Environ. Res. Lett. **2** (2007) 014003 (8pp) doi:10.1088/1748-9326/2/1/014003

How hybrid-electric vehicles are different from conventional vehicles: the effect of weight and power on fuel consumption

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Received 26 January 2007
Accepted for publication 7 March 2007
Published 28 March 2007
Online at stacks.iop.org/ERL/2/014003

Abstract
An increasingly diverse set of hybrid-electric vehicles (HEVs) is now available in North America. The recent generation of HEVs have higher fuel consumption, are heavier, and are significantly more powerful than the first generation of HEVs. We compare HEVs for sale in the United States in 2007 to equivalent conventional vehicles and determine how vehicle weight and system power affects fuel consumption within each vehicle set. We find that heavier and more powerful hybrid-electric vehicles are eroding the fuel consumption benefit of this technology. Nonetheless, the weight penalty for fuel consumption in HEVs is significantly lower than in equivalent conventional internal combustion engine vehicles (ICEVs). A 100 kg change in vehicle weight increases fuel consumption by 0.7 l/100 km in ICEVs compared with 0.4 l/100 km in HEVs. When the HEVs are compared with their ICEV counterparts in an equivalence model that differentiates between cars and sports-utility vehicles, the average fuel consumption benefit was 2.7 l/100 km. This analysis further reveals that a HEV which is 100 kg heavier than an identical ICEV would have a fuel consumption penalty of 0.15 l/100 km. Likewise, an increase in the HEV's power by 10 kW results in a fuel consumption penalty of 0.27 l/100 km.

Keywords: hybrid-electric vehicles, fuel consumption, performance, vehicle weight, system power

1. Introduction

Hybrid-electric vehicles (HEVs) use batteries, electric motors, regenerative braking and reduction of engine idling time to enhance a conventional internal combustion engine. This approach is a proven means of reducing the fuel consumption and/or improving the performance of light-duty passenger vehicles [1, 2]. The fuel consumption of HEVs is lower for a number of reasons: the electric motor provides a portion of the power for propulsion, especially at high-load conditions when the vehicle is accelerating; some of the vehicle's inertial energy can be recaptured through regenerative braking systems and stored in vehicle batteries; an engine-stop feature reduces idling fuel consumption whenever the car is coasting, braking, or stopped[5]. It has been argued that policies are needed

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[5] This feature is also employed by so-called 'mild hybrids', which are essentially conventional vehicles with oversized starter motors. Mild hybrids such as the Saturn VUE and the GM Silverado are excluded from this study.

to reduce transportation fuel consumption, as part of a suite of approaches to reduce carbon emissions worldwide [3–6]. Hybrid-electric technology is expected to play a significant role in achieving this. Yet these studies estimate potential fuel savings by simply scaling the fleet average fuel consumption by a given percentage. In order to more accurately calculate the magnitude of fuel savings, a more robust quantitative analysis of the relationship between weight, performance and fuel consumption of HEVs vis-à-vis conventional internal combustion engine vehicles (ICEVs) is needed.

Previous studies have successfully modeled the fuel consumption, weight, and performance tradeoffs of HEVs based on an assessment of one or two HEV models [7, 8]. This study aims to add to that body of work by analyzing specifications and fuel consumption data for 2007 model year hybrid-electric vehicles and their ICEV counterparts in the North American market. We begin by examining the expanding hybrid fleet in North America, and present data on the changing nature of the US HEV fleet as hybrid-electric technology is adopted across a more diverse array of light-duty passenger vehicle platforms. Using linear regression models, we analyze how vehicle weight and power affect the fuel consumption of HEVs and ICEVs independently, and then we compare the set of currently available HEVs (2007 model year) against a functionally equivalent set of conventional ICEVs. The 'equivalent set' are ICEVs of the same make and model, and with similar power. These analyses provide a more accurate quantitative picture of the relationship between fuel consumption, vehicle weight and system power, using empirical data from commercially available vehicles.

