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Comparing technological advancement of hybrid electric vehicles (HEV) in different market segments

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ABSTRACT

The Toyota Prius was first introduced in 1997 and since then over 150 hybrid electric vehicles (HEVs) have been brought to the automobile market around the world. This was spurred by a major interest in the future of vehicles using 'alternative fuel' for addressing environmental and fuel dependency concerns. Based upon previous work[1], which identified an input–output model that could successfully explain the progress of HEV technologies, this study evaluates and compares the technological advancement observed in different HEV market segments over the past 15 years. The results indicate that the introduction of a wide range of midsize HEVs is posing a threat to the two-seaters and compact HEV segments while an SUV segment shows a fast adoption with a significant performance improvement. The rates of change for each segment are also provided to give insights into the estimation of the future performance levels for new product development target setting purposes.

1. Introduction

Increasing fuel prices, government regulation, and a general desire to reduce environmental concerns have resulted in increased sales for fuel efficient vehicles. The Toyota Prius, introduced in 1997, was the first major hybrid electric vehicle (HEV) and since then most other manufacturers have introduced HEVs with varying success. While popular, the Prius and other vehicles were small and did not satisfy the needs of many other market segments. Over the following years, manufacturers developed HEVs to serve other segments.

Electric vehicles can be broadly categorized as 'pure-electric' (i.e. using only a battery and an electric motor for propulsion without tailpipe) or 'hybrid-electric' (i.e. combining the conventional internal combustion engine with an electric motor and battery). As the electric vehicle market grows, related technologies are progressing every year especially in terms of driving range and fuel economy. In particular, the anxiety on the travel range of pure electric vehicles has been reduced by the advent of HEV. Besides, the fuel economy of the HEV has been greatly improved in plug-in HEV that can be recharged from an external grid.

Jahromi et al. applied technology forecasting using data envelopment analysis (TFDEA) to the HEV industry in an attempt to build an accurate technological forecasting model [1]. Their work revisited the original study conducted by Tudorie [2] and identified the input and output parameters that can better explain the progress of HEV industry. Specifically, the original study selected two input parameters: weight of the vehicle and combined output power of electric motor and combustion engine. The output parameters were acceleration rate, CO_2 emission and fuel economy. Those parameters were mostly selected based on the dynamics of combustion engine and electric motors. The dataset used in this study included a diverse set of vehicles, which required more comprehensive assessment to take multifaceted performance factors into

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[1] An early version of this study was presented at the Portland International Conference on the Management of Engineering and Technology (PICMET '13) and published in the Proceedings [1].

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account. Jahromi et al. later revised the model by incorporating additional parameters; Manufacturing Suggested Retail Price (MSRP) was selected as the only input and acceleration rate, fuel economy, a measure for miles per gallon equivalent, and seating capacity were selected for outputs. The revised model was able to explain the technological advancement with improved forecasting accuracy.

The current study further extends the previously developed model considering different market segments as well as applies it to the up-to-date HEVs so that technological advancement observed over the past 15 years can be investigated. Furthermore, the rates of change for each segment are provided to give insights into the estimation of the future performance levels for new product development target setting purposes.

2. Research methodology

As technology becomes sophisticated, there are few technologies that truly possess only a single technical capability. The rate of change also varies over time, being affected by the maturity levels of component technologies. This structural complexity makes today's technological forecasting even more challenging, which leads to the question: how to combine growth patterns of each attribute to describe the multi-objective technology systems?

To tackle this multi-attribute problem, modern technological forecasting studies frequently use frontier analysis methods. The idea is to construct the production possibility set from the best practice technologies using multiple inputs and outputs of the systems so that underperforming technologies are identified and compared against constructed frontier of the production possibility set. The evolution of the frontier surfaces is then monitored over time to capture the rate of change by which future technological possibilities can be estimated. This approach is particularly advantageous when the multiple tradeoffs between product characteristics exist and vary by manufacturer, by market segment, and over time [3,4].

To accommodate time-series application of frontier analysis into technological forecasting, Inman developed a measure to quantify the rate of frontier expansion by which the arrival of following technologies can be estimated [5]. Specifically, his method, TFDEA, establishes the state-of-the-art technology frontier using the data points identified as relatively efficient using DEA (see Fig. 1). Note that the frontier is a set of convex combinations formed by state-of-the-art technologies hence it's not a curved surface but a piecewise linear combination. The tradeoffs between technical capabilities can be considered as a radial improvement within this frontier space. The TFDEA iterates the frontier formation process over time to track the rate of frontier shift. This momentum of progress is then used to make a forecast for the future technologies.

TFDEA, being an extreme point frontier analysis technique, uses only the state of the art technologies to measure the technological advancement. In contrast, central tendency approaches such as regression are influenced by non-state-of-the-arts or mediocre technologies as well. Comparisons of TFDEA to central tendency approaches have shown its usefulness in a wide range of technological forecasting applications [6–10].

TFDEA also inherits the ability to identify technology segments in an objective manner from its non-parametric nature (see Fig. 2.) The piecewise linear facets represent different tradeoffs, i.e. technologies subject to corresponding facet may have a similar mix of input–output levels [11], which makes it possible to distinguish fast/slow advancing technology segments within the benchmarking process. Lim and Anderson's study showed that capturing local rates of change from identified frontier facets and utilizing them for individual forecasting targets improve the forecasting accuracy in general [12].

Fig. 3 shows the process of TFDEA in the envelopment model assuming variable returns to scale and dynamic frontier year with three separate stages. The first stage, shown by (1)–(9), iterates efficiency measurement in a time series manner so that the evolution of the state-of-the-art frontier can be monitored. The variable $\phi_k^{h \in \{R,C\}}$ represents the radial output efficiency of technology k at the time of release (R) and current frontier time (C) in which the forecast is conducted. The variable, λ_{jk}^h, describes how much of technology j is used in setting a target of performance for technology k. The objective function (1) also incorporates minimizing effective dates to ensure reproducible outcomes

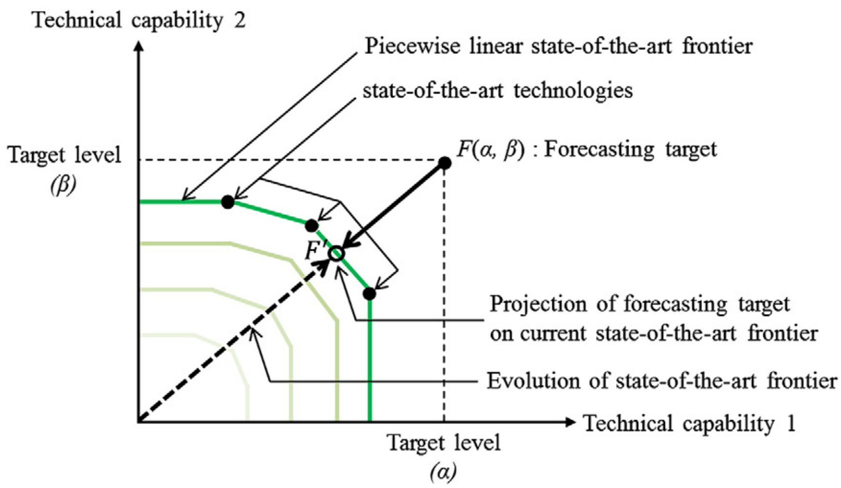


Fig. 1. Two-dimensional illustration of TFDEA.

