology development and the limited hydrogen supply infrastructure, we estimate an additional 10 years to achieve market competitiveness for the $HFCV_{H2}$. With the ongoing integration and refinement of fuel-saving technologies, these vehicle technologies would reach the fuel consumption level projected in Table 3 by 2020; further incremental technology improvements could then lead to an additional 7% reduction in fuel use by 2030. The trajectories of declining fuel consumption relative to the 2001, gasoline-fueled reference vehicle ($REFV_G$) are shown in Fig. 4. The projected fuel consumption trajectory for the $HICEV_G$ starts with the already demonstrated 38% lower fuel consumption level, the current Toyota Prius relative to the 2001 $REFV_G$, after adjusting for the vehicle mass difference. The same figure also illustrates the trajectory for the $HFCV_{H2}$, assumed to be available at around 2015–2020.

7.2. Penetration across vehicle production

Once a vehicle becomes market competitive (with regard to all the dimensions discussed in the previous section), this second phase—penetration across new vehicle production—depends upon the production plans

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[5] Between 1970 and 2001, the average price of a new car has increased from US$(1970) 3542 to US$ (2001) 21,605, i.e., by a factor of 6.1. During the same time, GDP/cap has grown from US$(1970) 1948 to US$ (2001) 25,616, i.e., by a factor of 6.9.

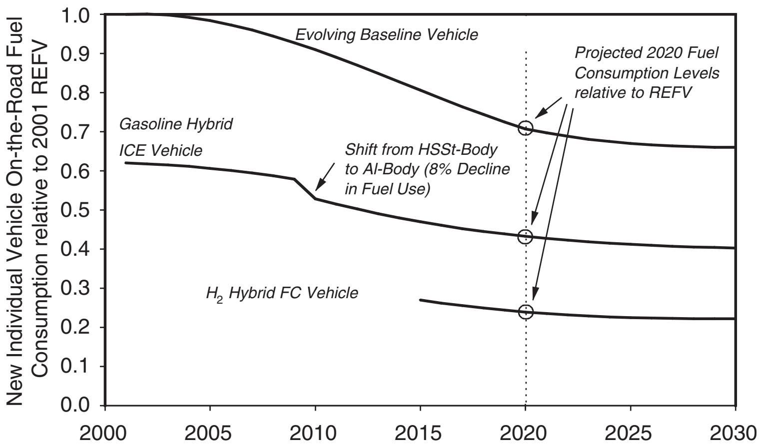

Fig. 4. Automobile fuel consumption relative to the 2001 reference vehicle for the evolving baseline vehicle, the gasoline-fueled, hybrid ICE vehicle, and the hydrogen-fueled, hydrogen fuel cell vehicle.

of the automobile industry,[6] which significantly depend on the market risk the industry is willing to take by producing an increasing share of vehicles with a new fuel-saving technology, and the availability of the capital required to expand the production volume of new technologies required. According to a historical analysis, some "new automobile components or production methods were introduced almost instantaneously, but more often the process lasted 10–30 years before the new technology was embodied in one half of new cars" [32].

We note that the spread of high-speed direct-injection diesel engine technology in major European countries has taken some 20 years to capture about 50% of new vehicle market share. ICE hybrid production penetration rates are likely to be slower, since much of the technology is new to the light-duty vehicle market. FC production penetration rates can only be guessed: they are likely to be still slower. Thus, we have assumed the $\mathrm{HICEV_G}$ to enter the market at a virtually zero rate today, gradually increase to 2.1% in 2010 (or nearly 400,000 vehicles, i.e., slightly more than twice the current US hybrid vehicle production), and ultimately level off at 50% market share of new automobiles sold in 2030. (The saturation level of 50% in 2050 implies a rapid increase in hybrid vehicles after 2010.) The other half of the new vehicles sold would be propelled with a mechanical drive train (spark-ignition or diesel engine), the lower cost option for smaller-sized vehicles. By contrast, the $\mathrm{HFCV_{H2}}$, introduced in 2015, achieves 1% market share in 2023, represents 12% of all new vehicles produced in 2030, and—because of a potential large-scale transition toward hydrogen—continues to grow to levels of above 50% thereafter. As the reader will notice, these are aggressive production penetration scenarios, and were chosen to illustrate the "maximum feasible" impact.

