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A SERIES ON TECHNOLOGY TRENDS IN PASSENGER VEHICLES IN THE UNITED STATES

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Hybrid Vehicles

TECHNOLOGY DEVELOPMENT AND COST REDUCTION

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SUMMARY

This briefing paper is a technical summary for policy makers of the status of hybrid vehicle development in the United States.

Both sales of hybrid vehicles and the number of hybrid models have risen steadily in the U.S. since their introduction, with that growth trend accelerating sharply starting in 2003. The forty-five hybrid models available in 2014 captured about 2.75% of the overall U.S. passenger vehicle market, down slightly from 3.19% in 2013. For purposes of comparison, hybrid market share is about 6% of vehicles sold in California and about 20% in Japan.

At their present state of development, full-function hybrids reduce fuel consumption by 25 to 30 percent, at a manufacturing cost increment of roughly $2,500 to $3,500. While mild-hybrid systems, such as belt-alternator or 48-volt (48v) systems, are not as efficient, their cost-benefit ratio can be better because they are less than half the cost of full-function hybrids.

Each new generation of the Toyota Prius hybrid has delivered about a 10% efficiency improvement while simultaneously reducing costs, increasing vehicle size, engine power, and electric motor power, and multiplying consumer features. The purple line in figure 1 illustrates reductions in Prius hybrid system cost based upon changes in the motor propulsion system and the Prius list price versus the price of a comparably equipped Corolla, without considering efficiency improvements. Costs fell almost 5% per year from 2000 to 2010, right in line with the rate of reduction from 2010 to 2013 (green line) as determined by the consultancy FEV. If Toyota continues to achieve the same rate of improvement in succeeding Prius generations, or if newer types of hybrid systems that are in much earlier stages of engineering development can replicate that rate of improvement, full-function hybrid system costs will be cut in half before 2025. And that projection does not consider modest hybrid system size and cost reductions associated with future vehicle lightweighting; for example, 10% reductions in weight would reduce hybrid system cost by about 5%. That the potential exists to maintain this rate of reduction is suggested by the accelerating development of improved designs and

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ABOUT THIS SERIES This is the first in a series of technical briefing papers on trends in energy efficiency of passenger vehicles in the United States. The series was conceived with the aim of summarizing technology developments relevant to passenger vehicle efficiency policy in the U.S.

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better, lower-cost hybrid subsystems. Another promising dimension is the development of mild-hybrid systems, which will likely provide one-half to two-thirds the fuel-efficiency benefits of full-function hybrids at less than half the cost.

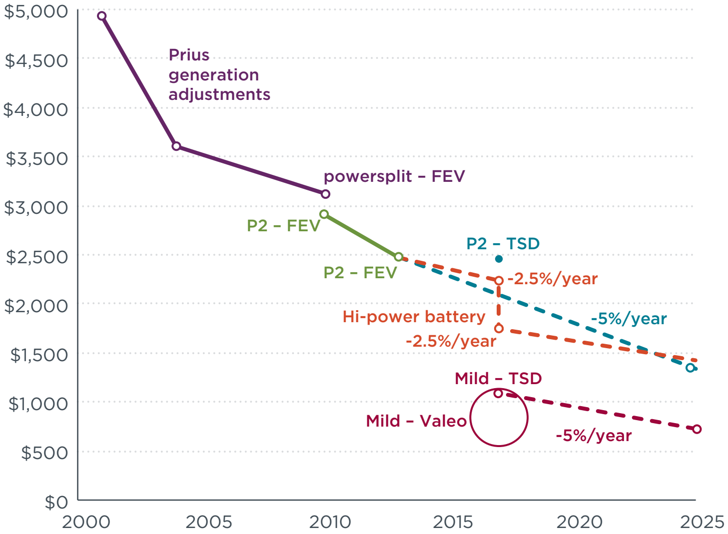

Figure 1. Historical and projected hybrid system direct manufacturing cost

It is beyond the scope of this briefing paper to assess all the factors—including consumer valuation of hybrid features and discounting of future fuel savings, improvements to other powertrains, and the stringency of future standards—influencing automakers' decision-making concerning design and manufacture of hybrid vehicles. Still, based upon assessments by ICCT of the cost per percent efficiency improvement of a wide range of technologies,[1] cutting costs in half for full-function hybrids would bring them well within the range of current technologies being used to comply with standards. And mild hybrid systems should be even more cost-effective.

BACKGROUND

Depending on the sophistication of the hybrid system, hybrids can capture and reuse energy normally lost to the brakes (known as regenerative braking); maintain performance while using a smaller, more efficient engine[2]; shut the engine off at idle and at very low load conditions, conserving fuel and cutting tailpipe emissions to zero; enable the engine to be run at lower speeds, where it is more efficient; replace the alternator as a means of generating electrical power with more efficient motor/generator systems; replace less-efficient mechanical water and oil pumps with electrical pumps that only operate when needed; and supply the large amounts of electrical power required by automated safety features, heated seats, dynamic chassis control, and other power-hungry components of modern cars. In addition, the electric motor provides instant torque for better response and low-speed acceleration.

Toyota introduced the first modern production hybrid, the Prius, in Japan in 1997, and Honda and Toyota introduced hybrids to the U.S. in 1999 and 2000. As figure 2 shows, Toyota dominates the U.S. hybrid market, with 66% of sales in 2014. Ford was second, with 14% of the market. Both manufacturers use the same hybrid powertrain design, an input power-split system. It is distinguished by the use of two large electric motors and a planetary gear system in place of the conventional transmission. Because Toyota, in particular, has come to dominate the U.S. market so thoroughly, when people talk about hybrids they sometimes mean this system specifically. But "hybrids" properly refers to a suite of technologies, which are described in detail in appendix 1.

Most other hybrid systems are in much earlier stages of development than the input power-split system. The primary examples currently in production are:

- Nissan, Hyundai/Kia, VW/Audi/Porsche, BMW, Subaru, and Mercedes have all recently introduced variants of a single-motor, twin-clutch hybrid system, commonly referred to as a P2 hybrid. Hyundai/Kia, with 8% of total 2014 hybrid sales, is by far the leading seller of P2 hybrids. P2 hybrid market share grew from 9% in 2013 to 12% in 2014.
- General Motors uses a mild hybrid system[3] that replaces the conventional alternator with a higher-power electric motor/generator and a high-tension belt drive that can work in both directions. This is commonly referred to as a belt-alternator-starter (BAS) system. GM had 2% of the U.S. hybrid market in 2014, down from 5% in 2013.

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[1] D. Meszler et al., Summary of the EU cost curve development methodology. ICCT working paper 2012-5 (2012), www.theicct.org/eu-cost-curve-development-methodology. Ricardo simulations of technology efficiency and FEV tear-down cost assessments were developed for the European Union, using the same basic methods as used by Environmental Protection Agency and the National Highway Traffic Safety Administration for costs and benefits in the U.S.

[2] One exception is for vehicles with high towing ratings, for which engines cannot be downsized without compromising towing capability.

[3] "Mild" hybrid is an undefined term loosely applied to hybrid systems that do not have all of the capability of full-function hybrids, such as the two-motor systems and the P2 hybrid, but have more functionality than stop-start systems or micro-hybrids. BAS systems and Honda's IMA system are examples of mild hybrid systems, as are 48-volt hybrid systems that are in development but not yet in production.

- Honda introduced its own two-motor hybrid system on the 2014 Accord. This differs from the power-split system in that the traction motor is powered electrically instead of through a planetary gear system. Honda uses a simpler single-motor system on its other hybrid vehicles, called Integrated Motor Assist (IMA), which it appears to be phasing out.
- The first production micro-hybrid system[4] is Mazda's i-ELOOP, which the company introduced in 2014 on the Mazda3 and Mazda6. It uses an ultracapacitor to capture a limited amount of regenerative braking energy and provide power for conventional vehicle electronics in place of the alternator. Hybridcars.com does not track sales for this system, so it is not included in figure 2.