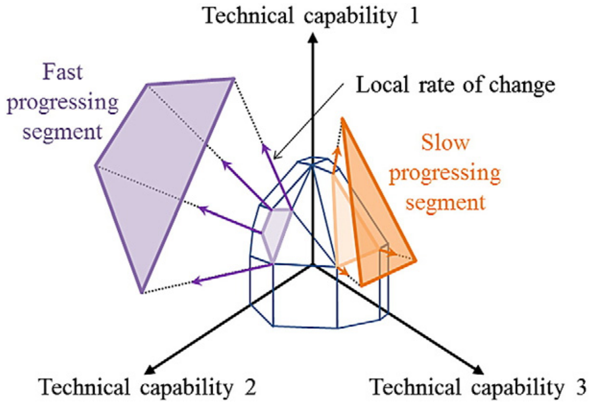


Fig. 2. Illustration of segmented rate of change in TFDEA.

from possible alternate optimal solutions by distinguishing between Pareto-efficient technologies [13,14].

The frontier separation is imposed by (7) to deal with the external nondiscretionary factor, i.e. categorical variables [11]. This restricts the reference set for each technology being evaluated to technologies presenting only same or more disadvantageous conditions in terms of the categorical index [15,16]. Therefore, this requires the categorical variables to be arranged in a rank order according to the favorable condition. We introduce a categorical variable for the HEV application in the following section to account for the nondiscretionary factor.

The second stage calculates the rate of change, γ_k^C, by taking all technologies that were efficient at the time of release, $\phi_k^R = 1$, but were superseded by new technologies at the current frontier time C, $\phi_k^C > 1$. The local rate of change, δ_j^C, can then be obtained by taking the weighted average of rates of change for each technology on the current state-of-the-art frontier [12].

The last stage makes a forecast of the arrival of future technologies. In (12), $t_k^{forecast}$ indicates the estimated time of arrival of future technology k based on the individualized rate of change obtained by combining the local rate of change of state-of-the-art technology j, δ_j^C, that constitutes the frontier facet onto which technology k is being projected.

3. Research model and dataset

3.1. TFDEA parameters

3.1.1. Input variable

3.1.1.1. MSRP. Manufacturer's suggested retail price can be considered as a reasonable proxy for manufacturing cost due to a high presumed correlation. The vehicles in the dataset were from different countries and released in different years therefore the actual MSRP for each vehicle was converted into 2013 U.S. dollar value through the following steps:

1. The vehicle's MSRP in the year of release was found through the manufacturers' website or car review websites.
2. If the MSRP was in currency other than U.S. dollars, the value was converted to the equivalent amount in U.S. dollars using the exchange rate of the year of release. This study used the historical exchange rates provided by OANDA Corporation for the conversions [17]. Eq. (13) shows the formula to convert the MSRPs in the original currency to U.S. dollar equivalent:

$$\mathrm{MSRP}_{\text{U.S.dollar equivalent}} = \text{Exchange rate}_{\text{year of release}} * \mathrm{MSRP}_{\text{in original currency}}. \quad (13)$$

3. To inflate a past dollar value into present value, Eq. (14) was used by applying the historical consumer price index (CPI) and the CPI of the year 2013. The CPI values were obtained from the Bureau of Labor Statistics and the formula can be found as below [18]:

$$\mathrm{MSRP}_{\text{2013 equivalent}} = \mathrm{MSRP}_{\text{year of release}} * (2013\,\mathrm{CPI})/(\text{Year of release CPI}). \quad (14)$$

3.1.2. Output variables

3.1.2.1. Acceleration rate. This value determines the time (in seconds) it takes for a vehicle to go from 0 to 100 km (or 60 miles). Eq. (15) shows the formula to calculate the acceleration rate:

$$\text{Acceleration rate}\left(\frac{\text{km}}{\text{hour}}\text{per second}\right) = \frac{\text{speed range}\left(\frac{\text{km}}{\text{h}}\right)}{\text{time(second)}}. \quad (15)$$

3.1.2.2. Fuel economy. Fuel economy shows the distance a vehicle can travel in one unit of fuel. The Environmental Protection Agency (EPA) provides information on fuel economy for the vehicles available in the U.S. market [19]. This study used the fuel economy value for combined city and highway driving cycles that was officially announced by the EPA.

Note that the fuel economy estimation is complicated in plug-in HEVs as they can drive in pure electric mode from having been charged with the grid. Therefore the fuel economy of plug-in HEV was modified so that it takes account of hybrid mode only. To consider the additional dimension of plug-in HEV's performance, i.e. pure electric mode, another output of fuel economy is needed to be incorporated in the model as discussed below.

3.1.2.3. Max of MPG and MPG equivalent. The EPA developed a mile per gallon equivalent (MPGe) for plug-in HEVs to take all-electric range into account. This value is based on the gasoline-equivalent energy of electricity [20]. Specifically, 1 gal of gasoline can be approximated to 33.7 kilowatt per hour of electric energy. For vehicles that were not introduced in the U.S. market, the value of MPGe was calculated using the Eq. (16):

$$\text{MPGequivalent} = \frac{33.7 * \text{drivingrange}}{\text{batterycapacity}}. \quad (16)$$

Stage 1. Efficiency measurement

$$\max \sum_{k=1}^{n}\left[\phi_k^h - \varepsilon\left(\frac{\sum_{j=1}^{n}\lambda_{j,k}^h \cdot t_j}{\sum_{j=1}^{n}\lambda_{j,k}^h}\right)\right] \tag{1}$$

$$s.t.\ \sum_{j=1}^{n} y_{r,j}\lambda_{j,k}^h \geq \phi_k^h y_{r,k}, \quad r = 1,\ldots,s \tag{2}$$

$$\sum_{j=1}^{n} x_{i,j}\lambda_{j,k}^h \leq x_{i,k}, \quad i = 1,\ldots,m \tag{3}$$

$$\lambda_{j,k}^R = 0, \quad \forall(j,k)\,|\,t_j > t_k \tag{4}$$

$$\lambda_{j,k}^C = 0, \quad \forall(j,k)\,|\,t_j > T \tag{5}$$

$$\sum_{j=1}^{n}\lambda_{j,k}^h = 1, \quad \forall\, k \tag{6}$$

$$\lambda_{j,k}^h = 0, \quad if\ y_{r,j} < y_{r,k} \quad r \in ND \tag{7}$$

$$\lambda_{j,k}^h \geq 0, \quad \forall\, j,k \tag{8}$$

$$h \in \{R, C\} \tag{9}$$

Stage 2. Rate of change calculation

$$\gamma_k^C = \left(\phi_k^C\right)^{\frac{1}{\frac{\sum_{j=1}^{n}\lambda_{jk}^C \cdot t_j}{\sum_{j=1}^{n}\lambda_{jk}^C} - t_k}}, \quad \forall k\,|\,\phi_k^R = 1, \quad \phi_k^C > 1 \tag{10}$$

$$\delta_j^C = \frac{\sum_{k=1}^{n}\lambda_{jk}^C \cdot \gamma_k^C}{\sum_{k=1,\gamma_k^C>0}^{n}\lambda_{jk}^C}, \quad \forall j\,|\,\phi_j^C = 1 \tag{11}$$

Stage 3. Forecasting

$$t_k^{forecast} = \frac{\ln\left(\frac{1}{\phi_k^C}\right)}{\ln\left(\frac{\sum_{j=1}^{n}\lambda_{jk}^C \cdot \delta_j^C}{\sum_{j=1}^{n}\lambda_{jk}^C}\right)} + \frac{\sum_{j=1}^{n}\lambda_{jk}^C \cdot t_j}{\sum_{j=1}^{n}\lambda_{jk}^C}, \quad \forall k\,|\,\phi_k^C < 1 \tag{12}$$

Fig. 3. TFDEA process.

Since this parameter takes the maximum of MPG and MPGe, conventional HEVs have the same value as their fuel economy. Consequently, adding this parameter can address the additional feature of plug-in HEV without penalizing conventional hybrid cars in TFDEA model.