2. Diversifying hybrid-electric vehicle fleet

Automotive manufacturers are offering an increasing variety of HEV model types. In 2007, there were nine light-duty HEV models available in the US, and this number is projected to double in the next two to three years [9]. Figure 1 shows the annual and cumulative sales of HEVs in the US between 1999 and 2006, as well as the number of car and sports-utility vehicle (SUV) models available in each year. SUVs made up approximately 30% total hybrid sales in 2006. In addition to the growing diversity of model offerings, HEV annual sales continue to grow both in numbers and as a proportion of the total light-duty vehicle sales. 2006 HEV sales in the US represent approximately 1.6% of the year's new vehicle sales [10, 11], with predictions of continued increase [12]. Vehicle manufacturers publish performance specifications for individual HEV models, including gasoline engine size (displacement), vehicle curb weight, net hybrid-electric system power[6], and acceleration. These HEV data are presented for all of the HEVs investigated in this study (table 1). An investigation of air pollutant emissions performance of HEVs is beyond the scope of this paper. However, it should be noted that since HEVs were introduced

[6] Torque is another characteristic that can be used to compare performance, since it influences vehicle acceleration. However, we have chosen system power as it is more commonly presented as a measure of powertrain performance, and it is directly related to torque through engine speed.

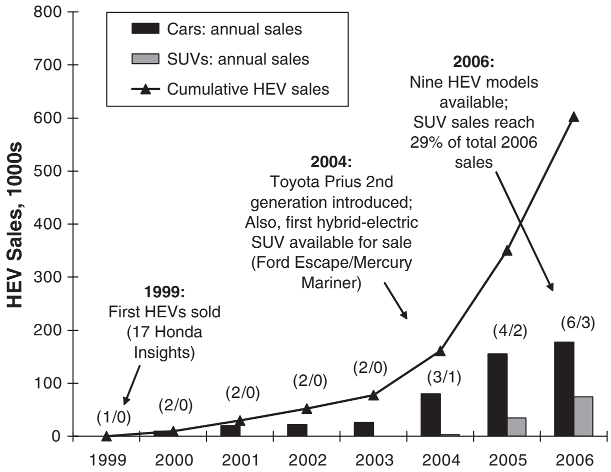

Figure 1. Car and sports-utility vehicle (SUV) shares of HEV annual sales in the United States; annual SUV sales have been increasing rapidly since their introduction in 2004. Cumulative HEV sales are also shown, which are assumed to closely represent the number of HEVs currently in use. Numbers in parentheses show numbers of car/SUV models available for sale in a given year [11].

in North America, they have been lower-emitting than their ICEV counterparts.

The combined fuel consumption rate is from US Environmental Protection Agency (EPA) 2-cycle test results, and refers to 45% highway and 55% city driving. The EPA has recently proposed a new 5-cycle methodology that will more accurately reflect actual driving behaviour and corresponding fuel consumption [13]. The EPA predicts that this methodology will increase combined fuel consumption by 8% for conventional light-duty passenger vehicles, and by 16% for hybrid-electric vehicles. It is likely that the new methodology will be implemented for the 2008 model year in the US, so this study uses fuel consumption figures that have been corrected by these factors (table 1). This approach has been used before [14], and is supported by the reported difference between real-world fuel consumption for the Toyota Prius and its EPA 2-cycle fuel consumption rating [15].

From 2000 to 2006, the sales-weighted average hybrid-electric vehicle in the US fleet has changed significantly, driven largely by the introduction of new sports-utility and high-performance HEV models. The average curb weight has increased by 30%. Propelling this larger weight is a hybrid-electric system that delivers 60% more power. The gasoline engine component of this system is 43% larger in terms of engine displacement. Some of the observed net power increase is explained by the need to provide a larger vehicle with acceptable performance. Over the same period, however, the manufacturer-reported acceleration times also increased: the average HEV in 2004 reaches 96.6 km h^{-1} (60 miles per hour) from a standing start in 20% less time than the average in 2003. Because vehicle weight and power both strongly influence fuel consumption, it is not surprising that average fuel consumption has gone up by 15% with the shift towards higher-performance HEVs (figure 2).