7.3. *Vehicle fleet penetration*

Assuming a significant increase with time of more fuel-efficient technology across vehicles sold in a given year, it would still take considerable additional time for that gain in fuel efficiency to achieve impact on a total fleet level. The mathematical formulation of such fleet turnover effects is straightforward.

If n is the number of new vehicles introduced in a given year τ, in each succeeding year a growing number of these vehicles will be retired. Assuming an identical, logistic shape (B, T_0) of the vehicle fleet's "death curves" over time, the number of vehicles, introduced in year τ, remaining in the fleet in any given year is given by

$$r(t) = \frac{n(\tau)}{1 + \mathrm{e}^{-B(t-(\tau+T_0))}}, \qquad (1)$$

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[6] When the vehicle goes into mass production, its competitiveness may further increase as learning-by-doing effects materialize.

where B is the parameter that describes the rate of vehicle withdrawal at the mean lifetime T_0. For example, assuming a mean vehicle lifetime of ($T_0 =$) 15 years, at ($t =$) 2000, the fleet of vehicles introduced in ($\tau =$) 1985 is only $n(1985)/2$ (i.e., half the original number). The size $s(t)$ of the total vehicle fleet at any given year is then simply the sum of all remaining vehicles introduced at different years τ, i.e.

$$s(t) = \sum_{\tau=t_0}^{\tau=t} \frac{n(\tau)}{1 + \mathrm{e}^{-B(t-(\tau+T_0))}} \tag{2}$$

with $t_0 \leqslant t - 2T_0$.

The latter condition ensures a sufficiently large summation interval for the build-up of the vehicle fleet. (Nearly all vehicles older than $t{-}2T_0$ have in practice been phased out.) Getting from fleet composition to total vehicle fleet energy use (E) requires multiplying the vehicles introduced in a given year by the corresponding new vehicle fuel consumption ($FC(\tau)$) and (the decline in) annual distance traveled as vehicles age ($ADT(t{-}\tau)$). Thus,

$$E(t) = \sum_{t_0}^{t} \frac{n(\tau) \cdot FC(\tau) \cdot ADT(t-\tau)}{1 + \mathrm{e}^{-B(t-(\tau+T_0))}} \tag{3}$$

with $t_0 \leqslant t - 2T_0$.

7.4. The impact of advanced vehicles on the US light duty vehicle fleet

We now use the vehicle stock model (Eq. (3)) to assess the GHG emission impact of the $\mathrm{HICEV_G}$ and the $\mathrm{HFCV_{H2}}$ for both automobiles and light trucks. As suggested by Eq. (2), a simulation of the future size of the vehicle fleet requires projected annual levels of the number of new vehicles to be introduced through 2030 ($n(\tau)$), the mean lifetime of a vehicle (T_0), and the parameter describing the initial growth rate of vehicle withdrawal (B). We assume the new vehicle fleet, consisting of 51% automobiles and 49% personal trucks in 2001, to increase in proportion to population growth, i.e., by 0.8%/yr [33]. To obtain the size of each of the two segments (automobiles and light trucks), we further assume the share of new personal trucks to continue to increase and level off at 60% market share in 2030; intermediate shares are estimated using a logistic function. In combination with the 26% increase in the light duty vehicle fleet, the projected decline in the automobile share of light duty vehicles results in an approximately constant level of the new automobile fleet of 8.5 million vehicles through 2030 compared to 12.6 million light trucks.

The mean vehicle lifetime (T_0) and the slope parameter (B) were derived from historical US automobile cohort data published by Wards [34]. An analysis of that data suggests that the median lifetime of an automobile was only about 10 years during the two oil crises in the 1970s, probably because of the early retirement of more fuel-intensive vehicles. After the second oil crisis, the median lifetime has increased to about 15 years in 1995; absent any drastic change in fuel prices we assume that value to remain constant through 2030. Since our stock model works with mean values, we multiply all median lifetimes by a factor of 1.16,[7] which causes a close match of the simulated vehicle stock predictions with actual data; this factor is roughly consistent with that underlying the vehicle scrappage data reported by Davis and Diegel [28]. Our analysis of historical Wards data also suggests that the slope parameter (B) is positively correlated with the median vehicle lifetime, i.e., $B = -0.5168 + 0.0201T_0$ ($R^2 = 0.9043$). Apparently the increase in the median vehicle lifetime causes a greater vehicle retirement around the median lifetime; fewer vehicles are retired early on. (To keep the discussion tight, we only report the model parameters for the automobile fleet; those related to light trucks are available from the authors.)