3.1.3. Categorical parameter

3.1.3.1. Vehicle class. Unlike the earlier work by Jahromi et al. [1] that included seating capacity as one of the output parameters to take capacity of the vehicle into account, this study used vehicle class as a categorical parameter. This is because seating capacity is more of design characteristics suitably determined for the target market than performance characteristic that manufacturers want to increase. Furthermore, vehicle class can be used to classify the different types of vehicle more precisely than seating capacity. For example, Prius C is a compact vehicle and Prius V is a midsize vehicle while they have the same seating capacity of five.

The EPA defines vehicle classes based on interior passenger and cargo volumes as well as design purposes [19]. This study adopted the EPA's criteria and grouped HEVs into 7 classes: two-seaters (TS), compact (C), midsize (M), large (L), sport utility vehicle (SUV), minivan (MV), and pickup truck (PT). By using the above order of vehicle classes[2] as categorical indices, HEVs can only be compared to HEVs in the same or following classes. For example, HEVs in the last class (i.e. pickup truck) are only compared with HEVs in the same class, but HEVs in category M are compared with HEVs in the same and/or following classes (i.e. M, L, SUV, MV, and PT) in terms of per price performances. Intuitively, the category M vehicle will not be compared against any vehicles from preceding classes (i.e. TS and C). Consequently, this enables to reflect a great deal of information contained in each HEV market segment that would be lost in any point-comparison without consideration on environmental factors [15].

3.2. Dataset

The dataset has been updated to cover total 154 HEVs including 11 plug-in HEVs from 1997 to 2013 (see Table 1 for a summary and Appendix 1 for the full dataset.) The EPA database was the main source to collect the required information of technical attributes. Other sources were cross referenced especially for the vehicles released outside the U.S. and, in such a case, information was prioritized in order of technical report, product manual, benchmarking journals, and review sites.

4. Analysis of the technological advancement

The model was implemented using the software[3] developed by Lim and Anderson [21]. Fig. 4 provides a sketch of what segment has been dominating the market in terms of technological superiority by showing how the state-of-the-art frontier of hybrid electric vehicles over time has been made up of vehicles from different segments. That is, the percentage indicates the amount of which each HEV segment stakes out the state-of-the-art frontier that any particular HEV is aiming for. In 1997 for example, the state-of-the-art frontier was constructed by a sole compact HEV, the 1st generation of Prius, without a competition therefore the dark blue region (i.e. compact segment) filled up the entire frontier space. As other types of HEVs began to be released in the market over time, the state-of-the-art frontier has been made up of a wide variety HEVs.

4.1. Two-seaters and compact segments: "stagnated"

Until 2003, all HEVs in our dataset were either two-seaters or compact automobiles. This resulted in these two segments dominating the HEV market but the introduction of vehicles in other segments resulted in an erosion of this dominance. Despite consecutive introductions of successful lineups such as Honda Insight and Toyota Prius C, the technological dominance has been shrinking as the other types of HEVs' market advance.

Note that there were no two-seaters or compact HEVs on the state-of-the-art frontier in 2013. This indicates that two-seaters and compact HEVs are no longer competitive with vehicles in other segments, though they presumably have a light weight advantage. This is particularly attributed to the encroachment of the midsize HEVs that is extending its target market with a fast technological advancement recently. One can verify this by the list of benchmarks of two-seaters and compact HEVs in 2013. Table 2 contains this information. The combination of benchmark and dominated set can be understood as a competitor group in terms of their product spec where the former is found to be outperforming the latter. For example, Prius (1st generation), indicated as vehicle number of 1, has become obsolete since its introduction in 1997 and it was superseded by its benchmarks: Accord Hybrid (21), Prius alpha (V) (80), and Fit Shuttle Hybrid (82).

Except for the Fit Shuttle Hybrid (82), benchmarks of all two-seaters and compact HEVs were found to be midsize HEVs. This suggests that midsize HEVs are outperforming HEVs from those two segments with similar technical characteristics. That is, midsize HEVs are penetrating the market niche that has been dominated by two-seaters and compact HEVs. In fact, the bar for energy efficiency is constantly being raised as more competitors including bigger vehicles have come into the market place with innovative features such as plug-in technology. Hence, high fuel economy is not entirely the domain of smaller vehicles any more [22]. This instigated makers of small HEVs to engage in more ingenious designs and development improvement (e.g. Toyota's new global architecture project) [23].

4.2. Midsize segment: "flourishing"

Continuing the previous discussion, it is noteworthy that midsize segment has shown a fast adoption rate with a superior technological performance recently. Indeed, hybrid technology has gained substantial popularity not only in fuel prices but also in reliability and longevity of powertrain that almost every auto manufacturers began to add hybrid version of their conventional midsize models to their brochures [24].

Fig. 5 further explains the market penetration of midsize HEVs into the compact segment. Although the average price of midsize HEVs is still slightly higher than compact HEVs, not only the acceleration of midsize HEVs outperforms compact HEVs but also the gap of average fuel economy between compact and midsize HEVs is getting narrower. Especially, recent midsize plug-in HEVs such as Ford C-Max Energi (152) and Fusion Energi (153) have surpassed the fuel economy of any other compact HEVs as shown in the bottom right figure. This would attract customers who pine for a sportier vehicle in addition to roomier interior and safety features to the midsize segment with a variety of purchase options.

Almost by definition, benchmarks (i.e. state-of-the-art HEVs) targeting a niche market won't have a big dominated set who cited them as a benchmark [25]. In contrast,

[2] This should be understood as the order of difficulty to achieve per price performances due to structural requirements for each market segment rather than mere vehicle sizes. For example, while pickup trucks have a range of sizes, the industrial loads that need to be carried in pickup trucks may cause design demands beyond that of minivans that are typically reflected in lower fuel economy. Also, note that the EPA only applies volume criteria for cars (TS, C, M, and L) and weight criteria for trucks (SUV, MV, and PT).

[3] R package for a standard TFDEA is available at http://cran.r-project.org/web/packages/TFDEA/index.html. A web-based version is also available at http://tfdea.com.

Table 1
Dataset summary.

Vehicle class		Two-seaters	Compact	Midsize	Large	SUV	Minivan	Pickup truck
Number of vehicles		9	32	56	8	37	4	8
First introduction (years)		2000	1997	2004	2009	2004	2003	2004
MSRP (2013 equivalent)	Max	$21,435	$49,650	$118,544	$104,300	$97,238	$38,085	$57,095
	Average	$19,521	$27,908	$37,335	$85,251	$47,495	$29,616	$39,819
	Min	$18,936	$14,072	$11,849	$25,200	$17,045	$16,394	$30,090
Acceleration (km/h/s)	Max	12.20	14.93	19.61	20.41	18.52	9.26	12.35
	Average	9.99	9.84	12.63	15.97	12.99	7.85	11.12
	Min	9.24	7.04	7.14	12.35	8.33	6.29	9.09
MPG	Max	60.69	68.21	72.92	43.00	33.64	58.80	22.35
	Average	50.08	43.54	35.82	26.06	26.22	49.28	19.89
	Min	37.00	28.00	20.00	21.00	18.82	40.46	17.00
Max of MPG and MPGe	Max	60.69	98.00	100.00	43.00	38.00	58.80	22.35
	Average	50.08	50.95	41.42	26.06	26.45	49.28	19.89
	Min	37.00	28.00	20.00	21.00	18.82	40.46	17.00

state-of-the-art HEVs with a broad scope must have been cited as a benchmark by many other competitors. Consequently, it would be possible to reveal whether an HEV on the 2013 state-of-the-art frontier is the niche or the broad player if the information on which and how many HEVs were compared with them was available. This has been done in Table 3.

In the midsize segment, three dominant players can be identified: Honda Accord Hybrid (21), Toyota Prius alpha (V) (80), and Infiniti M35h (145). One can further classify them such that Accord Hybrid as a low-end, Prius alpha (V) a middle-end, and M35h a high-end benchmark based on their MSRPs and performance characteristics.