Table 1. Specifications of the HEV models considered in the analysis (ref: manufacturer specifications). The first-generation Toyota Prius and the Honda Insight were discontinued in 2003 and 2006, respectively, and the reported fuel consumption for the Honda Accord was improved for the 2007 model year.

								Combined fuel consumption[c]	
Hybrid-electric vehicles	Model year	Drive type[a]	Trans-mission[b]	Engine displ. (l)	Curb weight (kg)	Net power (kW)	Accel'n. (0–96.6 km h^{-1}) (s)	EPA 2-cycle l/100 km (mpg)	Corrected l/100 km (mpg)
Cars									
Toyota Prius (1st Gen.)	2003	FWD	ECVT	1.5	1237	75	12.7	4.9 (48)	5.7 (41)
Toyota Prius (2nd Gen.)	2006/7	FWD	ECVT	1.5	1310	82	10.2	4.3 (55)	5.0 (47)
Toyota Camry	2006/7	FWD	ECVT	2.4	1669	140	8.9	6.0 (39)	7.0 (34)
Honda Insight	2006	FWD	CVT	1.0	896	53	10.7	4.2 (56)	4.9 (48)
Honda Civic	2006/7	FWD	CVT	1.3	1304	82	11.0	4.7 (50)	5.5 (43)
Honda Accord	2006	FWD	Auto	3.0	1627	189	6.5	8.4 (28)	9.7 (24)
Honda Accord	2007	FWD	Auto	3.0	1635	189	6.5	7.6 (31)	8.8 (27)
Lexus GS 450h	2006/7	RWD	ECVT	3.5	1875	254	5.2	9.0 (26)	10.5 (22)
Nissan Altima	2007	FWD	ECVT	2.5	1588	148	—	6.0 (39)	7.0 (34)
Sports-utility vehicles									
Toyota Highlander	2006/7	AWD	Auto	3.3	1925	200	7.2	8.1 (29)	9.4 (25)
Ford Escape/Mercury Mariner	2006/7	AWD	ECVT	2.3	1718	116	9.0	7.6 (31)	8.8 (27)
Lexus RX 400h	2006/7	AWD	ECVT	3.3	1980	200	7.3	8.1 (29)	9.4 (25)

[a] FWD = front-wheel drive; RWD = rear-wheel drive; AWD = all-wheel drive.
[b] ECVT = electronically controlled continuously variable transmission; CVT = continuously variable transmission; Auto = automatic transmission.
[c] Combined fuel consumption represents 55% city, 45% highway driving.

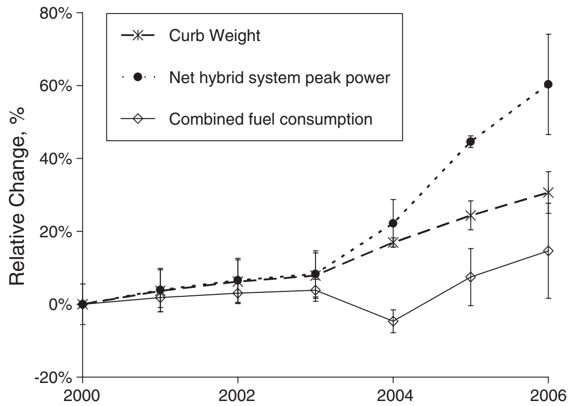

Figure 2. Vehicle performance trends over time for the average HEV: curb weight, net hybrid system peak power, and fuel consumption. Variability across models is indicated by the error bars representing one (sales-weighted) standard deviation.