Simple stop-start systems shut the engine off at idle and restart it when the brake pedal is released and are the easiest fuel-saving function to implement. They are usually not classified as hybrids and are not included in figure 2. In 2014, 6% of light-duty vehicles sold in the U.S. were equipped with stop-start systems.[5]

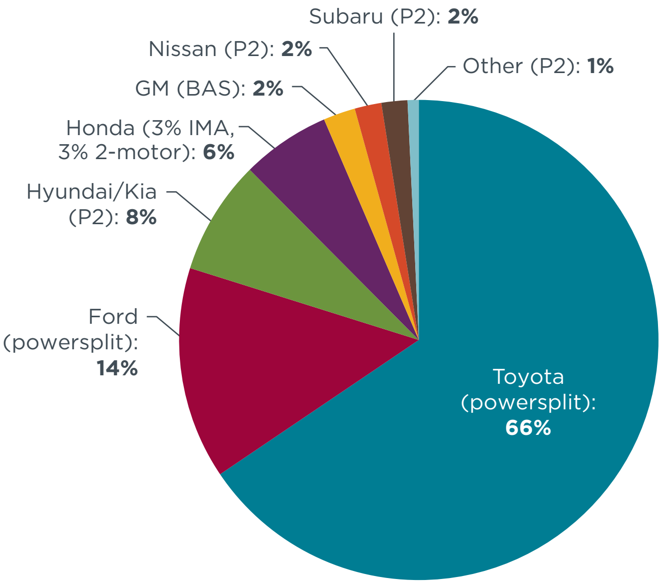

Figure 2. 2014 model year hybrid market share

Source: HybridCars.com (www.hybridcars.com/december-2014-dashboard/).

Sales of hybrid vehicles in the U.S. have risen steadily since their introduction and accelerated sharply in 2003, as illustrated in figure 3. (The decline in 2008–2011 corresponds to the economic recession, during which all vehicle sales declined.) In total, the 45 hybrid models available in the U.S. in 2014 captured about 2.75% of the overall passenger vehicle market, down slightly from 3.19% in 2013. A complete list of hybrid sales by model and year appears in appendix 2.

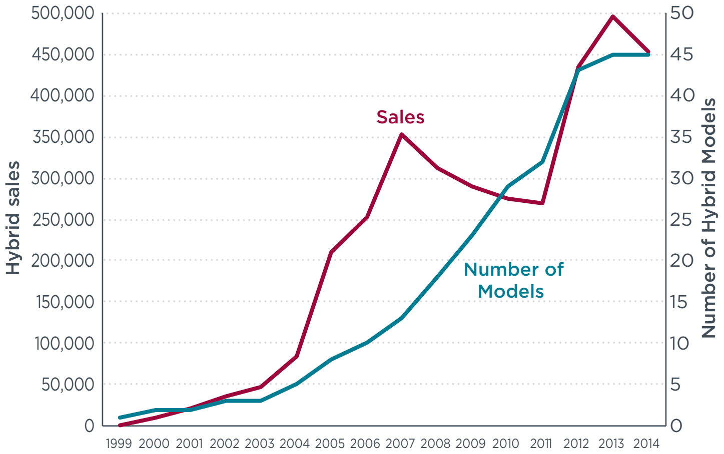

Figure 3. Historical U.S. hybrid sales and number of models

Source: U.S. Department of Energy, Alternative Fuels and Advanced Vehicles Data Center (www.afdc.energy.gov/data/#tab/fuels-infrastructure/data_set/1030).

For comparison, hybrids totaled about 6% of 2013 light-duty vehicle sales in California, or twice their overall U.S. sales share (fig. 4), suggesting some additional customer acceptance even of current hybrids is feasible. Sales in Europe vary significantly from country to country. Hybrid market share in Europe has been suppressed by the high penetration of fuel-efficient diesel engines, incentivized by lower taxes on diesel fuel. Given that diesels have more than half the total European market, hybrids have captured about the same proportion of the gasoline engine market as in the U.S. And in Japan hybrids have already gone mainstream, with over 20% market share — and over 30% of the market for conventional vehicles if Japan's unique "kei class" market segment is excluded[6].

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[4] A "micro-hybrid" system combines stop-start with replacement of alternator functions but does not have the other hybrid functions.

[5] U.S. Environmental Protection Agency, *Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 through 2014*, www.epa.gov/otaq/fetrends-complete.htm.

[6] Japan provides special tax and parking breaks for "kei-class" vehicles. These are small, lightweight vehicles with engine size capped at 660 cc (0.66L). For more information on hybrid sales in Japan, see Dan Rutherford, "Hybrids break through in the Japan auto market," www.theicct.org/blogs/staff/hybrids-break-through-japan-auto-market.

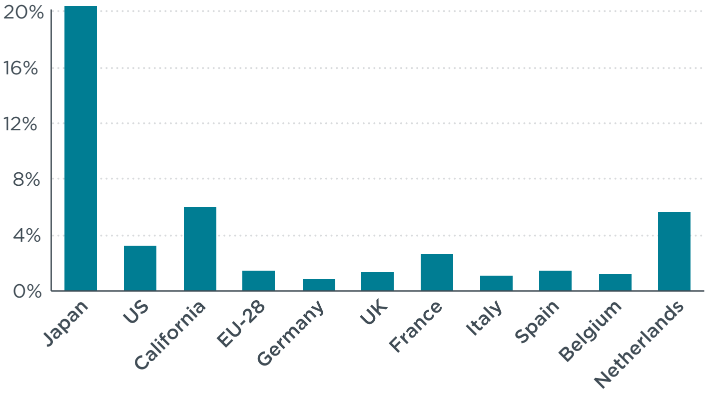

Figure 4. 2013 share of global hybrid market by country/region.

Sources: Peter Mock, ed., European Vehicle Market Statistics, 2014 (www.theicct.org/european-vehicle-market-statistics-2014). Japan hybrid sales: Japan Automotive Products Association: (www.japa.gr.jp/data/index.html). Japan PV sales: Japan Automobile Dealers Association http://www.jada.or.jp/contents/data/hanbai/index12.html Japan Minicar sales: Japan Light Motor Vehicle and Motorcycle Association (www.zenkeijikyo.or.jp/statistics/index.html). U.S. Department of Energy, Alternative Fuels and Advanced Vehicles Data Center (www.afdc.energy.gov/data/#tab/fuels-infrastructure/data_set/1030). California Auto Outlook, Feb. 2014 (www.theicct.org/sites/default/files/California%20hybrid%20share%202013%20CNCDA.pdf).

FUEL CONSUMPTION REDUCTION

Hybrid systems can reduce fuel consumption and CO_2 emissions by up to 35%, equivalent to more than a 50% increase in fuel economy.[7] The precise reduction varies with the sophistication of the hybrid system. The reduction can also be difficult to quantify if there is not a directly comparable non-hybrid vehicle. This second point is illustrated by the most comprehensive study to date, an October 2014 analysis done by the consultancy Vincentric, which compared 31 hybrids to the closest non-hybrid vehicle.[8]

The Vincentric Hybrid Analysis provides a direct comparison of the efficiency benefits and costs of hybrid systems. For any individual model the difference in efficiency between the hybrid model and the non-hybrid comparable may be affected by differences in powertrain, weight, tire rolling resistance, and aerodynamic drag. For example, all of the Toyota hybrid systems are similar, yet the calculated fuel consumption reduction ranged from 24% on the Lexus RX450h to 47% on the Lexus CT 200h.

While conducting a detailed analysis of the possible bias for each hybrid vehicle comparison selected by Vincentric is beyond the scope of this report, it is clear that in some cases the non-hybrid vehicle has lower performance and fewer consumer features than the hybrid vehicle (such as the Honda Accord) and in other cases the non-hybrid vehicle has higher performance and features (such as the Lincoln MKZ). If these offsets are random and are not systematically biased, averaging the data by manufacturer should reduce the bias in the results, although the amount of bias is still unknown. Figure 5 shows the average hybrid fuel consumption reduction by manufacturer calculated from the data in Vincentric's analysis. (Mercedes, BMW, and Subaru are grouped together because all had very similar reductions and low hybrid sales.)