Local rates of change of state-of-the-art HEVs indicate how much technological advancement has been observed from their dominated sets. Using the foregoing classifications, middle-end midsize HEVs have shown the fastest rate of change, i.e. 3.66% of annual improvement for acceleration and fuel economies, whereas low-end and high-end midsize HEVs' progresses were relatively moderate, 1.56% and 1.96% respectively.

It is also interesting to note that BYD F3DM (56) and Ford C-Max Energi (152) were found to be state-of-the-art plug-in HEVs that have been competed against other plug-in HEVs listed in their dominated sets. However the technological advancement of plug-in HEV in midsize segment appeared to be modest so far possibly due to the fact that the current battery technology has been struggling with technical challenges along with cost and complexity coming from dual powertrains [26,27].

4.3. Large segment: "emerging"

Two large HEVs are on the 2013 state-of-the-art frontier: the BMW ActiveHybrid 7 Series (61) and the Ford C-Max Hybrid FWD (116). One may notice that these HEVs are representing two very different regions within a large HEV segment. Indeed, the BMW ActiveHybrid 7 Series, which has a 2013 equivalent MSRP of $104,300, constitutes the most expensive HEV market segment. This is a noteworthy segment

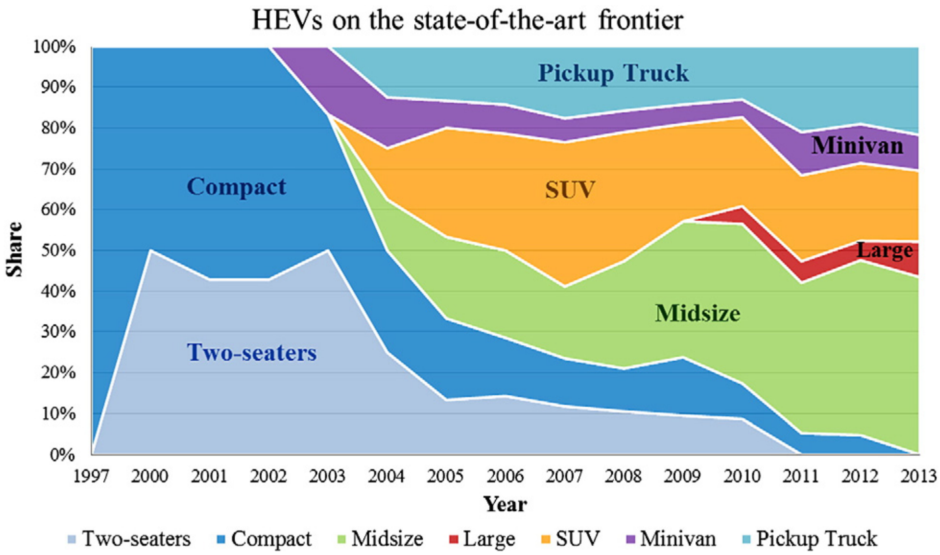


Fig. 4. State-of-the-art HEV distribution.

Table 2
Benchmarks of two-seaters and compact HEVs.

Benchmarks (class)	Dominated set[a]	
	Two-seaters	Compact
21 (M)	4, 6, 7, 9, 12, 18, 55, 90, 136	1, 3, 5, 10, 16, 19, 43, 47, 63, 66, 71, 77, 78, 79, 88, 97, 102, 111, 112, 113, 117, 138, 140, 141
40 (M)		10
56 (M)		99
67 (M)		2, 46, 81
80 (M)	4, 6, 7, 9, 12, 18, 55, 90, 136	1, 2, 3, 5, 16, 19, 43, 46, 47, 54, 63, 66, 71, 77, 78, 79, 81, 88, 97, 102, 111, 112, 113, 117, 138, 140, 141
82 (MV)	4, 6, 7, 9, 12, 18, 55, 90, 136	1, 3, 5, 10, 16, 19, 43, 47, 63, 66, 77, 88, 97, 102, 111, 117
145 (M)		46, 71, 78, 79, 112, 113, 138, 140, 141
152 (M)		68, 99, 154
153 (M)		103

[a] List of HEVs who cited the corresponding state-of-the-art HEV as a benchmark.

in that it is penetrating a niche of luxury market with a powerful engine and electric motor combination while still getting satisfactory MPG. In fact, the high-end automakers have finally begun to push green cars, e.g. Mercedes' S hybrid series or Porsche's Panamera S series, right after Tesla proved that there is a sufficient number of upscale customers in the electric vehicle market [28].

In contrast, the Ford C-Max Hybrid FWD, which has a 2013 equivalent MSRP of $25,200, stakes out the other end of the large segment. This unique vehicle is, in fact, targeting the niche between midsize and minivan segments to satisfy customers craving for stylish and spacious HEV but not as big as minivans [29]. Besides, the kinetic design deliberately shrinking the cargo space enables to deliver MPG of 43 which is the highest fuel economy in the large segment.

The local rates of change for the large segment could not be calculated due to their recent debut on the state-of-the-art frontier. That is, successive introductions of large HEVs could show two notable sub-segments within the frontier but the evolution of corresponding frontier facets hasn't occurred yet. Nevertheless, this emerging large HEV segment may be signaling one of the disruptive paths of future HEV development such as the recent adoption of diesel hybrid sheds light on an attempt to get a substantial boost in MPG and meet the stringent CO_2 regulations at the same time [30,31].

4.4. SUV segment: "forging ahead"

Many industry reports point out that the SUV market is declining mostly due to the growing crossover segments as well as a low fuel economy [32]. However, at the same time, SUV is still recognized as a pure utility of a 'go anywhere' spirit that no other segment can replace in today's auto market. This motivated manufacturers to incorporate hybrid technology, especially plug-in, into the SUV market so that the hybrid SUV segment can address a market demand with the improved fuel economy [33,34].

The fast rates of change observed by all four state-of-the-art SUVs, Saturn Vue Hybrid (51), Audi Q5 (58), Jeep Patriot EV (59), and Porsche Cayenne S Hybrid (94), are supporting the previous argument. In particular, a relatively inexpensive SUV niche represented by Jeep Patriot EV and its dominated set show the fastest local rate of change of 5.08% across all HEV segments. Furthermore, the dominant vehicles of medium and large SUVs: Audi Q5 and Cayenne S Hybrid, show local rates of change of 3.85% and 3.08% respectively. One may find it interesting to see how these cheap plug-in SUV and full-size luxury SUV segments would leverage the SUV market with current rate of technological advancement as opposed to the other crossover vehicles.

4.5. Minivan segment: "crossover"

As previously discussed, the cardinality of dominated set may imply the state-of-the-art HEV's positioning in the market. According to this, the Fit Shuttle Hybrid (82) can be regarded as a good all-round performer. Specifically, its dominated set includes all types of HEVs, which indicates that this vehicle would be one of the most representative designs across all HEV segments. However, the local rate of change of this cheap and economic minivan was found to be 1.97%. This is slower than the larger minivan segment's, represented by Estima Hybrid (26), 3.72%.

It should be noted here that minivans have been successful in Asia and Europe but have yet to be produced for the U.S. market. It is often pointed out that minivan's signature feature of three rows for 7 (or 8) passenger capacity would face a difficulty in the U.S. market without ensuring sufficient cargo and legroom space [35]. In addition, carmakers claim that minivans wouldn't get much fuel economy improvement due to their big and boxy structure. Furthermore, minivan customers want to have not only high fuel efficiency but also long cruising ranges, which requires the optimal placement of hybrid battery packs to keep them from using up valuable space. Therefore one may have to keep in mind that current minivan segment represented by Fit Shuttle Hybrid might be valid in a specific market that values economic design, hence, not be applicable to the U.S. market nor for the expected rate of technological advancement.