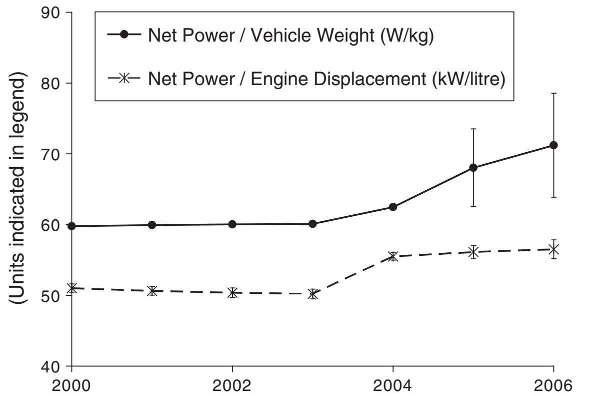

Figure 3. Trends in net system power per vehicle weight (a measure of vehicle performance) and net system power per engine volumetric displacement (a measure of the technological development of the propulsion system). Data dispersion is indicated by the weighted standard deviation.

The changing nature of HEV technology can be gauged by two further parameters, namely, the ratio of net system power to vehicle curb weight and the ratio of power/engine displacement. These parameters have been chosen because they are primarily a function of the propulsion system, and they offer insight into how hybrid-electric system technology has evolved over time (figure 3). In comparison, fuel consumption (another metric of performance) is influenced by vehicle aerodynamics and curb weight, as well as the choice of testing drive-cycle. Between 2000 and 2003, both parameters stayed approximately constant, since only two vehicles, the Toyota Prius and the Honda Insight, were offered for sale. In 2004, three new HEVs were released (the second-generation Toyota Prius, the Honda Civic and the Ford Escape) and the first-generation Prius was discontinued. The increased power per unit vehicle weight between 2003 and the present indicates a trend towards new vehicles having higher performance. This is similar to what has been observed across the whole light-duty vehicle fleet. For hybrid-electric propulsion systems, power per engine displacement reveals technological development; in other words, more system power is made

Table 2. Vehicle weight, net system power, and corrected fuel consumption differences between 2007 model year HEVs and their ICEV counterparts.

Hybrid-electric vehicles	'Equivalent' ICEV Vehicles	Delta weight (kg)	Delta power (kW)	Delta fuel consumption (l/100 km)
		Cars[a]		
Toyota Prius 2nd Gen. (I4)	Toyota Matrix (I4)	61	−12.0	−3.25
Toyota Camry (I4)	Toyota Camry (I4)	169	21.5	−2.40
Honda Civic (I4)	Honda Civic (I4)	84	−22.4	−2.21
Honda Accord (V6)	Honda Accord (V6)	110	6.7	−1.27
Lexus GS 450h (V6)	Lexus GS 430 (V8)	175	37.3	−1.60
Nissan Altima (I4)	Nissan Altima (I4)	150	17.2	−1.75
		Sports-utility vehicles[a]		
Toyota Highlander (V6)	Toyota Highlander (V6)	166	39.5	−2.69
Ford Escape/Mercury Mariner (I4)	Ford Escape/Mercury Mariner (I4)	165	1.5	−2.75
Lexus RX 400h (V6)	Lexus RX 350 (V6)	125	−1.5	−2.69

[a] Internal combustion engine type is indicated as follows: I4 = inline 4-cylinder engine; V6 and V8 refer to 6- and 8-cylinder engines in 'V' configuration, respectively.

available for a given internal combustion engine size. This parameter drops between 2000 and 2004 because the first-generation Toyota Prius, which has a lower power per engine displacement, captured an increasing proportion of sales. Between 2003 and 2004 the power to engine displacement ratio increased by about 10%, indicating that the newer HEV technology was significantly improved.

3. Weight, power and fuel consumption

A number of factors can independently affect the fuel consumption of conventional vehicles, including differences in powertrain type and peak power, vehicle weight, aerodynamics, rolling resistance, and accessory power demand. In general, heavier and more powerful vehicles have higher fuel consumption rates. Due primarily to the significant difference in powertrain type, engineering models have shown that conventional ICEVs have a different relationship between vehicle inertial weight, net system power and fuel consumption than HEVs [7, 16]. Until recently there have been insufficient HEV models to perform a statistical comparison with conventional ICEVs that differ only in terms of powertrain, so other analysts have used hypothetical hybrids based on the best understanding of the technology [16]. To evaluate the impact of current commercially available hybrid-electric technology on light-duty vehicle fuel consumption, we compare a set of nine model year 2007 HEVs to a set of nine equivalent 2007 vehicles powered by internal combustion engines. For the purposes of this study, 'equivalence' for any given ICEV is defined as being the same make and model as the HEV. Where different engine options are available for the ICEV, the engine with the closest power is used[7] (table 2). Only the Toyota Prius has no direct equivalent, so the Toyota Matrix (a mid-size hatchback of similar dimensions) is selected as its counterpart. Automatic transmissions were chosen for the equivalent ICEVs in the set, and each has the same drive type (two-wheel or all-wheel drive) as their HEV counterpart. Vehicle weight and engine power data were obtained from the published manufacturer specifications, and combined fuel consumption estimates were used, corrected using the EPA factors as described earlier.