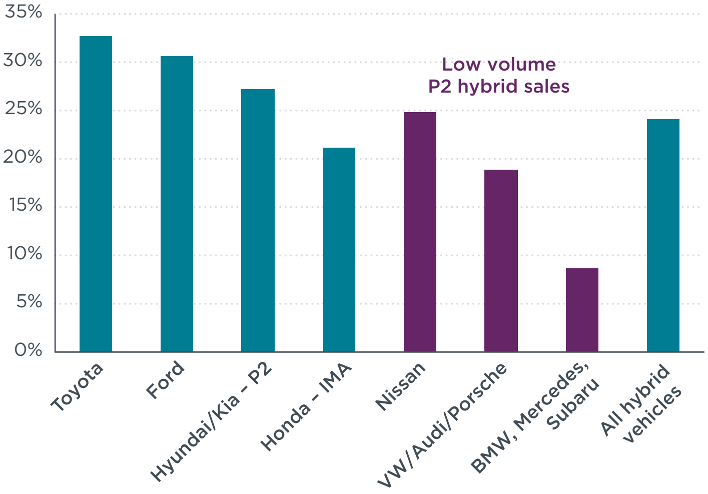

Figure 5. Hybrid fuel consumption reduction calculated from data in Vincentric Hybrid Analysis.

The U.S. EPA's 2014 Fuel Economy Trends Report includes a regression of fuel consumption on vehicle size (footprint) for current hybrid and non-hybrid models. Rather than attempt to match hybrids with comparable vehicles, as the Vincentric analysis did, EPA instead plotted how hybrid vehicles compare with similar size non-hybrid vehicles across all manufacturers. The EPA analysis showed (fig. 6) that average fuel consumption of hybrid vehicles in model year 2013 was 25% to 30% lower than conventional vehicles, which is similar to the pattern visible in the Vincentric data (fig. 5).

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[7] Fuel economy (e.g., miles per gallon or kilometers per liter) is the reciprocal of fuel consumption (e.g., gallons per 100 miles or liters per 100 kilometers). Like all inverse relationships, the impacts on fuel economy grow larger as fuel consumption approaches zero. Fuel consumption is the proper metric and is used throughout this report.

[8] Vincentric Hybrid Analysis, executive summary, www.vincentric.com/Home/IndustryReports/HybridAnalysisOctober2014.aspx. Detailed results are available in PDF and Excel files, linked from the summary page. Illustrating the observation about the challenge of precisely quantifying fuel consumption and emissions reductions in any given hybrid model: Vincentric was forced to exclude the Toyota Prius from its analysis, as there was no comparable non-hybrid vehicle.

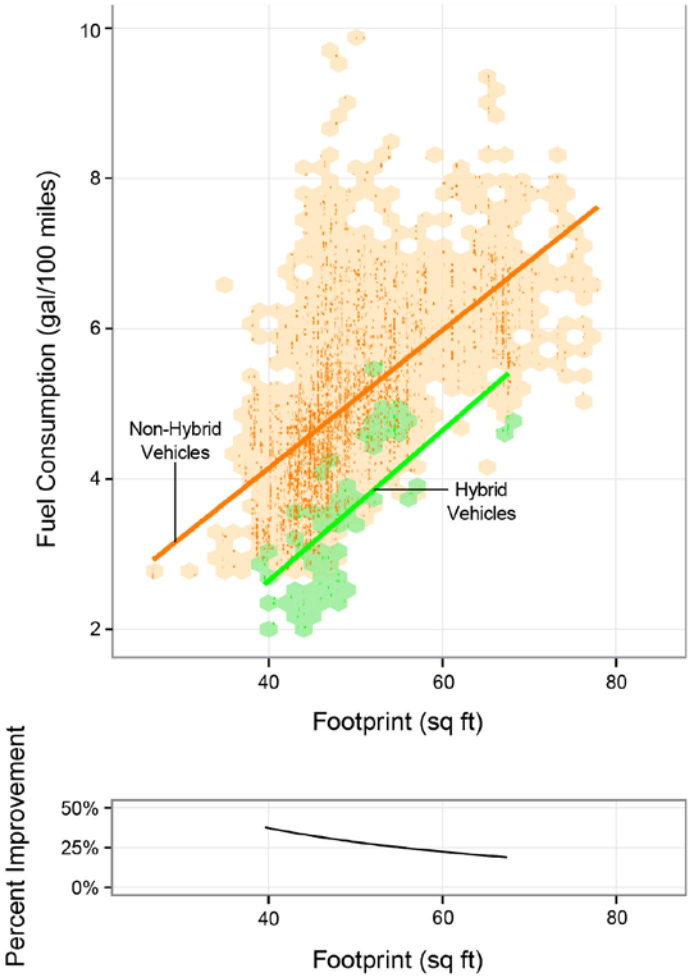

Figure 6. Percent Improvement in adjusted fuel consumption for hybrid vehicles, MY 2013.

Source: U.S. Environmental Protection Agency, Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2014, fig. 5.12.

CURRENT HYBRID COST ESTIMATES

It is even more difficult to determine precisely the cost of hybrid systems than the efficiency benefits they confer. Hybrids are often bundled with consumer features and options that have a far larger impact on vehicle price than on efficiency. Also, prices charged by manufacturers are set in a highly competitive market and may not reflect the real cost of the hybrid system.

As with the efficiency improvements, an initial approach to attacking this problem is simply to calculate averages by manufacturer from the Vincentric analysis. Figure 7 shows the average hybrid price premium (the difference in purchase price between a hybrid and a similar all-gasoline powered vehicle) determined by Vincentric.

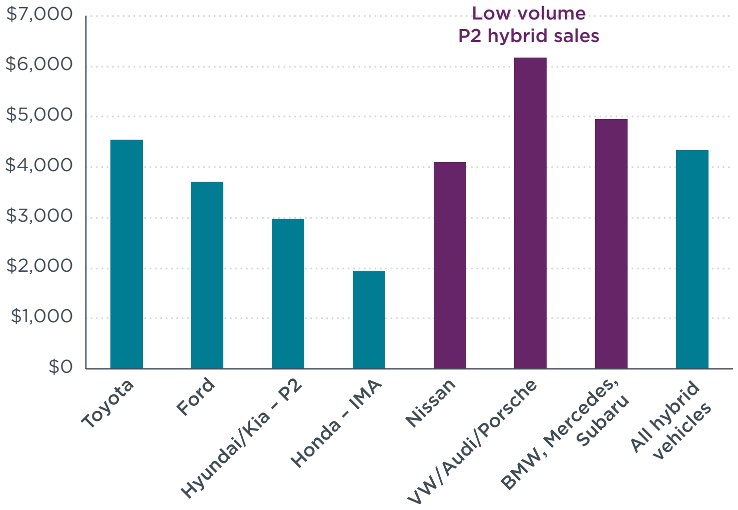

Figure 7. Hybrid price premiums from Vincentric data.

The Vincentric analysis shows that in 2014 full-function hybrids from Toyota and Ford carried an average hybrid price premium of roughly $3,500 to $4,500. The P2 hybrids from Hyundai/Kia were priced at an average increment of roughly $3,000. The Honda Integrated Motor Assist hybrids, using a less-sophisticated single-motor, single-clutch system, are priced at roughly a $2,000 increment. The Vincentric data did not include the GM BAS hybrid system. No reliable cost information is yet available for micro-hybrids, as the first micro-hybrid system, the Mazda i-ELOOP, only recently entered production.