4.6. Pickup truck segment: "steady"

There is actually only one hybrid pickup truck model (under two different brand names: Chevrolet Silverado and GMC Sierra both from General Motors) and therefore this segment reflects how much performance of this product line has advanced throughout the generations. Not surprisingly, the most recent model, Silverado 15 Hybrid 2WD (142), was found to be an state-of-the-art truck with annualized performance improvement of 3.72%.

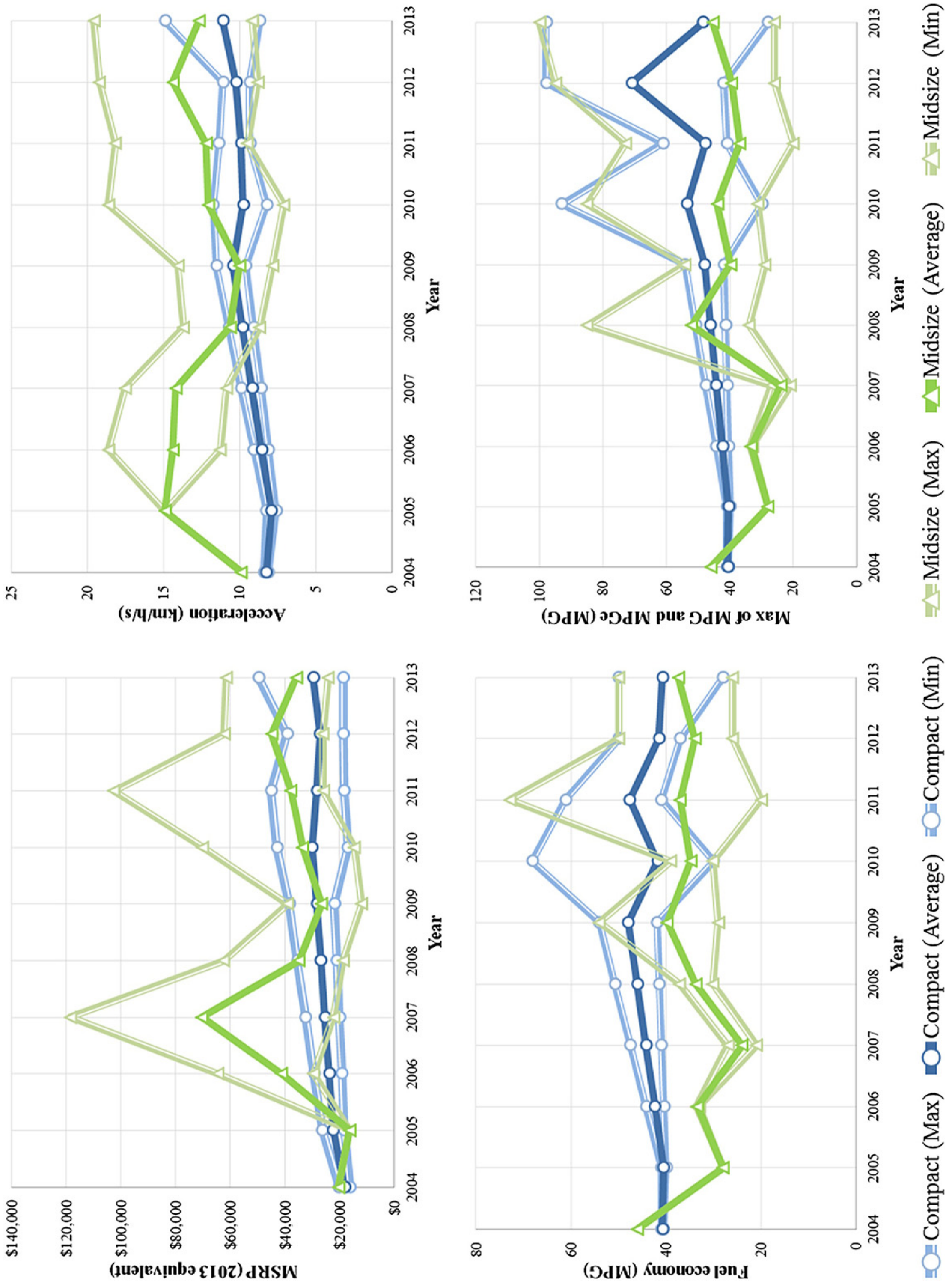


Fig. 5. Encroachment of midsize segment into the compact segment.

Table 3
Benchmarks and local rates of change observed from 2013 state-of-the-art HEVs.

Class	State-of-the-art HEV	Dominated set[a]	Local rate of change
Midsize	21	1, 3, 4, 5, 6, 7, 9, 10, 12, 13, 16, 18, 19, 21, 24, 27, 33, 38, 39, 43, 45, 47, 50, 55, 60, 62, 63, 64, 66, 70, 71, 77, 78, 79, 83, 84, 86, 88, 89, 90, 91, 92, 97, 102, 104, 105, 106, 107, 111, 112, 113, 114, 115, 117, 118, 119, 120, 121, 122, 123, 124, 125, 126, 136, 137, 138, 139, 140, 141	1.01562
	40	10, 40, 60	1.00422
	56	38, 56, 99	1.00083
	67	2, 25, 36, 46, 49, 67, 81, 100, 101, 108, 144, 146, 147	1.00867
	80	1, 2, 3, 4, 5, 6, 7, 9, 12, 13, 16, 18, 19, 24, 25, 27, 33, 36, 39, 43, 45, 46, 47, 49, 50, 54, 55, 62, 63, 64, 66, 70, 71, 77, 78, 79, 80, 81, 83, 84, 86, 88, 89, 90, 91, 92, 97, 101, 102, 104, 105, 106, 107, 111, 112, 113, 114, 115, 117, 118, 119, 120, 121, 122, 123, 124, 125, 126, 136, 137, 138, 139, 140, 141, 144, 146, 147	1.03664
	145	24, 25, 27, 30, 33, 39, 45, 46, 49, 50, 62, 64, 70, 71, 78, 79, 83, 84, 86, 89, 91, 92, 96, 100, 101, 104, 105, 106, 107, 108, 112, 113, 115, 118, 119, 120, 121, 122, 123, 124, 125, 126, 137, 138, 139, 140, 141, 144, 145, 146, 147	1.01961
	152	38, 68, 99, 152, 153, 154	1.01367
Large	61	30, 44, 58, 61, 76, 96, 103, 109, 148, 149, 150	N/A
	116	116, 148	N/A
SUV	51	17, 20, 28, 31, 34, 51, 52, 69, 72, 87, 93, 95, 110, 128, 131	1.04067
	58	11, 17, 23, 28, 29, 31, 32, 41, 53, 58, 69, 72, 73, 74, 87, 93, 110, 127, 128, 129, 131, 133, 134	1.03854
	59	20, 34, 59	1.05082
	94	11, 15, 23, 28, 29, 32, 37, 41, 42, 48, 52, 53, 57, 65, 73, 74, 94, 95, 110, 127, 128, 129, 130, 131, 132, 133, 134, 135, 148	1.03080
Minivan	26	8, 26	1.03721
	82	1, 3, 4, 5, 6, 7, 9, 10, 11, 12, 13, 15, 16, 17, 18, 19, 20, 23, 29, 31, 32, 34, 37, 41, 42, 43, 44, 47, 53, 55, 57, 60, 63, 65, 66, 69, 72, 73, 74, 76, 77, 82, 85, 87, 88, 90, 93, 97, 102, 109, 111, 114, 117, 127, 129, 130, 132, 133, 134, 135, 136, 149, 150	1.01971
Pickup truck	142	8, 142	1.03721

Kruskal–Wallis test has been conducted to verify the non-parametric significance of differences between groups. It was shown that identified segments are non-identical populations with respect to the local rates of change (chi-squared = 9.8938, df = 3, p-value = 0.02964).
[a] List of HEVs who cited the corresponding state-of-the-art HEV as a benchmark.