First, we examine how vehicle weight and net system power affects the fuel consumption within each vehicle set (HEVs and ICEVs). A simple regression model is used, with fuel consumption (Fc in table 3) as the dependent variable. Weight (100 kg) and power (10 kW) are examined independently in turn as predictors of fuel consumption. Each analysis yields significant results at the 95% confidence level for both HEVs and ICEVs. The results of this regression analysis are presented in table 3. A 100 kg increase in weight (not considering power) results in 0.72 l/100 km increase in fuel consumption for HEVs, and 0.77 l/100 km increase in fuel consumption for ICEVs. Similarly, a 10 kW power increase (not considering weight) results in 0.29 l/100 km increase in fuel consumption for HEVs, and an almost identical increase for ICEVs. When weight and power are evaluated simultaneously as predictors of fuel consumption, weight is found to be a significant predictor of fuel consumption for ICEVs, but not power. However, we find that the HEV sample does not produce significant results for weight and power coefficients at the 95% confidence interval. This is not surprising since weight and power are correlated (correlation coefficient = 0.84). Tolerance tests using inflated variation factors [17] did not detect significant multi-collinearity, and the Cook's-D test [18] did not reveal any outliers.

One way of coping with high correlation between weight and power is to directly estimate the relationship between *differences* in fuel consumption and *differences* in weight and power within each vehicle class (HEVs and ICEVs). This significantly increases the sample size ($N = 36$), and helps

[7] The analyses shown in this paper were also performed with three other assumptions for equivalent ICEs where different engine options were available. These included equivalents based on similar engine size, smallest IC engines, largest IC engines. Since there are not three powertrain options for each equivalent ICEV, these different choices made little or no difference to the conclusions of this study.

Table 3. Regression analyses results for HEVs and equivalent ICEVs. $N = 9$ for the simple regressions, and $N = 36$ for the pairwise difference regression. Fuel consumption is the predicted variable.

Predicted variable[a]	Predictor variables[b]	Regression coefficients C	W	P	95% confidence intervals	R^2
HEVs						
Fc	C, W	−3.94	0.72[c]	—	(C: −8.6, 0.7) (W: 0.44, 0.99)	0.84
Fc	C, P	3.34[c]		0.29[c]	(C: 1.2, 5.5) (P: 0.16, 0.42)	0.8
Fc	C, W, P	−1.5	0.43	0.14	(C: −7, 4) (W: −0.03, 0.9) (P: −0.6, 0.33)	0.89
Fc (pairwise difference)	C, W, P	0.16	0.4[c]	0.14[c]	(C: −0.2, 0.51) (W: 0.23, 0.58) (P: 0.07, 0.2)	0.85
Fcw	C, P	0.34		0.008[c]	(C: 0.25, 0.44) (P: 0.002, 0.014)	0.6
ICEVs						
Fc	C, W	−1.6	0.77[c]		(C: −6, 2.9) (W: 0.49, 1.07)	0.85
Fc	C, P	5.68[c]		0.31[c]	(C: 2.2, 9.16) (P: 0.09, 0.54)	0.61
Fc	C, W, P	−1.12	0.70[c]	0.04	(C: −6.8, 4.5) (W: 0.17, 1.24) (P: −0.2, 0.3)	0.86
Fc (pairwise difference)	C, W, P	0.13	0.72[c]	0.04	(C: −0.51, 0.25) (W: 0.53, 0.92) (P: −0.04, 0.13)	0.83
Fcw	C, P	0.74		−0.002	(C: 0.6, 0.88) (P: −0.01, 0.007)	0.025