"Tear-down" analyses are an accurate way to evaluate production costs to the manufacturer. A tear-down analysis published by the consultancy FEV in 2012 on 2010 production hybrids provides another view of hybrid system costs.[9] FEV disassembled a power-split hybrid system (the type of system used by Toyota and Ford), compared it with a comparable non-hybrid vehicle, and built up cost estimates based upon the differences in the parts and assembled components. FEV also estimated costs for the P2 hybrid system (the system used by Hyundai/Kia and others) based upon this tear-down work. The tear-down method has four advantages:

1. All hybrid components were accurately identified and costed.
2. Consistent methodologies and assumptions were applied.
3. Costs were assessed directly, rather than being inferred from price.

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[9] FEV, Light-Duty Vehicle Technology Cost Analysis – European Vehicle Market (Phase 1), (2012, updated 2013), available at www.theicct.org/cost-curves-resources.

4. All costs were assessed assuming high-volume production, which corrects for the differences in economies of scale between high-volume and low-volume manufacturers.

Table 1. FEV hybrid technology manufacturing costs for 2010 production EU midsize car, assuming 450,000 production volume. The FEV study gave costs in Euros, which were converted into dollars at the prevailing exchange rate of 1:1.4. The Euro has since fallen against the dollar, so the last line of the table adjusts the dollar value to the exchange rate at the time of writing.

	Input power-split	P2 hybrid
Power transmission/clutch system	$608	$300
Integrated electric motor/generator/ sensors/controls	$1,518	$675
Li-ion Battery Subsystem (1.0 kWh)	$1,375	$1,375
Electricity power distribution, inverters/converters	$379	$379
Brake, body, climate control systems	$461	$461
Credits – transmission, engine, service battery, alternator	-$1,217	-$276
TOTAL	**$3,122**	**$2,912**
Costs adjusted from 1.4:1 to 1.15:1 Dollar/Euro	**$2,565**	**$2,392**

Tear-down analyses also provide detailed information about the costs of the various subsystems. For example, table 1 shows the large credit (cost savings) from the elimination of the transmission on the input power-split system, which is more than offset by the lower cost of the smaller, single motor and related power transmission and controls on the P2 hybrid. The costs of the battery pack, power distribution, regenerative braking system, and air conditioning system are the same for both hybrid systems.

One limitation of the tear-down method is that it is very expensive. There have been no tear-down cost assessments to date for other hybrid systems, such as the GM BAS system and the Mazda micro-hybrid. The only estimate of BAS cost is from the rulemaking documents for the U.S. 2017–2025 LDV greenhouse gas emissions and CAFE standards.[10] The U.S. National Highway Traffic and Safety Administration (NHTSA) and the Environmental Protection Agency (EPA) used the FEV tear-down results noted above as the basis for P2 and power-split hybrid costs[11], and scaled the teardown data to estimate the manufacturing cost of an improved 110v BAS system: $1,087 for a standard size car in 2017.

It should also be noted that FEV's tear-down cost assessment specifically assessed the state of the art in 2010 and does not account for changes since, let alone project future improvements. As discussed below, FEV did a follow-up study of hybrid system costs, which are dropping rapidly and are already significantly lower than calculated by FEV for 2010.

In summary, the FEV tear-down analysis estimated direct manufacturing costs to be about $3,100 for a 2010 power-split system and $2,900 for a 2010 P2 system. Retail prices are always higher, as they also include manufacturer overhead and profits. Thus, the average Vincentric price data of about $4,000 for the power-split system is in general agreement with the FEV manufacturer costs, although the average price data for the P2 system of about $3,000 seems to be low compared with FEV's manufacturer cost estimate. Finally, an improved, future BAS system is projected by NHTSA and EPA to be less than half the cost of full-function hybrid systems in 2017.

PAYBACK PERIOD

Figure 8 plots the payback, in terms of fuel savings versus hybrid price premium, calculated for each hybrid vehicle from the data in the Vincentric analysis. The results vary widely from vehicle to vehicle, for the reasons noted above. Currently, roughly 29% of hybrid models (9 out of 31) pay back the initial hybrid price premium with fuel savings within 5 years. Roughly 61% of hybrid models (19 out of 31) pay back within the full useful life. On average, the fuel savings over the full useful life are about $1,300 more than the initial price premium.[12]

Given the roughly 3% market share for hybrid vehicles, it is clear that the fuel savings are not large enough to motivate most customers to pay for the incremental cost.[13] Hybrids also face the rising challenge of improved conventional vehicles, with increasing numbers of

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[10] U.S. Environmental Protection Agency and National Highway Traffic Safety Administration, Joint Technical Support Document: Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards. EPA-420-R-12-901, August 2012.

[11] The 2017-25 Joint Technical Support document cost estimates were $2,463 for a P2 hybrid and $3,139 for a power-split hybrid in 2017, suggesting that the agencies see more potential for future cost reduction for P2 hybrid systems.

[12] The Vincentric report did not state what fuel price they used for their analysis.

[13] On consumer preferences and payback periods, see D. Greene, D. Evans, and J. Hiestand, "Survey evidence on the willingness of U.S. consumers to pay for automotive fuel economy," *Energy Policy* 61 (2013): 1539–1550; D. Greene, J. German, and M. Delucchi, "Fuel Economy: The Case for Market Failure," in Reducing Climate Impacts in the Transportation Sector, D. Sperling and J. Cannon, eds., Springer Press, 2008.

Figure 8. Hybrid fuel savings over five years (blue) and full useful life (red) minus hybrid price premium calculated from Vincentric data, based upon 15,000 miles per year. Note that the Vincentric data had both a 2014 and a 2014.5 Camry hybrid.

conventional vehicles achieving at least 40 mpg on the highway at lower cost. This is good for the climate and energy security, but it reduces the incremental fuel savings from hybrid systems and, hence, lengthens the payback period.

On the other hand, the tenfold increase in hybrid sales from 2003 to 2013 suggests that many of the early concerns about hybrids, such as reliability, battery life, resale value, and safety, have been successfully addressed. In addition, the electric motor provides instant torque, improving drivability and performance especially at low speeds, which is a desirable feature. Thus, the key to increased hybrid market share is simply getting the cost down and improving the payback.

IMPACTS OF LEARNING AND IMPLICATIONS FOR FUTURE HYBRID DEVELOPMENT

The Toyota Prius hybrids have delivered about a 10% efficiency improvement with each new generation, while simultaneously reducing costs, increasing vehicle size, engine power, and electric motor power, and multiplying features (table 2 and figure 9). This was accomplished primarily by learning. Toyota built upon the best features of each design to improve the next design, with both better hardware and better integration and control of the various hybrid components. These improvements were delivered while reducing the price of the Prius relative to that of the Corolla LE.

Table 2. Toyota Prius Development

	Engine disp.	Engine (hp/kW)	Motor (kW)	Size - in. (LxWxH)	Curb weight	0-60 Accel	FE (comb.)	Prius MSRP	$ Prius / Corolla LE
1998–2000 (Japan only)	1.5L	58/43	30	168x67x59	2734	14.5	36		
2001–2003	1.5L	70/52	33	170x67x58	2765	12.5	41	$19,995	1.49
2004–2010	1.5L	76/57	50	175x68x59	2921	10.5	46	$20,295	1.37
2011+	1.8L	98/73	60	176x69x59	3042	10.1	50	$23,520	1.34

Sources: David Hermance, Advanced Powertrain Vehicles vs. "The Perfect Storm", presentation, Toyota Technical Center, August 2004. U.S. Department of Energy, www.fueleconomy.gov. *75 Years of Toyota: Vehicle Lineage* (http://www.toyota-global.com/company/history_of_toyota/75years/vehicle_lineage/car/id60012360/index.html).

