

History and Status of the Hybrid Electric Vehicle (HEV)

By Pat Murphy, Plan Curtail



1997 Toyota Prius – First Delivered in December 1997



2012 Toyota Prius c – Delivered in Mid 2012

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Introduction

The Prius Hybrid Electric Vehicle (HEV) represented approximately a billion dollar investment by Toyota to develop a compact car rated at 41 MPG. The program began in 1993 with initial Japan shipments in late 1997 and first shipments in the U.S. in late 2000. The MPG rating was about twice the average MPG of an equivalent 2000 car in the U.S.¹ The research and development (R&D) budget for the automobile industry is over \$100 billion dollars annually.² For about 1 percent of one year's R & D, an innovative major improvement was made in gasoline engine efficiency. There have been other billion-dollar efforts in the past that have resulted in little or no difference in MPG, including the diesel hybrids of the U.S. PNGV program, fuel cell cars, and the BEVs of the Californian Air Resources Board (CARB) era of the late 1990s. The gasoline HEV represents the most significant technological improvement in fuel economy achieved in the last three decades.

A very fuel efficient car such as the Prius HEV will sacrifice some attributes, including weight, size, style, convenience, and a sense of personal power. On the other hand, the car is much less expensive to buy and operate, and it does far less environmental damage. Typically, a car is purchased, driven for some time by its original owner, sold into the used car market, and passed through other owners for a period of about 14 years, at which time it is scrapped. It requires a substantial owner investment, including the purchase price, the costs of fuel, insurance, and repairs. If the purchaser's objective is both economical and ecological, then the Prius is the best choice available over hundreds of other cars. In 2009, *Consumer Reports* found the Prius to have the highest value rating of more than 300 cars it had recently tested.³ In 2011, a similar *Consumer Reports* value study was made. The Prius was ranked third.⁴ However, its 50 MPG rating was much higher than the 30 MPG and 39 MPG ratings for the other two value leaders.

As noted in earlier reports, the battery electric vehicle (BEV) and plug-in hybrid electric vehicle (PHEV) MPG numbers have been misrepresented by our government, automobile companies, utility organizations, large nonprofit organizations, and special-interest nonprofit groups.^{5, 6} There is little economic or ecological advantage to buying such cars. For the next two decades, gasoline HEVs such as the Prius will have a significant MPG advantage over both BEVs and PHEVs. A national policy to make high MPG HEVs more available is preferred to the government investments in high-risk unproven electricity-centric technologies.

This chapter will provide a brief history of the HEV and review the current HEV models available. It will become apparent that the Prius HEV is a unique development—a product much more fuel efficient than other HEVs. The Prius and its derivatives could serve as the basis for a paradigm shift for an economical, ecological way of driving.

HEV History – Shipments

The first early commercial models of the HEV in the U.S. were the Honda Insight, delivered in 1999, the Toyota Prius, delivered in 2000, and the Honda Civic HEV, delivered in 2002. These three models dominated the HEV market until 2004. Table 1⁷ shows the various HEVs available from 1999 to 2010. To conserve space, the sales are

shown for two year periods rather than for one year. The Honda Insight includes both the early, two-seat version (years 1999–2006) and the later, four-seat version (2009–2010).

HEV Electric Vehicle (HEV) Sales by Model							
Vehicle	1999/ 2000	2001/ 2002	2003/ 2004	2005/ 2006	2007 2008	2009/ 2010	Total
Honda Insight	3,805	6,942	1,783	1,388	0	41,534	55,452
Toyota Prius	5,562	35,675	78,591	214,868	339,795	280,610	955,101
Honda Civic		13,700	47,371	57,115	63,872	22,455	204,513
Ford Escape			2,993	38,946	38,559	25,969	106,467
Honda Accord			1,061	22,424	3,601	0	27,086
Lexus RX400h				40,835	32,491	29,583	102,909
Toyota Highlander				49,474	41,493	18,542	109,509
Mercury Mariner				4,172	6,051	2,583	12,806
Lexus GS 450h				1,784	2,323	774	4,881
Toyota Camry				31,341	100,749	37,474	169,564
Nissan Altima					17,207	16,067	33,274
Saturn Vue					7,323	2,706	10,029
Lexus LS600hL					1,844	387	2,231
Saturn Aura					1,057	581	1,638
Chevy Tahoe					3,745	4,726	8,471
GMC Yukon					1,610	3,154	4,764
Chevy Malibu					2,093	4,567	6,660
Cadillac Escalade					801	3,168	3,969
Chrysler Aspen					46	33	79
Dodge Durango						9	9
Ford Fusion						36,370	36,370
Mercury Milan						2,884	2,884
Lexus HS 250h						17,362	17,362
Sierra/Silverado						3,991	3,991
BMW ActiveHEV 7						102	102
BMW X6						205	205
Ford Lincoln MKZ						1,192	1,192
Honda CR-Z						5,249	5,249
Mazda Tribute						570	570
Mercedes ML450						627	627
Mercedes S400						801	801
Porsche Cayenne						206	206
Total	9,367	56,317	131,799	462,347	664,660	555,529	1,888,971

Table 1: Historical Shipments of HEVs, 1999–2010

The number of HEV models has increased from 2 to 32 in 11 years. Japanese manufacturers still dominate because of their better fuel economy. From a total of 274,210 HEV sales in 2010, over two-thirds (69 percent) were manufactured by Toyota. Ford and Honda together accounted for about a quarter of HEV sales, while GM and Nissan together sold about 5 percent. Other manufacturers' products, including Porsche, Mazda, Mercedes, and BMW, totaled less than 1 percent of HEV sales.⁸ (See fig. 1)