However, the hybrid pickup truck segment requires a cautious view on its future. The state-of-the-art hybrid truck today has fuel economy of 21 MPG and acceleration of 12.35 km/h/s with MSRP of $41,135. One may find it unclear if this hybrid truck is more appealing than its solid gasoline version, i.e. Silverado C15 2WD with 17 MPG, acceleration of 13.70 km/h/s, and $23,590 price tag. Assuming $5 a gallon gasoline and 20,000 miles per year, the payback period would be over 15 years. Although hybrid technology may be a good choice for other reasons, current efficiency-cost analysis suggests that the premium upfront cost for hybrid trucks is not likely offset by fuel savings. This indicates a faster rate of change through additional innovation may be needed for hybrid pickup trucks to become more prominent in the future HEV market.

5. Conclusion

This study evaluates and compares the technological advancement observed in different HEV market segments over the past 15 years. The results indicate that three sub-segments exist in midsize HEVs and middle class represented by Prius alpha (V) showed the faster technological progress than other two. The performance growth as well as diversification of midsize HEVs seems to be posing a threat to two-seaters and compact segments. The overall rate of the SUV segment's technological advancement, from low price plug-in to full-size, was shown to be the fastest across the all HEV segments. The large HEVs are targeting a luxury market niche whereas minivans are showing the universal design characteristics in non U.S. markets. Finally, hybrid pickup trucks showed a steady performance upgrade however they are competing against their own solid gasoline versions to prove the utility of hybrid technologies.

The rate of technological advancement identified in each market (sub) segment can give an insight into the target setting practice for a new product development planning. That is, manufacturers may position their products within the current state-of-the-art frontier and utilize the corresponding rate of change to see whether their design targets would locate on the estimated future frontiers. One can also make use of this information on pricing strategy such that offering the similar performance as current state-of-the-art HEVs but set the reduced price using the given rate of change. This is, in fact, a strategy that was used by Nissan to boost their sales for Nissan Leaf [36].

As a future work, trade-offs between technological characteristics need to be examined so that various future technological possibilities can be estimated based on identified rate of changes. Technological forecasting for Battery Electric Vehicles (BEV) using a similar approach could suggest another future work with the growing interest in pure electric vehicles. The performance of BEVs is highly dependent on their battery technology. The weight of the batteries is an important factor in the energy batteries produce; batteries also incorporate a significant amount of the cost of the pure electric vehicles. In 2012, Wall Street Journal published a report in which the price of the batteries was estimated to be one third of the total price of pure electric vehicles [37]. Charging time and driving ranges are among others that are also critical for pure electric vehicles. Therefore, a solid forecasting model for BEVs requires in-depth research on the battery technology to select the suitable performance metrics that would be the main indicators of performance for the different markets.

Appendix 1. Hybrid electric vehicle dataset

No.	Model	Date	MSRP (2013 equivalent)	Acceleration rate (km/h/s)	Fuel economy (MPG)	Max of MPG and MPGe (MPG)	Class
1	Prius (1st gen.)	1997	$24,509.74	7.46	41.26	41.26	C
2	Tino Hybrid	2000	$35,354.97	8.20	54.10	54.10	C
3	Prius (2nd gen.)	2000	$26,832.25	7.97	45.23	45.23	C
4	Insight	2000	$18,936.41	9.52	53.00	53.00	TS
5	Civic Hybrid 1st gen.	2001	$25,833.38	7.04	47.04	47.04	C
6	Insight	2001	$19,036.71	9.52	53.00	53.00	TS
7	Insight	2002	$19,137.01	9.71	53.00	53.00	TS
8	Alphard Hybrid	2003	$38,084.77	8.33	40.46	40.46	MV
9	Insight	2003	$19,137.01	9.52	53.00	53.00	TS
10	Civic Hybrid	2003	$14,071.92	8.62	41.00	41.00	C
11	Escape Hybrid	2004	$36,676.10	10.32	31.99	31.99	SUV
12	Insight	2004	$19,237.31	9.35	52.00	52.00	TS
13	Prius	2004	$20,355.64	9.90	46.00	46.00	M
14	Silverado 15 Hybrid 2WD	2004	$30,089.64	9.09	17.00	17.00	PT
15	Lexus RX400h	2005	$58,521.14	12.76	28.23	28.23	SUV
16	Civic Hybrid 2nd gen.	2005	$26,354.44	7.63	39.99	39.99	C
17	Highlander Hybrid	2005	$29,186.21	12.76	29.40	29.40	SUV
18	Insight	2005	$19,387.76	9.71	52.00	52.00	TS
19	Civic Hybrid	2005	$18,236.33	8.26	41.00	41.00	C
20	Escape Hybrid 2WD	2005	$19,322.56	9.52	29.00	29.00	SUV
21	Accord Hybrid	2005	$16,343.69	14.93	28.00	28.00	M
22	Silverado 15 Hybrid 2WD	2005	$32,647.26	11.11	17.00	17.00	PT
23	Mercury Mariner Hybrid	2006	$34,772.40	8.98	32.93	32.93	SUV
24	Camry Hybrid	2006	$29,853.25	11.28	33.64	33.64	M
25	Lexus GS450h	2006	$64,547.56	18.65	33.40	33.40	M
26	Estima Hybrid	2006	$36,012.70	9.26	47.04	47.04	MV
27	Altima Hybrid	2006	$29,524.75	13.29	32.93	32.93	M
28	Chevrolet Tahoe Hybrid	2007	$42,924.35	10.91	22.35	22.35	SUV
29	Kluger Hybrid	2007	$46,229.48	12.76	25.87	25.87	SUV
30	Lexus LS600h/hL	2007	$118,543.60	17.54	21.00	21.00	M
31	Tribute Hybrid	2007	$24,823.83	11.28	31.75	31.75	SUV
32	GMC Yukon Hybrid	2007	$57,094.81	12.28	21.78	21.78	SUV
33	Aura Hybrid	2007	$22,110.87	10.87	27.00	27.00	M
34	Vue Hybrid	2007	$22,938.33	10.75	26.00	26.00	SUV
35	Silverado 15 Hybrid 2WD	2007	$34,653.23	11.49	17.00	17.00	PT
36	Crown Hybrid	2008	$62,290.38	8.70	37.16	37.16	M
37	Cadillac Escalade Hybrid	2008	$78,932.81	9.09	22.35	22.35	SUV
38	F3DM	2008	$23,744.06	9.52	30.11	85.00	M
39	Altima Hybrid	2008	$18,675.63	13.70	34.00	34.00	M
40	A5 BSG	2009	$11,849.43	7.87	35.28	35.28	M
41	Lexus RX450h	2009	$46,233.36	13.47	31.99	31.99	SUV
42	ML450 Blue HV	2009	$60,519.83	12.60	23.99	23.99	SUV
43	Prius (3rd gen.)	2009	$24,641.18	9.60	47.98	47.98	C
44	S400 Hybrid/Hybrid Long	2009	$96,208.93	13.89	26.34	26.34	L
45	Mercury Milan Hybrid	2009	$30,522.57	11.55	40.69	40.69	M
46	Lexus HS250h	2009	$38,478.15	11.55	54.10	54.10	C
47	Avante/Elantra LPI	2009	$21,872.71	10.21	41.87	41.87	C
48	ActiveHybrid X6	2009	$97,237.90	17.96	18.82	18.82	SUV
49	SAI	2009	$39,172.44	11.55	54.10	54.10	M
50	Malibu Hybrid	2009	$24,768.79	9.09	29.00	29.00	M
51	Vue Hybrid	2009	$26,408.67	13.70	28.00	28.00	SUV
52	Aspen HEV	2009	$44,903.77	13.51	21.00	21.00	SUV
53	Durango	2009	$41,033.24	8.33	21.00	21.00	SUV
54	Auris HSD	2010	$35,787.29	8.85	68.21	68.21	C
55	CR-Z	2010	$21,435.54	9.24	37.00	37.00	TS
56	F3DM PHEV	2010	$23,124.59	9.24	30.15	85.00	M
57	Touareg HV	2010	$64,198.95	15.38	28.70	28.70	SUV
58	Audi Q5	2010	$37,510.86	14.08	33.64	33.64	SUV
59	Jeep Patriot EV	2010	$17,045.06	12.05	29.40	38.00	SUV
60	Besturn B50	2010	$14,586.61	7.14	31.28	31.28	M
61	ActiveHybrid 7 Series	2010	$104,300.43	20.41	22.11	22.11	L
62	Lincoln MKZ Hybrid	2010	$37,036.64	11.15	37.63	37.63	M
63	Fit/Jazz Hybrid	2010	$16,911.85	8.26	30.00	30.00	C
64	Sonata HV	2010	$28,287.66	14.70	37.00	37.00	M
65	Cayenne S HV	2010	$73,183.47	14.71	26.11	26.11	SUV
66	Insight	2010	$19,859.16	9.17	41.00	41.00	C
67	Fuga Hybrid/Infiniti M35h	2010	$70,157.02	18.65	33.64	33.64	M