Shifting from the vehicle stock to total vehicle-km traveled requires a projection of the average annual distance traveled by a new vehicle. Since 1986, the onset of roughly constant fuel prices, automobile km traveled have increased at an average rate of 1.3%/yr. Since with continuously rising income the value of (travel) time increases too, we assume only a quarter of that rate, i.e., 0.33%/yr, to apply through 2030. While the annual distance driven continues to increase on average, it differs substantially among individual vehicles.

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[7] The mean lifetime of an automobile is higher than the median, due to vehicles in the fleet with a very high age.

Empirical data shows that the annual distance traveled declines with vehicle age; according to US travel survey data, the average usage degradation rate has declined from 8.5%/yr in 1983 (a period of high oil prices) to 3.7%/yr today, probably because vehicles have become more robust and reliable [28]. We assumed the latter rate to remain constant through 2030.

Finally, a simulation of fleet fuel use requires fuel consumption levels for new vehicles. We use the already adjusted numbers from the US Environmental Protection Agency [35]. To match the model projected fuel use with the numbers reported in Highway Statistics [36], we multiply all annual EPA fuel consumption figures by a factor of 1.10. This correction appears to be necessary in part because the EPA fuel consumption adjustment factor of 17% does not capture all the inefficiencies that occur under real driving conditions, and because our simple stock model does not distinguish between different vehicle size classes with different fuel consumption levels and mean vehicle lifetimes. (Larger vehicles may live comparatively longer and thus increase total fuel use.)[8]

The simple stock model was tested by comparing the estimated historical trends in size, kilometer traveled, total fuel use, and fuel use per kilometer traveled of the US automobile fleet (continuous lines in Figs. 5a–d) to the transportation statistics derived data (data points in Figs. 5a–d). Because it takes the order of a vehicle lifetime to turn over the in-use vehicle fleet, a match between the model predictions (continuous curves) and the actual fleet data (data points) is only expected after 1980.

We now use the projected fuel consumption levels for the $\mathrm{HICEV_G}$ and the $\mathrm{HFCV_{H2}}$ shown in Fig. 4 to simulate future fuel consumption levels by the US light duty vehicle fleet (automobiles and light trucks). Multiplying the gasoline fuel use by 32.2 MJ/L and 19.6 gC/MJ and subsequently adding the projected fuel cycle and vehicle cycle GHG emissions leads to total light duty vehicle fleet life-cycle GHG emissions. The latter are shown in Fig. 6 for various scenarios of vehicle technology introduction. If technology-based fuel efficiency improvements will be traded for larger, more powerful vehicles and additional passenger amenities instead of reducing vehicle fuel consumption, total vehicle fleet life-cycle GHG emissions increase by about 60%, from about 420 MtC in 2001 to about 670 MtC in 2030; the associated cumulative emissions (2002–2030) result to 16.2 GtC.[9] These emission levels can be significantly reduced when introducing fuel-saving technologies. In the case of the $\mathrm{EBLV_G}$ with further gradual fuel efficiency improvements beyond 2020 (upper trajectory in Fig. 4), the 2030 emissions level can be reduced by slightly more than one-quarter (dashed line A), while cumulative emissions decline by 11%. About the same 2030 emissions level can be achieved through a later starting, but aggressive, introduction of $\mathrm{HICEV_G}$'s, accounting for 1% of all new vehicles sold in 2008, three stages that new technology must go through before it can have significant impact on in-use vehicle fleet fuel consumption and GHG emissions. Four of the examined powertrain–vehicle combinations are shown: the advanced gasoline engine vehicle (AV_G), the advanced high-speed diesel engine vehicle with effective exhaust treatment systems for particulates and NO_x (AV_D), the hybrid, gasoline-fueled internal combustion engine vehicle ($HICEV_G$), and the hybrid, hydrogen-fueled FC vehicle ($HFCV_{H2}$). The first three technologies are at

Table 7
Light duty vehicle carbon dioxide emissions, absolute and cumulative for the examined cases