[a] Fc = fuel consumption (l/100 km); Fcw = fuel consumption per 100 kg vehicle weight (l/100 km/100 kg).
[b] C = regression constant; W = weight coefficient (100 kg); P = power coefficient (10 kW).
[c] Significant at the 95% confidence level.

mitigate the effects of high correlation between power and weight. Here we find that HEVs and ICEVs perform quite differently. Both weight and power difference are significant for the HEVs, with a 100 kg weight increase and 10 kW power increase resulting in 0.4 l/100 km and 0.14 l/100 km increase in fuel consumption, respectively. However, only a change in weight is a significant predictor of fuel consumption for the ICEVs, with a 100 kg increase in weight resulting in a 0.72 l/100 km increase in fuel consumption. Additionally, the coefficient for power is not significant at the 95% level. Increasing the sample size of ICEVs to include all engine options available does not change this result. In order to confirm our findings we also tested an alternative model using weight-corrected fuel consumption (Fcw in table 3) to control for the effect of correlation between weight and power. We again found that a change in power is a significant predictor of weight-corrected fuel consumption only for HEVs.

HEVs tend to have lower fuel consumption in urban driving (with more stop–start driving) than highway driving due to regenerative braking technology. This is contrary to fuel consumption findings in conventional vehicles, which have significantly lower fuel consumption under highway driving conditions. Therefore we separately analyze fuel consumption in city and highway driving as a function of weight and power (table 4). Under city driving conditions, differences in weight are not a significant predictor of differences in fuel consumption for HEVs, but power is important. This is because braking and acceleration are common during city driving, and the full fuel-saving benefits of hybrid-electric technology are realized. In contrast, during city driving weight is a significant predictor of fuel consumption for ICEVs because conventional technology cannot recover the energy lost during deceleration. For highway conditions, on the other hand, differences in weight are a strong determinant of differences in fuel consumption for both HEVs and ICEVs. In highway driving mode, both types of vehicle operate primarily using their internal combustion engine, and hence differences in weight (rather than peak system power) dictate fuel consumption.

In summary, the analysis has demonstrated that differences in fuel consumption between different HEVs are explained by both weight and power, while for the equivalent ICEVs they are explained primarily by weight. This is an important finding: despite the fact that hybrid-electric propulsion systems use less fuel than conventional internal combustion engines, heavier and more powerful vehicles are eroding the fuel consumption benefit. Also, due to the way that hybrid-electric systems recapture energy during vehicle braking, increased weight is less of a factor in HEVs than in ICEVs.

4. Comparing HEV and ICEV fuel consumption

The share of HEVs in the North American light-duty passenger vehicle fleet is expected to continue increasing, driven by their potential for fuel savings and steadily reducing cost. A 2004 study forecasted that HEVs could capture 4–7% of the light-duty vehicle market by 2008 and 10–15% by 2012 [12]. This raises the question of how best to estimate the change in fuel consumption that a given vehicle would realize, were it to use a hybrid-electric system rather than a conventional engine. We approach this problem by comparing the set of HEVs against the sample of equivalent ICEVs, rather than within each set. We regress fuel consumption differences using three ‘models’ of equivalence between HEVs and ICEVs (table 5).

Table 4. Regression analyses results for HEVs and equivalent ICEVs with city and highway fuel consumption (pairwise comparison, $N = 36$).