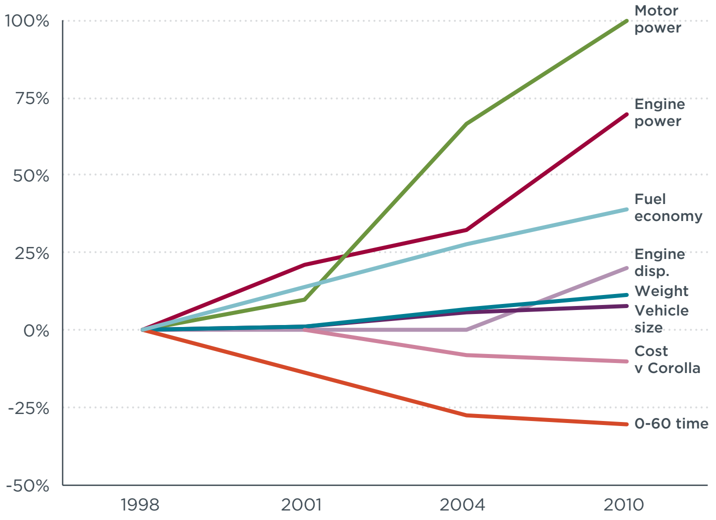

Figure 9. Prius improvements for each generation, indexed to first generation.

Data on the cost reduction associated with each generation of the Prius is not directly available. Estimates of the cost reduction for each generation are calculated here based upon changes in the manufacturer's suggested retail price (MSRP) of the Prius relative to the price of the Corolla with the same trim package, and increases in the electric propulsion motor size. Table 3 converts the Prius MSRP and the change in the ratio of the Prius LE to the Corolla LE price to calculate the increase in the hybrid system price for previous generations. The EPA's indirect cost multipliers (ICM) from its 2017–2025 LDV CO_2 rule were used to convert the price reductions to reductions in manufacturer cost. EPA's highest ICM value was used for the 2001 Prius (1.77) and its second-highest for the 2004 Prius (1.56), in recognition that this was new technology.

Table 3. Calculation of cost increase for earlier Prius generations.

	Prius MSRP	$ Prius / Corolla LE	Price Increase	ICM	Cost Increase
Prius 2011	$23,520	1.34	Base		Base
Prius 2004	$20,295	1.37	$454	1.56	$291
Prius 2001	$19,995	1.49	$2,238	1.77	$1,265

The estimated cost reductions in table 3 were achieved despite increasing the electric propulsion motor size in each generation, at additional cost. FEV's 2013 cost report for the ICCT included hybrid cost assessments for different vehicle classes. FEV calculated power-split system costs for five different European vehicles, with different motor sizes. A linear regression of these hybrid system costs on motor size yielded a variable cost of 14.15 Euros per kW[14]. Table 4 uses this value to calculate the additional cost reduction associated with increasing motor size while decreasing overall system cost.

Table 4. Regression of FEV 2010 motor size and total power-split cost

		Euros	$ (1.4:1)
Prius 2011	60	Base	Base
Prius 2004	50	€ 142	$198
Prius 2001	33	€ 382	$535

The total cost reduction from 2001 to 2011 is estimated to be about $1,800. Added to the baseline cost estimate from table 3 of $3,122, the estimated cost for the 2001 Prius hybrid system was roughly $4,922, which yields an average annual cost reduction of almost 5% per year. Note that this result is likely to be conservative, as it does not include the value of increasing the system efficiency with each generation.

Additional evidence of rapid learning in hybrid vehicle manufacturing comes from an updated assessment of P2 hybrid costs. FEV's 2012 cost report was based on 2010 model year hybrid designs. FEV followed that with a study assessing improvements from 2010 to 2013.[15] FEV evaluated known cost reductions that have been implemented in the three years since their original P2 hybrid tear-down cost study. The study only assessed improvements in the motor/generator and clutch assembly subsystem. Cost-reduction opportunities in other subsystems, such as the electric power supply (high-voltage battery pack and supporting wiring and controls), brake-by-wire, and climate control (electric air-conditioning compressor) were not considered in the analysis.

FEV found five places where improvements have been made over the last three years, summarized in table 5.

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[14] FEV's cost reductions for engine downsizing due to the addition of the hybrid system were backed out before the regression of cost on motor size was performed. This removes a source of variation and reduces the cost per motor kW by about 20%.

[15] FEV, P2 Hybrid Electrification System Cost Reduction Potential Constructed on Original Cost Assessment. Analysis Report BAV 11-683-001_4B, December 5, 2014

Table 5. Known cost reductions, 2010–2013, selected P2 hybrid subsystems.

Improvement	Benefit	Savings[1]
Better integration of electric motor and clutches	Smaller case	$27
Improvements in clutch design	Elimination of clutch hydraulic system	$14
Development of oil accumulator	Replaced auxiliary oil pump	$27
More efficient electric motor	Downsized traction motor	$36
Expand engine cooling system capacity and electric pump	Replaced separate hybrid cooling system	$42

1. FEV results converted from Euros to US dollars at an exchange rate of 1:1.4.

Collectively, these simple, incremental improvements reduced the cost of the motor/generator/ clutch subsystem in a midsize European car by $147, or about 15% of the 2010 cost of the P2 motor/generator and clutch assembly subsystem ($975, table 1), in just three years.[16] If a similar rate of cost reduction applies to the entire P2 hybrid system, as seems likely, overall manufacturing costs for the P2 hybrid have already fallen from FEV's 2010 estimate of about $2,900 to about $2,500 in 2013. By themselves, the improvements to just those two subsystems reduced the cost of the total hybrid system by 5%.

Toyota's record of generational improvements by learning and the detailed FEV cost assessments both support an estimate of potential annual cost reductions in hybrid systems, or improvements in other areas that are equally valued by customers, of about 5% per year. At that rate, the manufacturing cost of a full-function hybrid can be expected to be cut in half before 2025.

The two critical questions are:

- Will this rate of cost reduction continue, or even accelerate, especially for hybrid systems that are just now coming to the market?
- Will lower-cost micro-hybrid and mild-hybrid systems provide a better value proposition than full-function hybrids and be a faster path to mainstream customer acceptance?

Hybrid systems other than the input power-split used by Toyota and Ford are at very early stages of development; there is more potential for costs to come down, hybrid efficiency to go up, and payback to improve. This includes the full-function P2 hybrid system, which was recently introduced and is still in its first generation. Not only should P2 hybrid systems be more cost-effective than the input power-split system in the future, but micro-hybrid and mild-hybrid systems may be more cost-effective yet. As noted above, NHTSA and EPA estimate the high-volume manufacturing cost for an 110v BAS system in 2017 at $1,087, compared with $2,463 for a P2 and $3,139 for the power-split systems.

This expectation is in line with EPA's market-penetration estimates for hybrid vehicles in the 2017–2025 light-duty CAFE/CO_2 standards. EPA's analyses found that hybrids would still have a relatively low share of the market in 2021, (4% full hybrid, 7% mild hybrid, and 8% stop/start) but designs would diversify and would drop in cost enough to significantly increase market share by 2025 (5% full hybrid, 26% mild hybrid, 15% stop/start). Note that the agency found that mild (110v BAS) hybrids would see far more growth in market share than full-function hybrid vehicles after 2021. In addition, EPA only considered an 110v BAS system; 48v systems may be even more cost effective in the future, as discussed below and in appendix 3.

HYBRID SYSTEM IMPROVEMENTS IN DEVELOPMENT

Hybrids, especially the P2 and lower-cost hybrid systems, remain at a relatively early stage of development. Seamlessly integrating engine, electric motor, battery, and regenerative braking functions is complex and difficult, requiring sophisticated simulations in the development process and powerful onboard computers to avoid drivability problems. One factor in the early success of the input power-split hybrid is that the planetary gear system helps to smooth out the transitions between the different power sources and reduces the development burden. Honda's early IMA system similarly reduced the development burden by bolting the motor directly to the engine. Unfortunately, as discussed earlier, the input power-split is a relatively expensive solution, and the IMA system is not competitive on benefits and costs with newer systems.