	Emissions (MtC_{eq}) 2030		Cumulative Em. (GtC_{eq}) 2002–2030	
	Absolute	% Reference	Absolute	% Reference
Reference case	671	100	16.2	100
Evolving baseline ($EBLV_G$)	491	73	14.4	89
ICE hybrid ($ICEV_G$)	489	73	14.8	91
H_2 hybrid fuel cell ($HFCV_{H2}$)	660	98	16.2	100
$EBLV_G$ & $HFCV_{H2}$	383	57	13.5	83

Notes: The reference case has constant 2001 fuel efficiency of all new light-duty vehicles through 2030, the evolving baseline has gradual fuel efficiency improvements to meet the projected level of the $EBLV_G$ in 2020 and continuous gradual improvements thereafter, ICE hybrid vehicle penetration case achieves saturation at a market share of 50% of new vehicles sold in 2030, the hybrid hydrogen fuel cell vehicle ($HFCV_{H2}$) case has a market share of 12% of new vehicles sold in 2030 with further growth thereafter.

Table 8
Time scales for significant US fleet impact

Implementation stage	Gasoline DI spark-ignition downsized engine AV_G	High-speed DI diesel with particulate trap, NO_x catalyst AV_D	Gasoline SI engine/battery-motor hybrid $HICEV_G$	Fuel cell on board hydrogen storage $HFCV_{H2}$
Market competitive vehicle[1]	~5 years	~5 years	~5 years	~15 years[2a]
Penetration across new vehicle production[3]	~10 years	~15 years	~20 years	~25 years[2b]
Major fleet penetration[4]	~10 years	~10–15 years	~10–15 years	~20 years[2c]
Total time required	~20 years	~30 years	~35 years	~55 years

Notes:

[1] Market competitive means competitive overall vehicle performance, cost, and convenience.

[2] Hydrogen infrastructure developed to necessary scale and availability for each technology stage: (a) limited hydrogen supply system, (b) significant distributed hydrogen supply system, and (c) major hydrogen infrastructure in place.

[3] Production penetration times scaled from prior examples.

[4] Significant in-use fleet penetration (two-thirds mileage driven) based on average vehicle lifetime (15 years), newness of technology, and (where appropriate) hydrogen infrastructure scale requirements.

least one development cycle (3–5 years) from market viable status. The production build-up timescales are 10–20 years, depending on the scale and "newness" of the technology. In-use fleet penetration times are a minimum of 10 years, and could be much longer. While there is some overlap between production expansion and in-use fleet penetration, it is modest and has been allowed for.

As can be seen, total timescales to significant impact are 25–50 plus years. And these timescales assume that intensive effort is now going into the technology development stage of this total timescale. What is important is that a framework such as that used in Table 8 be used to estimate these impact timescales. These three steps all have to occur in sequence with only modest time savings available due to the overlap between production penetration and in-use fleet penetration. Understanding these limited short-term opportunities for reducing GHG emissions through technology changes is also important when designing relatively near-term GHG emission reduction schemes such as the Kyoto Protocol.

The life-cycle GHG emissions shown in Fig. 6 also include those released during the production of vehicle materials, in particular those resulting from the comparatively energy-intensive aluminum electrolysis. As shown in Table 3, the hybrid ICE and FC vehicles include a significant (about 30%) share of aluminum, compared to below 10% for the $REFV_G$ and $EBLV_G$. Since insufficient amounts of secondary aluminum are

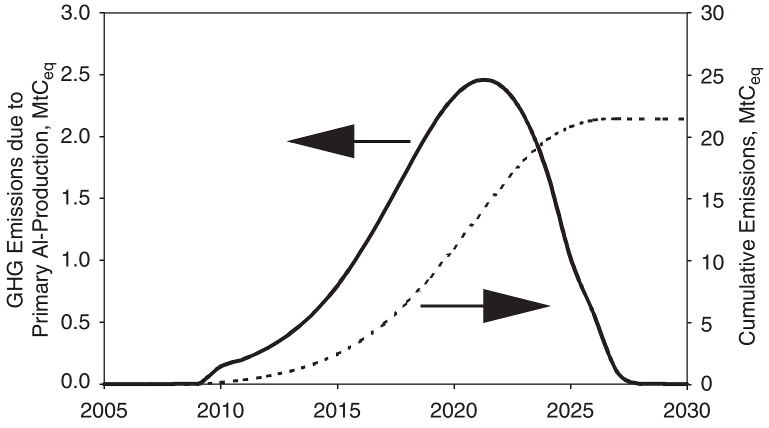

Fig. 7. GHG emissions resulting from primary Al-production during the introduction of the hybrid internal combustion engine vehicle, annual (left scale) and cumulative (right scale).