Predicted variable[a]	Predictor variables[b]	Regression coefficients C	W	P	95% confidence intervals	R^2
HEVs						
Fc (City)	C, W, P	0.11	0.15	0.26[c]	(C: −0.33, 0.56) (W: −0.06, 0.36) (P: 0.17, 0.34)	0.77
Fc (Highway)	C, W, P	0.32	0.75[c]	−0.02	(C: 0.13,0.53) (W: 0.67, 0.87) (P: −0.06, 0.014)	0.93
ICEVs						
Fc (City)	C, W, P	0.16	0.29[c]	0.26	(C: −0.53, 0.68) (W: 0.02,0.61) (P: −0.13, 0.38)	0.65
Fc (Highway)	C, W, P	−0.32	1.21[c]	−0.18[c]	(C: −0.91, 0.28) (W: 0.9, 1.5) (P: −0.3, −0.05)	0.73

[a] Fc = fuel consumption (l/100 km).
[b] C = regression constant; W = weight coefficient (100 kg); P = power coefficient (10 kW).
[c] Significant at the 95% confidence level.

Table 5. Across-group comparison of fuel consumption differences between HEVs and ICEVS. C represents the difference in fuel consumption between HEVs and ICEVs due to the difference in propulsion system technology.

Dependent variable[a]	Independent variables[b]	Regression coefficients C	W	P	Confidence intervals	R^2
Model 1: Each HEV versus equivalent ICEV ($N = 9$)						
Fc	C, W	3.06[c]	0.5	—	(C: 1.68, 4.4) (W: −0.48, 1.48)	0.17
Fc	C, P	2.5[c]		0.1	(C: 1.66, 3.46) (P: −0.1, 0.3)	0.17
Fc	C, W, P	2.8[c]	0.25	0.06	(C: 0.4, 5.2) (W: −1.75, 2.26) (P: −0.35, 0.47)	0.18
Model 2: HEV versus ICEV (group comparison $N = 81$)						
Fc	C, W	3.4[d]	0.74[d]	—	(C: 3.15, 3.63) (W: 0.67, 0.81)	0.85
Fc	C, P	2.7[d]		0.30[d]	(C: 2.24, 3.0) (P: 0.25, 0.34)	0.70
Fc	C, W, P	3.25[d]	0.56[d]	0.1[d]	(C: 3.01., 3.48) (W: 0.45, 0.68) (P: 0.04, 0.14)	0.87
Model 3: HEV versus ICEV (group comparison with car and SUV sub-groups $N = 162$)						
Fc	C, W	3.3[d]	0.86[d]	—	(C: 2.97, 3.7) (W: 0.75, 1)	0.86
Fc	C, P	2.5[d]		0.32[d]	(C: 2.34, 2.67) (W: 0.3, 0.35)	0.96
Fc	C, W, P	2.7[d]	0.15[c]	0.27[d]	(C: 2.43, 2.87) (W: 0.02, 0.3) (P: 0.22, 0.32)	0.97

[a] Fc = fuel consumption (l/100 km).
[b] C = regression constant; W = weight coefficient (100 kg); P = power coefficient (10 kW).
[c] Significant at the 95% confidence level.
[d] Significant at the 99% level.

In each model, the dependent variable is the fuel consumption difference between an HEV and an equivalent ICEV, and corresponding differences in weight and power are the independent variables. In each case, the regression constant, C, is the difference in fuel consumption (in units of l/100 km) between HEVs and ICEVs. This difference can be attributed to the effect of using hybrid-electric technology instead of conventional internal-combustion-engine technology for the vehicle's propulsion system. Model 1 is based on the assumption that consumers will switch from a conventional vehicle to its hybrid counterpart; model 2 allows for any HEV to substitute for any ICEV; and model 3 embeds the assumption that consumers will only switch from conventional cars to hybrid-electric cars, and likewise for SUVs. In model 1, each HEV is compared *only* with its equivalent ($N = 9$). In model 2, we compare HEVs and ICEVs *as a class*, i.e., each HEV was compared with every ICEV ($N = 81$). In model 3 we split each HEV and ICEV set into two groups, SUV and cars, and compare all vehicles within each group ($N = 45$). This is because car and SUV HEVs are likely to contribute to different relationships between weight, power and fuel consumption.