(continued on next page)

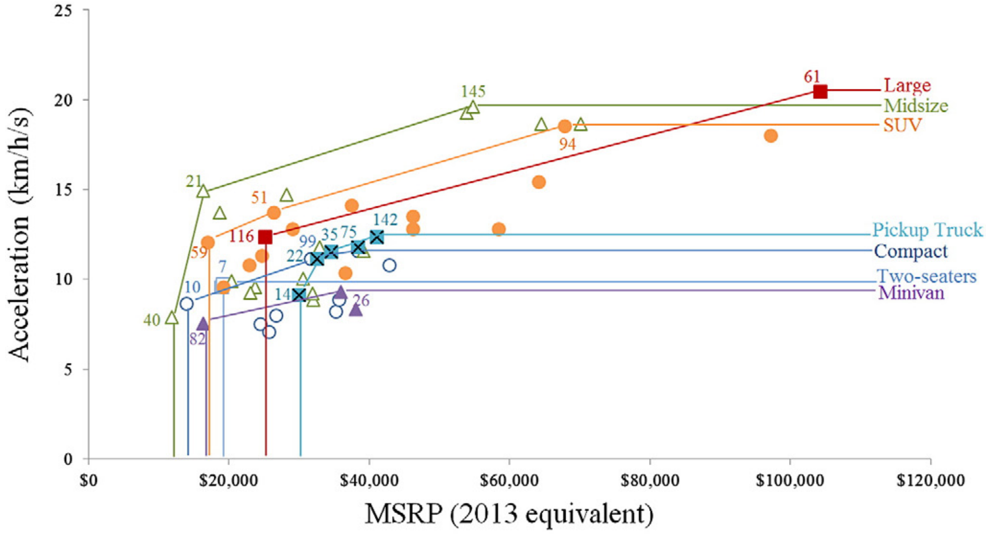
Appendix 1 (*continued*)

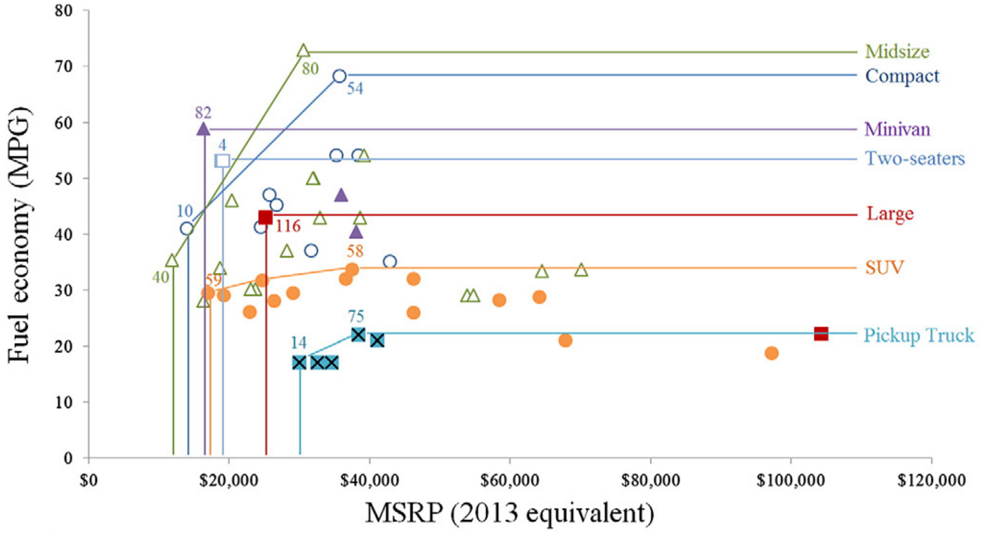
No.	Model	Date	MSRP (2013 equivalent)	Acceleration rate (km/h/s)	Fuel economy (MPG)	Max of MPG and MPGe (MPG)	Class
68	Chevrolet Volt	2010	$42,924.35	10.78	35.00	93.00	C
69	Tribute Hybrid 4WD	2010	$27,968.32	12.35	29.00	29.00	SUV
70	Fusion Hybrid FWD	2010	$28,033.51	11.49	39.00	39.00	M
71	HS 250h	2010	$34,753.53	11.76	35.00	35.00	C
72	Mariner Hybrid FWD	2010	$30,194.95	11.63	32.00	32.00	SUV
73	RX 450h	2010	$42,812.54	13.89	30.00	30.00	SUV
74	ML450 Hybrid 4natic	2010	$55,164.33	12.99	22.00	22.00	SUV
75	Silverado 15 Hybrid 2WD	2010	$38,454.56	11.76	22.00	22.00	PT
76	S400 Hybrid	2010	$88,212.78	12.99	21.00	21.00	L
77	Aqua	2011	$22,850.87	9.35	50.00	50.00	C
78	Lexus CT200h	2011	$30,082.16	9.71	42.00	42.00	C
79	Civic Hybrid 3rd gen	2011	$24,999.59	9.60	44.36	44.36	C
80	Prius alpha (V)	2011	$30,588.35	10.00	72.92	72.92	M
81	3008 Hybrid4	2011	$45,101.54	11.36	61.16	61.16	C
82	Fit Shuttle Hybrid	2011	$16,394.36	7.52	58.80	58.80	MV
83	Buick Regal eAssist	2011	$27,948.93	12.05	25.99	25.99	M
84	Prius V	2011	$27,272.28	9.51	32.93	32.93	M
85	Freed/Freed Spike Hybrid	2011	$27,972.07	6.29	50.81	50.81	MV
86	Optima K5 HV	2011	$26,549.16	10.54	36.00	36.00	M
87	Escape Hybrid FWD	2011	$30,661.34	12.35	32.00	32.00	SUV
88	Insight	2011	$18,254.38	9.52	41.00	41.00	C
89	MKZ Hybrid FWD	2011	$34,748.52	11.49	39.00	39.00	M
90	CR-Z	2011	$19,402.80	12.20	37.00	37.00	TS
91	Sonata Hybrid	2011	$25,872.07	11.90	36.00	36.00	M
92	Camry Hybrid	2011	$27,130.82	13.89	33.00	33.00	M
93	Tribute Hybrid 2WD	2011	$26,213.09	12.50	32.00	32.00	SUV
94	Cayenne S Hybrid	2011	$67,902.28	18.52	21.00	21.00	SUV
95	Touareg Hybrid	2011	$50,149.39	16.13	21.00	21.00	SUV
96	ActiveHybrid 7i	2011	$102,605.66	18.18	20.00	20.00	M
97	Prius C	2012	$19,006.62	9.35	50.00	50.00	C
98	Prius PHV	2012	$32,095.61	8.82	50.00	95.00	M
99	Ampera	2012	$31,739.55	11.11	37.00	98.00	C
100	ActiveHybrid 5 Series	2012	$62,180.23	16.67	26.00	26.00	M
101	Lexus GS450h	2012	$59,126.14	16.95	31.00	31.00	M
102	Insight	2012	$18,555.28	9.42	42.00	42.00	C
103	Chevrolet Volt	2012	$39,261.96	11.11	37.00	94.00	C
104	Camry Hybrid LE	2012	$26,067.66	13.16	41.00	41.00	M
105	MKZ Hybrid FWD	2012	$34,858.84	11.49	39.00	39.00	M
106	M35h	2012	$53,860.45	19.23	29.00	29.00	M
107	LaCrosse eAssist	2012	$30,049.52	11.36	29.00	29.00	M
108	ActiveHybrid 5 Series	2012	$61,132.11	17.54	26.00	26.00	M
109	Panamera S Hybrid	2012	$95,283.85	17.54	25.00	25.00	L
110	Yukon 1500 Hybrid 2WD	2012	$52,626.77	13.50	21.00	21.00	SUV
111	Prius C	2013	$19,080.00	8.70	50.00	50.00	C
112	Jetta Hybrid	2013	$24,995.00	12.66	45.00	45.00	C
113	Civic Hybrid	2013	$24,360.00	10.20	44.00	44.00	C
114	Prius	2013	$24,200.00	10.20	50.00	50.00	M
115	Fusion Hybrid FWD	2013	$27,200.00	11.72	47.00	47.00	M
116	C-Max Hybrid FWD	2013	$25,200.00	12.35	43.00	43.00	L
117	Insight	2013	$18,600.00	11.76	42.00	42.00	C
118	Camry Hybrid LE	2013	$26,140.00	13.51	41.00	41.00	M
119	Camry Hybrid LXLE	2013	$27,670.00	13.33	40.00	40.00	M
120	Sonata Hybrid	2013	$25,650.00	11.76	38.00	38.00	M
121	Optima Hybrid	2013	$25,900.00	11.63	38.00	38.00	M
122	Sonata Hybrid Limited	2013	$30,550.00	11.76	37.00	37.00	M
123	Optima Hybrid EX	2013	$31,950.00	11.36	37.00	37.00	M
124	Malibu eAssist	2013	$24,985.00	11.49	29.00	29.00	M
125	LaCrosse eAssist	2013	$31,660.00	11.36	29.00	29.00	M
126	Regal eAssist	2013	$29,015.00	12.20	29.00	29.00	M
127	RX 450h	2013	$46,310.00	12.99	30.00	30.00	SUV
128	Highlander Hybrid 4WD	2013	$40,170.00	13.89	28.00	28.00	SUV
129	Q5 Hybrid	2013	$50,900.00	14.71	26.00	26.00	SUV
130	Cayenne S Hybrid	2013	$69,850.00	16.39	21.00	21.00	SUV
131	Touareg Hybrid	2013	$62,575.00	16.13	21.00	21.00	SUV
132	Escalade Hybrid 2WD	2013	$74,425.00	11.63	21.00	21.00	SUV
133	Tahoe Hybrid 2WD	2013	$53,620.00	11.90	21.00	21.00	SUV
134	Yukon 1500 Hybrid 2WD	2013	$54,145.00	11.88	21.00	21.00	SUV
135	Yukon 1500 Hybrid 4WD	2013	$61,960.00	13.33	21.00	21.00	SUV
136	CR-Z	2013	$19,975.00	11.11	37.00	37.00	TS