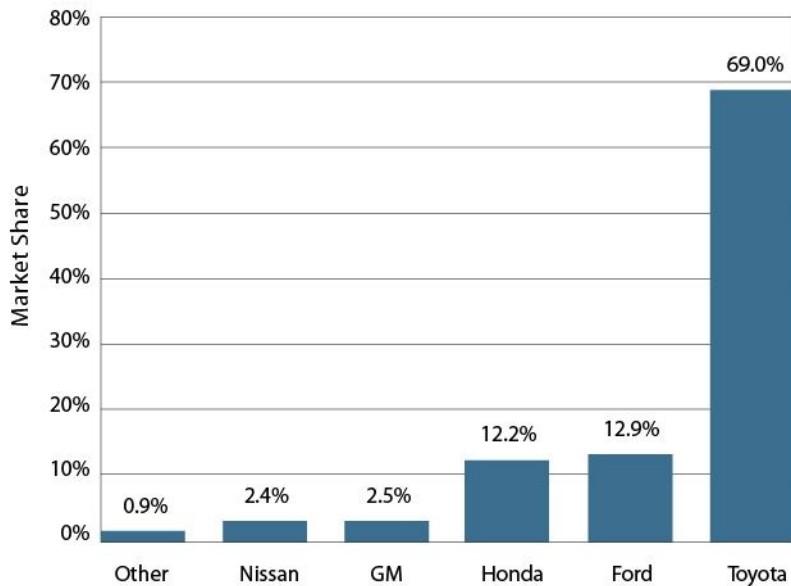


Figure 1: Manufacturers' Market Share of HEVs, 2010

HEV History – Costs and CO₂ Savings

A 2010 British Columbia Automobile Association (BCAA) report⁹ compared HEV cars with their corresponding conventional versions. It included a cost analysis over a five-year period as well as the CO₂ savings realized. The report shows that HEVs' costs for the first five years are higher than the costs of conventional vehicles. The author qualifies this point, however, by noting that cost is not typically the main motivator for someone who purchases a HEV and that many consumers are willing to pay a bit more for a HEV if it will reduce their carbon footprint.

Table 2 summarizes the details for the 16 pairs of cars taken from the report.¹⁰ Each entry shows the conventional car on the first line and the HEV version on the second line. The initial purchase price and total five-year costs are listed, along with the dollar savings for the HEV. The next two columns show the CO₂ emissions per year and the reduction in CO₂ from the HEV version. With one exception, the Mercedes, the HEV cost is higher. But the CO₂ savings in most cases are also higher than the Mercedes CO₂ savings. If the costs were extended to cover total lifetime of the car, total dollar savings would be higher for the more efficient HEV versions in most cases. The five-year period, which is an important measure to many people, is somewhat arbitrary; it does not reflect the full life-cycle costs of the car.

R	Make, Model and Type	Purchase	Total	5-year	CO ₂	Reduction
a	C - Conventional	Price	5-year	HEV	emissions	in CO ₂
n	H - HEV	(MSRP)	cost (\$)	saving /	kg/year	emissions
k		(\$)		(extra cost) (\$)		(%)
1	Mercedes-Benz S450 - C	108,000	150,622		5,474	
	Mercedes-Benz S400 HEV - H	105,900	145,265	5,357	4,370	20%
2	Honda Civic EX - C	24,880	42,374		3,266	
	Honda Civic HEV - H	27,350	42,664	-290	2,070	37%
3	Honda Civic DX-G - C	20,780	37,154		3,266	
	Honda Insight - H	23,900	38,326	-1,172	2,162	34%
4	Toyota Matrix XR - C	21,800	38,606		3,664	
	Toyota Prius - H	27,500	40,324	-1,718	1,748	55%
5	Lexus IS 250 - C	36,000	58,245		3,864	
	Lexus HS 250h - H	39,900	60,084	-1,839	2,622	32%
6	Toyota Camry SE Auto - C	27,310	44,667		3,542	
	Toyota Camry HEV - H	30,900	46,815	-2,148	2,622	26%
7	Toyota Highlander AWD V6 SUV - C	37,150	60,760		4,968	
	Toyota Highlander HEV SUV - H	42,315	63,578	-2,818	3,542	29%
8	Ford Fusion SEL I4 - C	25,799	44,778		3,888	
	Ford Fusion HEV - H	31,999	49,260	-4,482	2,352	38%
9	Ford Escape XLT SUV - C	27,999	49,497		4,416	
	Ford Escape HEV SUV - H	34,899	54,388	-4,891	2,806	36%
10	Nissan Altima 2.5S - C	24,495	41,194		3,542	
	Nissan Altima HEV - H	33,398	50,053	-8,862	2,668	25%
11	Cadillac Escalade - C	84,575	128,985		6,716	
	Cadillac Escalade HEV - H	94,775	138,740	-9,755	5,336	21%
12	Lexus RX 350 Premium SUV - C	46,900	73,403		5,009	
	Lexus RX400h HEV SUV - H	59,500	84,941	-11,538	3,390	32%
13	Chevrolet Silv./Sierra Pickup - C	31,845	58,991		6,210	
	Chevrolet Silv./Sierra HEV Pkup - H	47,505	74,679	-15,688	4,370	30%
14	GM Tahoe/Yukon SLT SUV - C	54,045	83,647		5,980	
	GM Tahoe/Yukon HEV SUV - H	68,255	101,635	-17,988	4,370	27%
15	Lexus LS460 L - C	103,150	145,813		4,968	
	Lexus LS600h L - H	119,950	168,382	-20,463	4,554	8%
16	Lexus GS 350 - C	52,500	82,504		4,600	
	Lexus GS 450h HEV - H	71,900	103,889	-21,384	3,772	18%

Table 2: Comparison of HEV and Conventional Equivalent Models

The cost differential between the conventional/HEV pairs covers a wide range—almost nothing for the Honda Civic and over \$20,000 for the Lexus GS. The CO₂ reductions also cover a wide range—from 8 percent for the Lexus LS to 55 percent for the Prius. One could conclude that there are HEV cars designed to reduce fuel consumption and CO₂ emissions as well as ones designed for style, luxury, or speed. Some manufacturers have used the HEV concept to provide faster acceleration rather than better miles per gallon.