Less expensive hybrid systems will benefit greatly from the ongoing revolution in computer simulations, computer-aided design, and on-board computer controls. Indeed, the revolution in computers is essential to development of lower-cost systems with good drivability. This section outlines some of the more promising improvements that have recently emerged: batteries with higher power density, design improvements for P2 hybrids, and lower-cost 48v hybrid systems. A more extensive discussion is presented in appendix 3.

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[16] John German, "Driving down the cost of hybrid systems, €10 at a time," www.theicct.org/blogs/staff/driving-down-cost-hybrid-systems.

Higher power density batteries.[17] Battery subsystems are a significant part of the cost of hybrid systems; on average, the cost of a 1.0 kWh Li-ion battery pack is about $1,375 (table 6). Current hybrid batteries are oversized, in order to provide the power needed for acceleration assist and regenerative energy capture without excessive deterioration. Hybrids will greatly benefit from battery packs that have been designed from the ground up for high power, including cell chemistries optimized for high power. Such high-power batteries have been in development for several years and should reach the market as early as 2015. Instead of 1.0 kWh, future high-power Li-ion batteries for typical full-function hybrid applications should be only about 0.3 to 0.5 kWh. These high-power batteries will cost more per kWh than current Li-ion designs, but the cost savings should still be at least $500, as illustrated in table 6.[18]

Table 6. Current and future hybrid Li-ion battery power density and cost.

	FEV 2010 teardown	2015 Production Sonata (Li-ion)	USABC targets	
			Min.	Max.
Power (kW)	25	47	25	35
Energy (kWh)	0.99	1.4	0.3	0.5
Power/Energy	25	33	83	70
Cost	**$1,375**	**—**	**$500**	**$800**

P2 hybrid learning opportunities. While the input power-split hybrid design used by Toyota and Ford is in its fourth generation of learning and development, first-generation P2 hybrids were just recently introduced and are at a much earlier point on the learning curve. For example, all current P2 hybrids, including the P2 hybrids used by FEV in their tear-down cost assessments, install the motor between the engine and the transmission. This minimizes the amount of redesign required, which is important for first-generation systems, but it requires a separate case, cooling system, oiling system, and clutch for the motor. It also compromises packaging of the powertrain, as extra space must be found to insert the motor. Installing the motor and other hybrid components inside the transmission will result in large cost reductions and packaging improvements. In fact, Hyundai recently announced that its upcoming second-generation design will fully integrate the electric motor and almost all of the hybrid powertrain components within the transmission.[19] Additional opportunities to reduce cost and improve efficiency in the future include removing the torque converter, use of a less expensive conventional manual transmission (enabled by using the electric motor to fill in the engine torque gaps), and less expensive designs to coordinate the friction brakes and regenerative braking.

Lower-cost hybrid systems. More sophisticated and better-optimized mild hybrid systems offer the greatest opportunity to improve hybrid cost-effectiveness. It is difficult to assess costs and benefits of these lower-cost systems because they are in relatively early stages of development and the designs are multiplying. This is a positive trend, because manufacturers and suppliers are searching for the right level of hybridization with the best payback for the consumer. The first production designs are the GM 110v BAS system and the Mazda i-ELOOP[20] (details of the systems can be found in the appendices). Unfortunately, GM and Mazda have bundled their hybrid systems in ways that disguise the price of the systems, and there is no tear-down cost data yet.

There is a great deal of development taking place on other types of low-cost systems. Manufacturers and suppliers are still sorting out the relative advantages and costs of the many different possible configurations, such as voltage level (12v–48v), energy storage (lead-acid, lead-acid plus ultracapacitors, NiMH, Li-ion) and drive type (BAS or P2 configurations). An additional advantage of 48v systems is that they can power an electric motor integrated within the turbocharger, commonly referred to as e-boost, to reduce turbo lag and improve turbocharged engine efficiency and response. The major turbocharger manufacturers, including BorgWarner, Hitachi, Valeo, and Honeywell, all have prototypes under customer evaluation. Examples include:

- A prototype "HyBoost" engine from Ricardo.[21]
- A Valeo 48v "e-booster," with an electric motor integrated within the turbocharger and powered by regenerative energy stored in ultracapacitors.[22] Valeo also estimated that optimized 48v hybrid systems

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[17] Energy density refers to how much electricity a battery can store for a given size/weight. It determines how long the battery will last with a constant load. Power density is how fast the electricity can be charged to and discharged from the battery, or energy delivered per second. High power density batteries can release energy and be recharged quickly.

[18] U.S. Advanced Battery Consortium targets from U.S. DOE, Advanced Battery Development, FY 2013 Annual Progress Report, www.energy.gov/sites/prod/files/2014/05/f15/APR13_Energy_Storage_d_III_Adv_Battery_Dev_0.pdf, Table III - 3: Summary of USABC performance targets for power assist hybrid electric vehicles.

[19] Hyundai Motor Launches Motor Integrated Six-Speed Transmission For Latest Hybrid Models, October 28, 2014. http://worldwide.hyundai.com/WW/Corporate/News/News/DF_WW_GLOBALNEWS_141028.html?selx2=

[20] Mazda Global, i-ELOOP, www.mazda.com/technology/env/i-eloop/

[21] Ricardo, HyBoost—Intelligent Electrification, www.ricardo.com/en-GB/What-we-do/Technical-Consulting/Research--Technology/HyBoost---Intelligent-Electrification/. Don Sherman, "Blowing Your Way to Savings: How Electric Superchargers Boost MPG," *Car and Driver*, October 2014, blog.caranddriver.com/blowing-your-way-to-savings-how-electric-superchargers-boost-mpg/.

[22] Automotive News, "Electric turbocharger eliminates lag, Valeo says", August 4, 2014, p. 34.

should have more than 15% efficiency improvements at less than $1,000 direct manufacturing cost.[23]

- VW-Audi is putting an e-booster system in production in 2015 on a V6 diesel.[24]
- Schaeffler Group NA is demonstrating a concept 48v hybrid system on a 2013 Ford Fusion with about a 45% increase in mpg.[25]
- BorgWarner stated that 48v systems are more affordable, as they use conventional components and have nice synergies with e-booster systems.[26] A 48v e-boost system alone can reduce CO_2 emissions by 5–8 g CO_2, with higher peak power and slightly improved low end torque.[27]
- Eaton's analyses found 48v hybrid systems can reduce CO_2 by 10%–20% (depending on test cycle and the inclusion of e-boost superchargers), are 50%–75% cheaper than a full hybrid, and improve safety by staying below the 60v lethal threshold. They projected up to 3 million 48v units globally by 2020.[28]
- Punch Powertrain found that mild hybrids could be moved to 48v at lower cost without much degradation in benefits.[29]

Note that this is far from an exhaustive list of hybrid system and subsystem developments. As illustrated by the FEV updated cost study, there have been many improvements in motor subsystems over the last three years (table 5). High-power electronics is a relatively new field and costs are coming down rapidly. This briefing has only touched upon the many developments taking place.

In addition, there will be new developments that we are not aware of yet, just as 48v hybrid systems are a very recent development. Hybrid component and system development is accelerating, providing strong support for the continued improvements and cost reductions discussed above.

IMPACT OF WEIGHT REDUCTION ON COST

Reducing vehicle weight means that the powertrain can be downsized and still maintain constant performance. This applies directly to the electric motor propulsion system. A 10% reduction in weight will allow a 10% reduction in the electric propulsion motor and all supporting hybrid system components.

FEV's baseline costs of $3,122 for the input power-split hybrid system in table 1 were for a European midsize car with a 78 kW motor. Thus, a 10% weight reduction would reduce the motor size 7.8 kW. Using the cost derived above for table 4 of 14.15 Euros per kW, the cost of the hybrid system would be reduced by $155, or about 5% of the total cost of the hybrid system.