Equivalence model 1

Only 'technology' (i.e. the use of a hybrid-electric propulsion system rather than an internal combustion engine) was found to be a significant predictor of the difference in fuel consumption. On an average, the use of hybrid-electric technology resulted in a fuel consumption benefit of 2.8 l/100 km. Both weight and power differences were found *not* to be significant at the 95% level. The mean differences in power and weight for an HEV and its ICEV equivalent were small (5% and 9%, respectively), and the impact of these changes cannot be observed in the face of substantial differences in fuel consumption. Though significant, the constant has a large confidence interval and the model has a low R^2 (0.18). This suggests wide variation in the implementation of hybrid technology from model to model, resulting in large variation in fuel consumption benefits.

Equivalence model 2

When HEVs and ICEVs are compared as a class, the model shows highly significant results for each of the three predictors (at the 99% confidence level). An HEV of the same weight and power uses approximately 3.2 l/100 km less fuel than its ICEV counterpart. Further, an increase in weight of 100 kg results in a fuel consumption increase of 0.56 l/100 km, and an increase in power of 10 kW results in a fuel consumption increase of 0.10 l/100 km. On an average 2007 HEVs are 136 kg heavier than equivalent ICEVs, resulting in a weight-related fuel consumption penalty of 0.75 l/100 km. Further, 2007 HEVs have 10 kW more average power than equivalent ICEVs, resulting in a fuel consumption penalty of 0.1 l/100 km. The total penalty amounts to a reduction in the fuel consumption benefits of HEVs by 27%.

Equivalence model 3

This model of equivalence allows us to differentiate between cars and SUVs. Here we find significant effects (at the 95% confidence level) for all three predictors. The average gain from using hybrid technology was 2.7 l/100 km, while the weight and power penalties were 0.15 l/100 km and 0.27 l/100 km, respectively. This is an interesting result, because the weight coefficient is almost half the magnitude of the power coefficient. Compare this result to model 2, where the weight coefficient is over five times as large as the power coefficient. The reason for the change in magnitude of the coefficients is because this model compares like vehicles with like, and cars are different from SUVs in a number of important ways. The three hybrid-electric SUVs use all-wheel drive rather than two-wheel drive, which results in an extra fuel saving since all of the four wheels provide regenerative braking capability [7]. Also, SUVs generally have a higher coefficient of drag than cars and have a larger frontal area.

5. Conclusions

In summary, based on this statistical analysis of 2007 model year HEVs and their equivalent ICEVs sold in the United States, this study presents the following conclusions.

(1) Heavier and more powerful hybrid-electric vehicles are eroding the fuel consumption benefit of this technology.
(2) The fuel consumption penalty imposed by increased vehicle weight is significantly lower in HEVs than in equivalent ICEVs. A 100 kg change in vehicle weight increases fuel consumption by only 0.4 l/100 km in HEVs, compared with 0.7 l/100 km in ICEVs.
(3) Three different equivalence models (based on different comparisons of HEVs against ICEVs) yielded fuel consumption benefits ranging from 2.7 to 3.25 l/100 km, with varying effects of changes in weight and power.
(4) When the HEVs are compared with their ICEV equivalents (model 3, grouped into cars and SUVs), the average fuel consumption benefit of an HEV was 2.65 l/100 km. This analysis reveals that an HEV that is 100 kg heavier than an identical ICEV, holding everything else constant, has a fuel consumption penalty of 0.15 l/100 km. Likewise, an HEV that is 10 kW more powerful than the ICEV results in a fuel consumption penalty of 0.27 l/100 km.

Hybrid technology is new, and it will evolve as the technology matures and diffuses within the automobile fleet. We have shown that, even in the relatively short time that HEVs have been commercially available, there have been significant changes in the dimensions, performance and fuel consumption of the fleet. The number of models available is small, and this small sample size will be an inevitable challenge for analyses of the fleet done today. As the number of HEV types increases, we will no doubt get a more robust picture of the technology.

Acknowledgments

We thank Kimberly Jones for her assistance assembling vehicle sales and specifications data, and Gordon McTaggart-Cowan and Julian Marshall for valuable comments on a draft of this article. The University of British Columbia Bridge Program, the Natural Science and Engineering Research Council of Canada, and the Auto21 Network of Centres of Excellence provided support for this research.

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