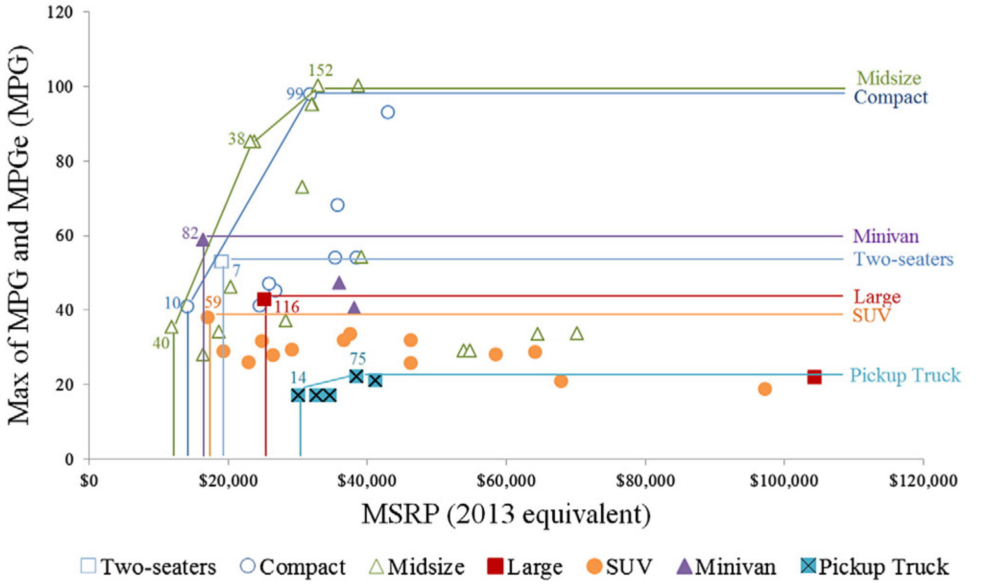
Appendix 1 (*continued*)

No.	Model	Date	MSRP (2013 equivalent)	Acceleration rate (km/h/s)	Fuel economy (MPG)	Max of MPG and MPGe (MPG)	Class
137	MKZ Hybrid FWD	2013	$35,925.00	14.03	45.00	45.00	M
138	CT 200h	2013	$32,050.00	10.31	42.00	42.00	C
139	ES 300h	2013	$39,250.00	12.35	40.00	40.00	M
140	ILX Hybrid	2013	$28,900.00	9.26	38.00	38.00	C
141	ActiveHybrid 3	2013	$49,650.00	14.93	28.00	28.00	C
142	Silverado 15 Hybrid 2WD	2013	$41,135.00	12.35	21.00	21.00	PT
143	Sierra 15 Hybrid 2WD	2013	$41,555.00	10.00	21.00	21.00	PT
144	GS 450h	2013	$59,450.00	16.67	31.00	31.00	M
145	M35h	2013	$54,750.00	19.61	29.00	29.00	M
146	E400 Hybrid	2013	$55,800.00	14.93	26.00	26.00	M
147	ActiveHybrid 5 Series	2013	$61,400.00	12.99	26.00	26.00	M
148	ActiveHybrid 7L	2013	$84,300.00	18.18	25.00	25.00	L
149	Panamera S Hybrid	2013	$96,150.00	18.52	25.00	25.00	L
150	S400 Hybrid	2013	$92,350.00	13.89	21.00	21.00	L
151	Prius Plug-in Hybrid	2013	$32,000.00	9.17	50.00	95.00	M
152	C-Max Energi Plug-in Hybrid	2013	$32,950.00	11.76	43.00	100.00	M
153	Fusion Energi Plug-in Hybrid	2013	$38,700.00	11.76	43.00	100.00	M
154	Chevrolet Volt	2013	$39,145.00	11.11	37.00	98.00	C

Appendix 2. 2013 state-of-the-art frontiers of different HEV segments







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