DISCUSSION AND IMPLICATIONS

Hybrids are far from a mature technology, and innovations and improvements are coming rapidly. Improved batteries designed with high power density for hybrid applications will start arriving soon. Hybrid systems other than the input power-split design pioneered by Toyota 17 years ago are still in early stages of development, and present huge opportunities to reduce cost through better designs, learning, and economies of scale.

Figure 10 summarizes the data and analyses in this briefing. The purple line illustrates the estimated reductions for each new generation of the Prius (note that the 2001 model was introduced in 2000 and the 2011 model in 2010). The green line reflects FEV's 15% cost reduction for the power transmission/clutch/motor subsystems from 2010 to 2013, assuming that the same reductions are achieved in all parts of the hybrid system. The lighter dashed blue line projects future P2 hybrid system costs assuming that the 5% annual cost reduction continues into the future. The darker blue lines illustrate an alternative path to similar cost reductions, with 2.5% annual cost reductions plus implementation of higher-power Li-ion batteries that should reduce future battery costs by at least $500. Also shown on the graph are the 2017 cost estimates from the Technical Support Document (TSD) for the P2 (light blue) and BAS (red) systems, plus the mild hybrid cost estimate range from the Valeo presentation in 2014 at The Battery Show (red circle). The red dashed line projects the mild hybrid cost estimates using the same 5% annual cost reduction.

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[23] Mitti Vint, "Optimizing the Value Proposition of Low Voltage Electrified Powertrain Systems," presentation at The Battery Show, September 16, 2014, Novi, Michigan.

[24] SAE Automotive Engineering, "E-boosting for VW-Audi's 2015 V6 diesel", November 4, 2014, p. 24.

[25] "Schaeffler electrifies its fuel-efficiency demonstrator, aims for 35 mpg combined rating", Automotive Engineering Magazine, October 8, 2014. http://articles.sae.org/13592.

[26] Paul Nahra, BorgWarner, IC Engine Evolution and Effective Electrification, presentation at the 2015 SAE Government/Industry meeting, January 2015.

[27] Mart Verschoor, BorgWarner, "Technologies for enhanced fuel efficiency with engine boosting," presentation at Automotive Megatrends USA, March 17, 2015.

[28] Michael Omotoso, Eaton, "Lighter, Better, Greener: Powering Tomorrow's Vehicles with Advanced Valvetrain and Engine Air Management Systems", March 17, 2015, Automotive Megatrends USA 2015.

[29] Alex Serrarens, Punch Powertrain, "Overview of 48V technologies, deployment and potentials", presentation at Automotive Megatrends USA, March 17, 2015.

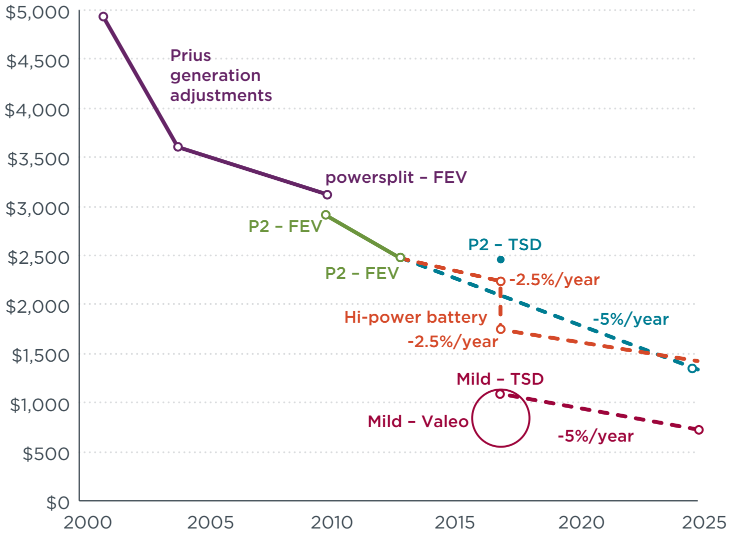

Figure 10. Historical and projected hybrid system direct manufacturing cost

The analyses suggest that full function P2 hybrids are likely to be half the cost of 2010 systems before 2025, without considering the additional hybrid cost reduction enabled by vehicle weight reduction (about a 5% reduction in cost for every 10% decrease in vehicle weight).

Lower-cost 48v systems offer the potential to be significantly more cost effective, achieving most of the benefits of a full-function hybrid at much lower cost. They might also be used by some manufacturers as stepping stones to higher-voltage systems, with the lower-cost systems used to accelerate market acceptance while the costs of all hybrid systems come down. Low-cost hybrid systems have already been made standard on a few mainstream models, such as eAssist on the Buick Lacrosse and stop/start systems on 6% of 2014 vehicles.

It is difficult to determine the tipping point at which the various types of hybrid systems become cheap enough to be accepted by mainstream customers and manufacturers start making them standard equipment. This involves a variety of considerations that are beyond the scope of this briefing paper, such as consumer valuation of additional features offered by hybrids, consumer discounting of future fuel savings, consumer concern with reliability of hybrid systems, competition from improvements in other powertrain technologies, and the stringency of future efficiency/CO_2 standards. Still, some insight may be derived from comparing the modeled cost-benefit of a full-function P2 hybrid system to an advanced turbocharged engine with stop-start. ICCT developed technology cost-effectiveness curves for Europe in 2012, using data sources similar to those that EPA and NHTSA used in the US.[30] For a system including an advanced turbocharged engine with cooled ERG and stop/start, the estimated incremental cost was 1,751 Euros with an estimated efficiency improvement of 36%. For the system with P2 hybrid, Atkinson cycle engine, and dual-clutch automated manual, the incremental cost was 2,910 Euros, with estimated efficiency improvement of 46%. The cost per percent improvement (Euros/%) was 49 for the advanced turbo and 63 for the P2 hybrid, illustrating why the advanced turbo with cooled EGR was selected by EPA and NHTSA as one of the core technologies for their 2025 cost assessments. If the cost of full function hybrids can be cut in half, the cost-effectiveness will be well within the range of current technologies being used to comply with standards. Even considering only the incremental hybrid benefits versus cost, which is 1,159 Euros for an incremental 10% benefit, or 116 Euros/%, cutting the hybrid cost in half should still make the technology competitive. And mild hybrid systems should be even more cost-effective. Thus, even without considering the other consumer benefits of hybrid systems (such as instant low-speed torque and lots of electrical power), it appears likely that cutting hybrid costs in half and development of mild hybrid systems should enable acceptance by mainstream customers.

Because most hybrid systems are at a relatively early stage of development, costs are still relatively high and manufacturers are looking to recover some of the costs by charging customers a premium for hybrid vehicles. Thus, currently the hybrid system needs to offer a major improvement in fuel economy to entice customers to pay the price premium. This favors full-function hybrids and works against mild hybrid systems. However, in the future, lower cost, mild hybrid systems will be able to compete directly against conventional technology improvements on a cost-benefit basis. Thus, hybrid market penetration will likely increase only modestly in the near term, but as costs drop hybrids will become just another technology that manufacturers sell on its positive efficiency and drivability impacts, not on the technology itself, similar to what is currently occurring with turbocharged gasoline engines.

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[30] D. Meszler et al., Summary of the EU cost curve development methodology.

APPENDIX 1: DESCRIPTION OF DIFFERENT HYBRID SYSTEMS

Input power-split. As its name implies, this system uses a planetary gear to distribute power between the engine, generator, traction motor, and drivetrain. It is the most sophisticated of all the currently available hybrid systems and excels in optimizing engine efficiency during city driving. It is also easily adaptable to plug-in operation. The downside is the cost associated with the requirement for two large electric motors and their associated power electronics. This system is used by Toyota and Ford for all of their hybrids. Toyota dominated the U.S. hybrid market with 66% of sales in 2014, and Ford was second with 14% of the market.

Two-motor systems. These are similar to the input power-split system in that part or all of the energy for the traction motor is provided from the engine through the generator, but they do not use a planetary gear system to transmit power. Two-motor systems offered in the past by GM, Chrysler, BMW, and Mercedes had similar, if not better, efficiency than the input power-split, but at higher cost. All have been discontinued. Honda recently introduced a two-motor system on the 2015 Accord, which captured 3% of the hybrid market in 2014.