Table 3 shows a 2009 HEV analysis from the Union of Concerned Scientists that has a slightly different format, including a grade for each car.^{11,12}

HEV Car	MPG	EIS*	Grade	HEV Value	Forced Features	CO ₂ Cut
Non-Luxury Models						
Toyota Prius	50	9.2	B	\$3,665	\$0	44%
Honda Civic HEV	41	7.2	B	\$3,658	\$3,687	29%
Honda Insight	41	6.5	C	\$4,000	-\$1,700	24%
Ford Fusion HEV	39	7.8	B	\$4,190	\$3,435	33%
Hyundai Sonata HEV	37	6.8	C	\$5,400	\$0	30%
Honda CR-Z	37	6.2	B	\$1,837	\$1,753	22%
Toyota Camry HEV	33	6.1	C	\$4,350	\$1,455	21%
Nissan Altima HEV	33	5.7	C	\$4,215	\$2,295	18%
Ford Escape HEV FWD	32	7	C	\$5,505	\$2,595	28%
Ford Escape HEV 4WD	29	6.5	C	\$5,505	\$2,595	28%
Toyota Highlander HEV	28	7.1	C	\$5,230	\$2,115	32%
Chevy Tahoe HEV 2WD	21	4.3	D	\$5,445	\$7,720	19%
GMC Yukon HEV 2WD	21	4.3	D	\$5,446	\$7,219	19%
Chevy Silverado HEV 4WD	21	4.3	C	\$5,115	\$0	19%
GMC Sierra HEV 4Wd	21	4.3	D	\$4,033	\$1,082	14%
Chevy Tahoe HEV 4WD	21	4.3	D	\$7,865	\$8,250	10%
GMC Yukon HEV 4WD	21	4.3	D	\$5,401	\$6,014	10%
Chevy Silverado HEV 2WD	21	3.7	F	\$5,115	\$0	14%
GMC Sierra HEV 2WD	21	3.7	D	\$4,033	\$1,082	14%
Volkswagen Touareg HEV	21	3	F	\$7,865	\$8,250	10%
Luxury Models						
Lexus CT 200h	42	8.6	A	-\$2,230	-\$2,465	43%
Lincoln MKZ HEV	39	9.5	A	\$0	\$0	46%
Lexus HS 250h	35	7.0	B	\$2,035	\$0	31%
Lexus RX 450h FWD	30	6.8	C	\$5,010	\$250	30%
Lexus RS 450h AWD	29	6.9	C	\$5,500	\$250	31%
InifinitiM HEV	29	5.5	C	\$6,000	\$0	28%
Lexus GS 450h	23	4.5	C	\$2,320	\$1,160	16%
Mercedes-Benz S400 HEV	21	5.2	A	-\$2,000	\$0	14%
Cadillac Escalade 4WD	21	5.6	B	\$3,170	\$7,510	24%
Cadillac Escalade 2WD	21	5.0	B	\$3,170	\$7,510	24%
Porsche Cayenne S HEV	21	3.7	C	\$3,300	\$0	14%
Lexus LS 600h L	20	4.1	F	\$31,585	\$10,930	10%
BMW ActiveHEV 750i	20	3.7	F	\$13,900	\$2,900	15%
BMW ActiveHEV X6	18	3.2	F	\$7,700	\$18,500	11%
*Envr. Improvement Score (EIS)						

Table 3: UCS Ratings of HEVs

The referenced document uses grades of Superior, Very Good, Good, Poor, and Very Poor; I have substituted equivalent letter grades of A, B, C, D, and F. The report also includes a symbol rating from 1 to 5 for the Forced Features column. Forced Features are options that one must buy for the HEV model that may not be required to be purchased on an equivalent non-HEV car. These do not reflect the true cost of adding HEV functionality. I have provided the actual dollar numbers from the body of the report instead of the symbol.

Table 3 shows the actual HEV additional costs, so it is better for determining the relative increase in price as compared to the five-year additional cost/savings value. An environmental rating is given, but it is not clear exactly how it is derived. Tables 1, 2, and 3 are extremely useful, showing first customer ship dates, volumes, five-year costs, HEV incremental costs, CO₂ reductions, and MPG. Such information makes it much easier to do cost-benefit comparisons and also to determine which HEV manufacturers are more focused on fuel economy and which are focused on marketing.

There are two important measures for a HEV: the incremental cost of the technical improvements over a conventional equivalent car and the MPG improvement. These numbers, combined with the lifespan of the car, provide the full life-cycle costs of a HEV compared to a conventional car. The HEV offers one major and significant benefit—it increases a car’s fuel economy, that is, its MPG. It does not substitute a different power train for the gasoline engine or attempt to have two different power trains running off two different fuel sources. It is essentially an optimizer of the gasoline internal combustion engine. In a HEV, a smaller, more efficient engine can be used, which provides better gas mileage. The architecture is an efficiency improvement that uses a small battery periodically to save up to 40 percent on fuel consumption, at least in the case of the Prius. BEVs and PHEVs, in comparison, are fuel substitution schemes that use batteries to substitute electric power for gasoline and replace the fuel tank.¹³ The HEV is a simple gasoline-motor MPG improvement.