available at the beginning of the introduction of the $HICEV_G$ and $HFCV_{H2}$, nearly the entire demand for aluminum needs to be satisfied with more energy-intensive primary material. Fig. 7 indicates the increase in GHG emissions due to the production of primary aluminum during the introduction of the $HICEV_G$.[10] Over time more and more aluminum intensive hybrid vehicles are retired, proving a growing resource base of secondary aluminum. By 2026 a sufficient amount of scrapped aluminum would be available, requiring no further primary aluminum production. Although the primary Al-related carbon emissions, at their height, account for 2.5 million tons of carbon equivalent (a cumulative amount of 22 MtC_{eq}), they are small when compared to the level of total life-cycle GHG emissions.

8. Conclusions

Compared to the average new automobile sold in the US today, a combination of existing and emerging fuel saving technologies can reduce fuel consumption of new automobiles by nearly 30% over the next 20 years. Since two decades provide ample time for further technology advance and for adjusting the production equipment and tooling, our economic assessment suggests an associated increase in retail price of only about 6%. Although a significant potential exists for further reducing energy use and GHG emissions through use of more sophisticated technology (diesel and hybrids), subsequent reductions would result in a larger increase in the vehicle retail price, and the large-scale market appeal of these technologies is uncertain.

While lowest levels of on-the-road energy use and GHG emissions can be achieved with the hybrid hydrogen FC vehicle, these vehicles perform similar to hybrid ICE diesel vehicles when compared on a life cycle basis with hydrogen produced as it is today from natural gas. Only slightly higher amounts of energy use and GHG emissions are emitted by hybrid ICE and standalone FC gasoline vehicles. Our life-cycle assessment thus suggests that—until beyond 2030—no clear advantage of FC vehicles exists with regard to energy use or emissions of GHGs. The hydrogen consumed would need to be produced from non- or low-carbon releasing processes for a significant FC technology benefit to result.

The production, distribution, and disposal of today's vehicles accounts for less than 10% of life-cycle energy use and GHG emissions. However, that share increases substantially with higher vehicle fuel-efficiency. For a number of the vehicle concepts examined, energy use and emissions resulting from vehicle manufacturing exceed those from producing and distributing fuel. Thus, the production stage of the total life-cycle analysis needs to be studied in more detail.

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[10] Based upon the 2020 electricity generation mix, projected by the US Energy Information Administration (EIA, 1999), the GHG emission factor results in 194 gC_{eq}/kWhel; this number already includes 9% transmission losses and 2 g carbon emissions from methane releases during coal mining.

The impact of improved-technology vehicles on automobile fleet energy use and emissions depends on the time required to achieve (i) market competitiveness, (ii) significant market shares of new vehicle sales, and (iii) a significant penetration into the existing vehicle fleet. Since the evolving baseline vehicle requires the shortest time for becoming market competitive and for achieving significant market shares of new vehicle sales (since it imposes the lowest risk for vehicle manufacturers), such vehicles can provide substantial reductions in fleet energy use and GHG emissions relatively early on.[11] In contrast, hybrid hydrogen FC vehicles are still far from becoming market competitive. Our analysis shows that even if we assume these vehicles start to enter the new vehicle market in 2015, it will be well into the second half of the 21st century before significant reductions in fleet energy use and GHG emissions can be anticipated. The largest reduction in fleet energy use and GHG emissions can be achieved through a combination of fuel efficiency improvements in more conventional vehicle designs combined with a rapid introduction of hybrid ICE vehicles.

Hydrogen fuel and FC vehicles are potentially important in the longer term if the hydrogen is produced with much lower carbon emissions than would occur with the currently used production from natural gas. Thus, a comprehensive short- and long-term strategy for reducing automobile energy use and emissions includes both the continuous improvement of ICE vehicles and simultaneous research and development of hydrogen FC cars.

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