Table 4 is a comparison of two pairs of cars. The first is the HEV Civic, which is the second most popular HEV after the Toyota Prius (see table 1).

Car (All 2011)	Honda	Honda	Toyota	Toyota
	Civic	Civic	Prius	Matrix
	HEV			
Engine Size-liters	1.3	1.8	1.8	1.8
Volume (cu. ft)	91	91	94	94
City MPG	40	25	51	25
Hwy MPG	43	36	48	32
Combined MPG	41	29	50	28
BOE Annual Consumption	8.3	11.8	6.9	12.2
CO ₂ Annual Emissions (tons)	4.6	6.5	3.8	6.7
Prius Gas Savings	16.9%	41.5%	0.0%	43.4%
Prius CO ₂ Savings	17.4%	41.5%	0.0%	43.3%

Table 4: Comparison of Leading 2011 HEVs to Conventional Cars

The Honda Civic was the first car model with both an HEV version and a conventional version. The other car is the Toyota Prius, which does not have a non-HEV version. I

selected the Toyota Matrix as a comparison non-HEV for the Prius car on the basis of engine size, passenger volume, and weight. BOE stands for Barrel of Oil Equivalent.

The Prius consumes 43.4 percent less gasoline than the Matrix and 41.5 percent less gasoline than the Honda Civic regular model. It consumes 16.9 percent less than the HEV Civic. The numbers are almost identical for CO₂ comparisons. This shows that the Prius is a better HEV than the Honda Civic HEV for fuel economy. And it shows that a 40 percent reduction in energy use for a similar sized conventional car is possible for a well-designed and well-built HEV. There are many different HEVs, and some are better than others. The measurable key benefit of the Prius is a 40 percent cut in emissions and energy use.

HEV Life Cycle Benefits – Cost Savings & CO₂ Reductions

A HEV costs somewhat more than a conventional model to buy but costs less to fuel. It is important to understand the initial cost for the HEV and the fuel savings over the lifetime of the car. It is also important to understand that the capability added to a conventional car to make it a HEV also requires more energy for manufacturing, referred to as additional “embodied energy.” And the additional energy used will generate more CO₂. This difference can be measured by either the additional energy or the additional CO₂ generated.

Two cars, the Honda Civic and the Toyota Camry, are used to illustrate comparisons between a HEV and a conventional car. As previously noted, the Honda Civic HEV was first shipped in 2002.¹⁴ In August 2011, Toyota announced the 2012 version of the Toyota Camry and Toyota Camry HEV. The first version of the Camry HEV shipped in 2006. Both the HEV and the non-HEV Camry models showed a significant improvement in fuel economy.^{15,16} The 2012 Camry HEV LE has a fuel economy of 43 MPG city/39 MPG highway/41 MPG combined. The earlier generation Camry HEV’s corresponding numbers are 31 MPG city/35 MPG highway/33 MPG combined. This is a 39 percent, 11 percent, and 24 percent boost in fuel economy for city, highway, and combined driving cycles, respectively, compared to the previous generation. This is due largely to a new HEV power train. The eight MPG improvement represents a 25 percent improvement over a six-year period, which is about 4 percent per year, far higher than historical improvements.

For the non-HEV 2012 Camry with a 2.5 liter engine, fuel economy figures are 25 MPG city/35 highway/28 MPG combined. The previous conventional Camry was 22 MPG city/32 highway/26 MPG combined. The combined improvement is two MPG over the earlier conventional generation while the combined improvement for the HEV versions is eight MPG. This eight MPG for the HEV as contrasted to the two MPG improvement for the conventional model shows what is possible with the HEV synergy drive. The Camry has been described in detail because recent HEV models have obtained a surprising improvement in MPG.

Table 5 shows a lifetime comparison for the conventional and HEV versions of the 2012 Honda Civic and 2012 Toyota Camry. Lifetime costs and lifetime CO₂ emissions should be clearly understood and this understanding should influence purchase decisions. If the focus is on only the first 5 years of a car’s life, then purchasers are making bad economic and ecological decisions. The price of gasoline used for this comparison is

\$4.00 per gallon. The CO₂ consumption is calculated by assuming 20 pounds of CO₂ per gallon of gasoline burned. Mileage per year is assumed to be 12,000 miles and average car life is 14 years, numbers from the Department of Energy’s Alternative Fuels and Advanced Vehicles Data Program.¹⁷ Total miles driven during the lifetime of the car is 170,000 miles.

Model (all 2012)	Civic Gas	Civic HEV	Camry Gas	Camry HEV
Mileage and MPG				
MPG	29	41	30	41
Mileage Lifetime-14 Yrs.	170,000	170,000	170,000	170,000
Years Lifetime	14	14	14	14
Gallons Burned Lifetime	5,862	4,146	5,667	4,146
Costs				
MSRP (Price)	\$19,000	\$23,000	\$22,500	\$25,900
Lifetime Gasoline Costs	\$23,448	\$16,585	\$22,667	\$16,585
Lifetime Gas & Car Cost	\$42,448	\$39,585	\$45,167	\$42,485
CO₂ Emissions				
Lifetime CO ₂ (lbs)	117,241	82,927	113,333	82,927
Embodied CO ₂ (lbs)	13,000	13,600	13,000	13,600
Total CO ₂ (lbs)	130,241	96,527	126,333	96,527

Table 5: Comparison of 2012 Civic and 2012 Camry—Gasoline and HEV Versions

Costs include the sales price (MSRP), the lifetime gasoline costs, and the sum of the two. This table is a simple, useful life-cycle analysis for purchase and operating cost, fuel consumed, and CO₂ generated. Although the initial cost of the HEV is higher than the conventional version, the total cost of the car and gasoline over its lifetime is much lower for the HEV. In the same manner, more CO₂ is generated in making an HEV than its conventional version while operating the HEV generates much less CO₂. The lifetime CO₂ emissions are lower for the HEV.

The second row from the bottom, labeled Embodied CO₂ (lbs), shows the amount of CO₂ generated when making the car, including the mining, melting, and shaping of iron, and the manufacturing and shaping of glass. Making an HEV version takes more energy and generates more CO₂ than making its conventional counterpart. Typically, the amount of CO₂ generated in making a car is about 15 percent of its total lifetime CO₂ generation, the other 85 percent being mostly from burning gasoline.

Many reports, such as the 2010 Canadian report summarized in table 2, provides information on only the first five years of ownership, which is useful but incomplete. Another example of a short-term perspective is the new U.S. car window stickers published in May 2011, which provide fuel cost savings, compared to the average car, for only the first five years of a car’s life. But the total lifetime of a car should be considered because it will at some point go into the used car market until the end of its lifetime.

Table 5 shows that the purchase price and gasoline costs of an HEV over the lifetime of a car are about 10 percent less than those of a comparable conventional car. Admittedly,

the initial purchase price is higher just as the price of an energy efficient house—with more insulation, better windows, and more fuel-efficient appliances—is higher. The two HEVs considered here reduce CO₂ emissions by a sizable amount, in this case about 30 percent. A Prius would offer greater reductions because its fuel economy rating is 50 MPG compared to the 41 MPG of the Honda Civic and Toyota Camry in this comparison. Table 5 can be combined with tables 1, 2, and 3 to provide the basic understanding that for both emissions and costs, e.g., CO₂ and fuel purchased, it is more economical and more ecologically positive to drive a HEV. As stated earlier, HEVs are focused on lower total costs and lower total CO₂ emissions compared to equivalent conventional cars.

Rate of Automobile MPG Improvement

In testimony to the Senate Committee on Energy and Natural Resources on January 30, 2007^{18, 19} John German, manager of Honda's Environmental and Energy Analysis Office said,

From 1987 to 2006, technology has gone into the fleet at a rate that could have improved fuel economy by almost 1.5 percent per year, if it had not gone to other attributes demanded by the marketplace. . . . [T]here is a lot of room for improvement given sufficient lead time for technology development.

Automakers have not focused on energy efficiency so much as style and comfort. Efficiency was a choice but a choice that was not made. Figure 2²⁰ shows average MPG change from 13 MPG in 1975 to 22.4 MPG in 2009. Prior to the 1975 beginning of this curve, fuel efficiency was around 14 MPG from 1923 to 1935. It then declined gradually to about 12 MPG in 1973.²¹ So, car MPG hardly improved from the 1920s to the mid-1970s.

The chart shows a rapid increase in fuel economy from 1975 to 1981, followed by a slower increase until reaching a peak in 1997, and then a gradual decline until 2004. Since 2004, fuel economy has increased each year with the largest increase in 2009.

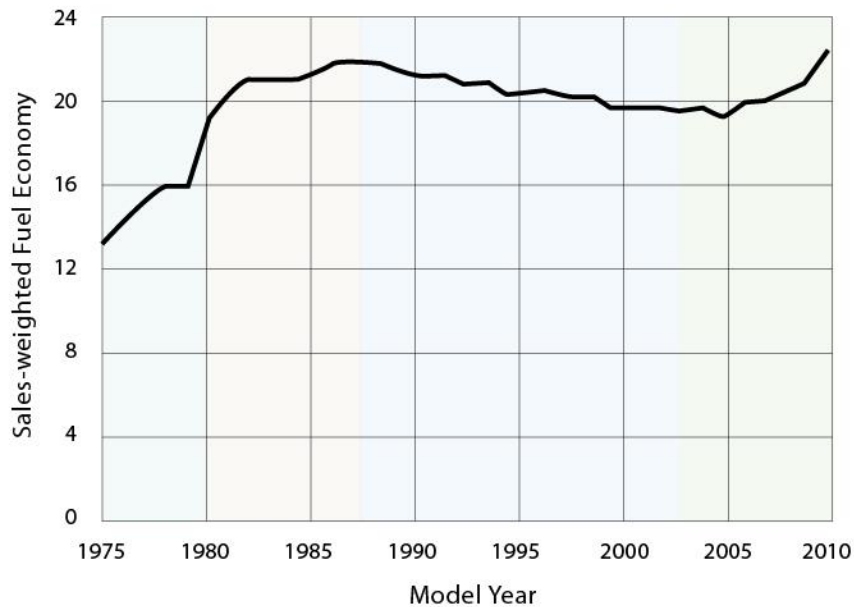


Figure 2: U.S. Fuel Economy (MPG) 1975–2009

In the six-year period from 1975 to 1980, mileage improved from about 13.1 MPG to 19.2 MPG, an impressive increase of about 50 percent or about 8 percent per year. The very significant improvement in this period was the result of the establishment of the Corporate Average Fuel Economy (CAFE) standards by Congress in 1975. The improvement from 1980 to the current time, about 30 years, was from 19.2 MPG to 22.4 MPG, about 17 percent or less than ½ percent per year. The improvement from 1975 to 2011, about 35 years, was from 13.1 miles to 22.4 MPG, about 1.5 percent per year.

The SUV was a style change for a larger heavier vehicle with faster acceleration. The large number of new model cars announced every year has much to do with style and little to do with performance. Could there have been a three to one difference in overall performance for cars? Between 1975 and 1980, automobile efficiency went up by 50 percent. But performance stagnated after that because other factors became more important than reducing fuel consumption and CO₂ emissions. Table 7 shows the change in key characteristics between the average light-duty vehicle in 1980 and 2007, a 27-year period, as well as a partial set of numbers for the 2011 Prius.

Model Year	MPG	Weight	Horse power	0-60 Time	Top Speed
1980	19.2	3,228	104	14.3	107
2007	20.2	4,144	223	9.6	139
2011 Prius	50	3,042	134	10	112

Table 7: Vehicle Characteristics for Both Cars and Trucks, 1980–2007 ²²

One might think that better materials over the last 30 years would have led to lighter weight, even if the car size was the same as a car 30 years ago. This is only marginally true. In general weight has not decreased significantly over time.

The latest Prius may be as large in terms of space as the typical 1980 car. A car with a top speed of 139 mph offers little benefit over one with a top speed of 112 mph, our maximum speed set by law being 75 mph. The Prius gets 2.5 times the MPG of the average 1980 car. The annual increase in performance over this period was about 3 percent. Hybridization is a technology concept that added a large MPG improvement jump of around 40 percent. Such shifts are rare.

In the early years of car transportation, models did not change every year. Later cosmetic changes were made so the same model looked slightly different every year. However, the basic frame, engines, and other components were used for multiple years. To some extent, this is a marketing issue whereby manufacturers use styling changes to persuade people to buy new cars more frequently. Under the hood and body, however, the same drive trains and frames may be used for several years.

Americans need to understand technological improvements and their limitations. Often we are mesmerized by rapid improvements in computer technology. It is noted that if cars advanced at the rate of computers, they would cost a few dollars. But progress is not that fast. Figure 3 shows the long-range trend of energy efficiency for passenger transport in International Energy Agency countries.²³ This is about .5 percent per year. Note that this .5 percent improvement is the rate of improvement that brought the fuel economy of U.S. cars from 20 MPG in 1981 to 23 MPG in 2004.

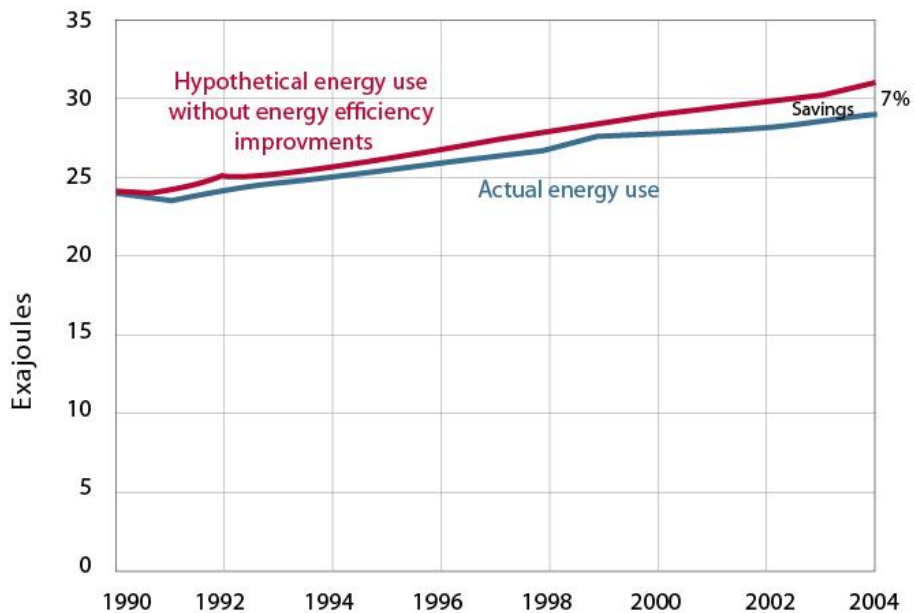


Figure 3: Long-Term Increase in Energy Efficiency

Sometimes change is actually negative, as shown in table 8. Energy intensity measured in BTU per passenger mile for the period 1970 to 2008 shows that automobiles reduced their energy use per passenger mile by .8 percent annually, while transit and rail increased their annual energy use per passenger mile by 1.5 percent and .4 percent, respectively.

Mode	1970 BTU/passenger mile	2009 BTU/passenger mile	Annual % Change
Automobile	4,868	3,538	-.8 %
Transit Bus	2,472	4,242	-.2 %
Air	10,115	2,901	-3.3 %
Amtrack	3,548	2,435	-1.9 %
Rail	2,157	2,516	.5 %
Commuter Rail	2,804 (1984)	2,812	.4 %

Table 8: Energy Intensity, BTU/Passenger Mile, 1970–2009 ²⁴

Car Technology Development Time

Americans often hope for a high-tech “quick-fix” solution to some of their problems. This is unlikely to happen with cars. A 2011 National Research Council report on light-duty vehicles ²⁵ noted,

Newly styled, engineered, and redesigned vehicles can take from 4 to 8 years to produce, each with an increasing amount of new content. Further, the engine development process often follows a path separate from that for other parts of a vehicle. Engines have longer product lives, require greater capital investment, and are not as critical to the consumer in differentiating one vehicle from another as are other aspects of a car. The normal power train development process evolves over closer to a 15-year cycle, although refinements and new technologies will be implemented throughout this period.

The International Organization of Motor Vehicle Manufacturers, also known as the “Organisation Internationale des Constructeurs d’Automobiles” (OICA) was founded in 1919 to further the interests of vehicle manufacturers, assemblers, and importers. It studies issues of mutual interest relating to the development and future of the automobile industry, including CO₂ emissions. In a pamphlet on CO₂ the OICA notes, ²⁶

Long “lead times” are necessary in the production of automobiles. Typically, 5–7 years are needed to design, test, build and introduce new models, especially with new power units which need extensive development and testing, government certification and very complex automated production tools. Proposed CO₂ reduction programs must recognize this lengthy process. Any policy that is implemented without allowing sufficient time can adversely affect manufacturers, their suppliers, their employees, and consumers.

The first Prius used the Toyota HEV system consisting of an aluminum 1.5-liter VVT gasoline engine with 70 horsepower at 4,500 rpm and a 25-kilowatt battery pack

producing 34 horsepower. This was the Prius power train from 1997–2003 (U.S. 2001–2003 models). The 2004, second-generation Prius used the HEV Synergy Drive power train, which combined a 1.5-liter four-cylinder gasoline engine, providing 76 horsepower and an electric drive motor resulting in a maximum power of 60 kilowatts (80 horsepower). This drive train was used from 2004 through 2009. In 2010, a third drive train entered manufacturing with a 1.8 liter gasoline engine that provided 98 horsepower and a 110 kW electric drive motor that provided 134 hp. The first drive train was used from 1997 to 2003 and the second version from 2004 to 2009. The third version of the Prius drive train is in its early years of production. Three power train versions have been developed in the 14-year period. Furthermore, an initial development period began in 1993, adding 4 years to make the total development period of the three Prius drive trains about 18 years, or 6 years per drive train.

It is important to understand that long development times apply to most transportation technologies. The same multi-year development period applies to airplanes, trucks, and rail engines. The yearly announcement of a multitude of new cars does not refute this basic idea. Many of the yearly changes are cosmetic and done for marketing reasons. If we could eliminate yearly model changes but only change models when there is a major improvement in drive trains, car value might be held longer, as is the case of the Prius. And people might drive their cars much longer, resulting in a decrease of embodied energy.

Failed car technologies also take a lot of time. Fuel cell development efforts span four decades and only concept models are available. The PNGV program for diesel hybrids lasted eight years before cancellation and the BEV program has lasted 14 years with marginal results so far. Many of these efforts employed high-risk technologies that should have stayed in the research labs much longer. The important thing to remember is that the technology failures are still long term, taking years to design, then taking more years to get to market, before closing down. Understanding the development cycle for drive train technologies and their potential benefit gives a long-range perspective.

The Prius HEV Achievement

The Prius HEV stands head and shoulders above most of the other HEVs at 50 MPG. I project a continued annual 1.5% increase in MPG, which is the rate of performance increase from the 41 MPG of the 1997 Prius to the 50 MPG of the 2011 Prius version (a 14-year period).

The Prius is a combination of better HEV technology, more efficient internal combustion engines, and a revolutionary change of attitude by car owners. It shows that a commitment to meeting the climate change goals of an 80 percent reduction in CO₂ emissions by 2050 is possible. We do not have to give up the private car per se but could probably eliminate most of the approximately 300 different models, settling on a few dozen extremely well built ones designed to mitigate climate change. The nation could increase our current national average from 22 MPG and our proposed mileage of 34 MPG by 2025 to a fleet performance range of 50-60 MPG within 14 years. As noted before, a 1.5 percent annual performance improvement is assumed, which is approximately 7.5 percent every five years. Table 9 shows this potential improvement for the Prius. This evaluation is to show that very high MPG is possible with a HEV designed for the best mileage.

Year	Prius MPG		Year	Prius MPG
2010	50		2035	71.8
2015	53.8		2040	77.2
2020	57.8		2045	83
2025	62.1		2050	89.2
2030	66.8			

Table 9: Suggested Future MPG from Prius Evolution

The Prius is exceptional in its success. Figure 1 showed that Toyota has sold about 70 percent of all HEVs made.²⁷ The Prius alone represents half of all the HEVs sold in the U.S. in 2010.²⁸ Toyota's commitment has been stronger than that of other companies. Figure 4 shows the patents for HEVs.

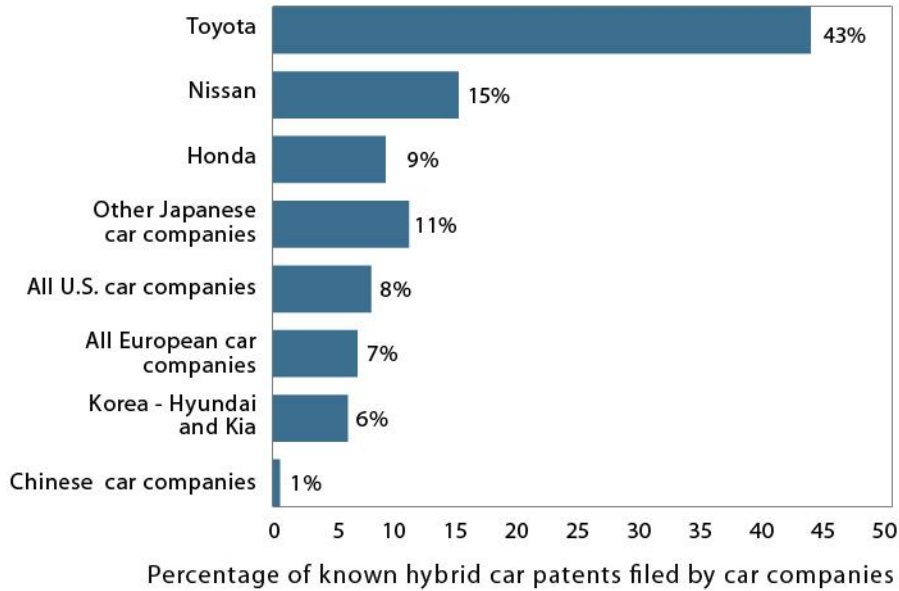


Figure 4: Percent of Known HEV Car Patents Filed by Car Companies

The Prius and its recently announced derivatives,²⁹ including the larger Prius v (to be shipped in 2011) and the smaller Prius c (to be shipped in 2012) might be the basis for a new brand of highly efficient cars from Toyota that could force other manufacturers to develop competitive responses. There are already indications that this may be happening with the announcement of Ford's first 1.0 liter engine³⁰ and its commitment to its use in a new Focus car in Europe to be delivered in 2012.³¹ The auto industry is beginning to shift to more efficient gasoline and diesel cars.

The Future of the Gasoline Engine

Historically, the MPG for a car is determined largely by the thermal efficiency of a gasoline engine. In general, the current thermal efficiency is about 20–25 percent for the internal combustion engine and 75–80 percent for electric motors. Because the power plant that generates the electricity is only about 33 percent efficient after taking into account electricity generation and transmission line losses, then the 75–80 percent efficiency for electric motors is misleading—it might be closer to 25–27 percent (one third of 75–80 percent). One can argue that power plant efficiency will improve. But it is as difficult to improve heat engines that generate electricity as it is to improve the internal combustion heat engines that lead to the rotary motion that moves a car. Table 10 shows the historical efficiency evolution of electrical generation systems.³² The rate of improvement for both natural gas and hard coal between 1974 and 2003 was 0.5 percent per year. New technologies, such as higher temperature combustion for coal or combined cycle natural gas plants, will increase efficiency, but these are relatively long-term projects and their efficiency improvements will still be in the 0.5 – 1.0 percent per year range.

	Natural Gas Efficiency			Hard Coal Efficiency		
	1974	1990	2003	1974	1990	2003
US	37	37	43	34	37	37
Western Europe	39	40	49	32	38	39
Japan	40	42	44	25	39	42
China	-	35	44	27	31	33
Russia	36	33	33	-	-	-
World	36	35	42	30	34	35

Table 10: Evolution of Electrical Efficiency - Natural Gas and Hard-Coal Plants (%)

Major thermal improvements have been made with the Prius. Toyota claims that the engine used in the first- and second-generation Prius (the 1.5L 1NZ-FXE) had a thermal efficiency of about 37 percent and that the thermal efficiency of the new 1.8L unit in the third-generation Prius (2ZR-FXE) has a thermal efficiency of about 38 percent. Toyota is targeting a thermal efficiency of more than 40 percent with its Future Concept 1, followed by thermal efficiency of more than 45 percent in its Future Concept 2. Toyota suggests that such an engine applied in a HEV would result in total lifecycle greenhouse gas emissions comparable to that of an electric vehicle.³³

A unique development path to improve gasoline engine performance has been under way for 18 years—since 1993 when Toyota initiated the Prius project. As noted earlier, Toyota’s HEV development began at the same time as the diesel HEVs of the Program for a New Generation of Vehicles, which was not successful. Eight years later, the U.S. changed paths to the fuel cell car. Eight years later (note program changes seem to occur with new administrations), the path was changed again to the Plug-In HEV. The Prius represents a successful significant improvement over the conventional internal combustion engine. The good news is the internal combustion engine makes the gasoline HEV a strong candidate for the “car of the future.” Electric cars will probably

have very little effect unless there are breakthroughs in generating electricity without CO₂ at power plants. Such a breakthrough could take decades to deploy.

Conclusion

In my opinion, early HEVs like the Prius, the Insight and the Civic, were the cause of the so called “killing of the electric car” a decade ago, which was ignored in the movie “Who Killed the Electric Car?” It is likely that the 2012 50 MPG Prius will effectively “kill” the current models of EVs and PHEVs, including the Nissan Leaf and the Chevrolet Volt. The gasoline HEV is the only major breakthrough in automobile fuel economy in decades. Fuel cells, BEVs, PHEVs, and other architectures cannot compete with its MPG performance. In addition, the Prius has been a strong contender against other HEV manufacturers, leveraging its HEV Synergy Drive into a family of power trains being implemented throughout its fleet. Its dominance in the market suggests that it may be able to maintain this lead for some time. The Prius itself is now moving into a family of products—larger, smaller, and “pluggable.” Its pluggable version is a very small step to provide some electric drive capability; but its advantage still lies in its high MPG. Prius sales in the US in 2009, 2010 and 2011 were respectively 140,000, 141,000 and 136,000 cars out of total hybrid sales for the same year of respectively 290,000, 274,000 and 269,000 cars. This is a consistent 50%.

For those concerned about fossil fuel availability and climate change, the HEV is the technology of choice. HEVs can obtain 30-40% better MPG than their conventional versions. Toyota is the leader in HEV technology providing several models with very high MPG performance. Honda and Ford seem to be the next best providers. Other companies have yet to catch up. However, there are now sufficient models to choose from should a buyer want to focus on value and low CO₂ emissions. There seems to be no near term competition to this technology from BEVs, PHEVs or fuel cell cars. This will probably remain the case for at least a decade.

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