Parallel hybrid with two clutches (P2). Uses a single electric motor and two clutches, one between the engine and the electric motor and the second between the motor and the drivetrain. This system is highly scalable, from modest electric motor power to motors capable of plug-in hybrid operation. Different variations of this system have been recently introduced by Nissan, Hyundai/Kia, VW/Audi/Porsche, Subaru, BMW, and Mercedes. Hyundai/Kia is by far the leading seller of P2 hybrids, with 8% of total 2014 hybrid sales.

- Honda has traditionally used a less efficient version of this system that does not have a clutch between the engine and the electric motor, which they call Integrated Motor Assist (IMA). This system was not discussed in this paper, as it offers significantly lower efficiency gains with only a modest reduction in cost relative to more advanced systems and only has 3% of the 2014 hybrid market. In fact, Honda is starting to replace their IMA system with a P2 hybrid system, beginning with the Japanese version of the 2015 Fit.

Belt Alternator-Starter (BAS). BAS systems replace the conventional alternator with a higher power electric motor and a high-tension belt drive that can work in both directions, to provide power assist to the engine or to capture regenerative braking energy. The system is lower cost than hybrid systems with dedicated motors and minimizes packaging concerns by simply replacing the alternator. However, belt drives are not as efficient as the gear drives used in more advanced systems and the maximum power is limited by the belt. A 12v–24v BAS system is usually referred to as a micro-hybrid, and higher power BAS systems are usually referred to as mild hybrids. General Motors pioneered a higher power and voltage (115v) BAS system with the 2012 Buick Lacrosse. GM's BAS system had 2% of hybrid market share in 2014, down from 5% in 2013.

Mild hybrids. "Mild" hybrid is an undefined term loosely applied to hybrid systems that do not have all of the capability of full-function hybrids, such as the two-motor systems and the P2 hybrid, but have more functionality than stop-start systems or micro-hybrids. BAS systems and Honda's IMA system are examples of mild hybrid systems. New concepts using 48-volt hybrid systems are in development and often include a small, electric motor integrated into the turbocharger to eliminate turbo lag and allow additional engine downsizing.

Micro-hybrids. In addition to stop-start, provides limited amounts of regenerative braking energy and some additional functions, such as providing energy to replace most of the alternator functions, and shutting the engine off and disconnecting it from the drivetrain during higher speed decelerations (commonly called "sailing"). The system also provides faster engine restarts with less vibration than conventional starters. Many different types of micro-hybrids are being developed, from 12v systems using advanced lead-acid batteries to 12v or 24v systems assisted by small ultracapacitors or using NiMH or Li-ion batteries. The first production micro-hybrid system is Mazda's i-ELOOP, which was introduced in 2014 on the Mazda3 and Mazda6. It uses an ultracapacitor to capture a limited amount of regenerative braking energy and provide power for conventional vehicle electronics in place of the alternator.

Stop-start. The most basic system, usually not classified as a real hybrid, which uses an improved battery and a higher-power starter motor to shut the engine off at idle and restart it when the brake pedal is released. Such systems are popular in Europe and are just starting to appear as standard equipment in the US. According to the 2014 EPA Fuel Economy Trends Report, 6% of 2014 models will be equipped with stop-start systems.

APPENDIX 2: HYBRID VEHICLES AND SALES

Hybrid Electric Vehicle (HEV) Sales by Model

System	Vehicle	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Input powersplit	**Toyota Prius**		5,562	15,556	20,119	24,600	53,991	107,897	106,971	181,221	158,574	139,682	140,928	136,463	164,618	145,172	122,776
Input powersplit	**Lexus RX400h**							20,674	20,161	17,291	15,200	14,464	15,119	10,723	12,223	11,307	9,351
Input powersplit	**Toyota Highlander**							17,989	31,485	22,052	19,441	11,086	7,456	4,549	5,921	5,070	3,621
Input powersplit	**Lexus GS 450h**								1,784	1,645	678	469	305	282	615	522	183
Input powersplit	**Toyota Camry**								31,341	54,477	46,272	22,887	14,587	9,241	45,656	44,448	39,515
Input powersplit	**Lexus LS600hL**									937	907	258	129	84	54	115	65
Input powersplit	**Lexus HS 250h**											6,699	10,663	2,864	650	4	
Input powersplit	**Lexus CT 200h**													14,381	17,831	15,071	17,673
Input powersplit	**Lexus ES Hybrid**														7,027	16,562	14,837
Input powersplit	**Toyota Avalon Hybrid**														747	16,468	17,048
Input powersplit	**Toyota Prius C**														30,838	41,979	40,570
Input powersplit	**Toyota Prius V**														28,450	34,989	30,762
Input powersplit	**Ford Escape**						2,993	18,797	20,149	21,386	17,173	14,787	11,182	10,089	1,440		
Input powersplit	**Mercury Mariner**							998	3,174	3,722	2,329	1,693	890				
Input powersplit	**Ford Fusion**											15,554	20,816	11,286	14,100	37,270	35,405
Input powersplit	**Mercury Milan**											1,468	1,416				
Input powersplit	**Ford Lincoln MKZ**												1,192	5,739	6,067	7,469	10,033
Input powersplit	**Ford C-Max Hybrid**														10,935	28,056	19,162
P2	**Hyundai Sonata**													19,673	20,754	21,559	21,052
P2	**Kia Optima Hybrid**														10,245	13,919	13,776
BAS	**Saturn Vue**									4,403	2,920	2,656	50				
BAS	**Saturn Aura**									772	285	527	54				
2-motor	**Chevy Tahoe**										3,745	3,300	1,426	519	533	376	65
2-motor	**GMC Yukon**										1,610	1,933	1,221	598	560	288	31
BAS	**Chevy Malibu**										2,093	4,162	405	24	16,664	13,779	1,018
2-motor	**Cadillac Escalade**										801	1,958	1,210	819	708	372	41
2-motor	**Chevrolet Sierra/Silverado**											1,598	2,393	1,165	471	169	30
BAS	**Buick Lacrosse**													1,801	12,010	7,133	7,353
BAS	**Buick Regal**													123	2,564	2,893	662
BAS	**Chevy Impala Hybrid**															51	565
IMA	**Honda Insight**	17	3,788	4,726	2,216	1200	583	666	722	0	0	20,572	20,962	15,549	5,846	4,802	3,965
IMA	**Honda Civic**				13,700	21,800	25,571	25,864	31,251	32,575	31,297	15,119	7,336	4,703	7,156	7,719	5,070
2-motor	**Honda Accord**						1,061	16,826	5,598	3,405	196					996	13,977
IMA	**Honda CR-Z**												5,249	11,330	4,192	4,550	3,562
IMA	**Acura ILX Hybrid**														972	1,461	379
2-motor	**Acura RLX Hybrid**																133
P2	**Porsche Cayenne**												206	1,571	1,180	615	650
P2	**Porsche Panamera S**													52	570	113	
P2	**VW Touareg Hybrid**													390	250	118	30
P2	**Audi Q5 Hybrid**														270	854	283
P2	**Volkswagen Jetta Hybrid**														162	5,655	1,939
Input powersplit	**Nissan Altima**									8,388	8,819	9,357	6,710	3,236	103		
P2	**Nissan NX**																354
P2	**Nissan Infiniti M35h**													378	691	475	180
P2	**Nissan Infiniti Q50**															307	3,456
P2	**Nissan Infiniti QX60**															676	1,678
P2	**Nissan Pathfinder Hybrid**															334	2,480
P2	**BMW ActiveHybrid 7**												102	338	230	31	45
P2	**BMW X6**												205	43	3		
P2	**BMW ActiveHybrid 3 (335ih)**														402	905	151
P2	**BMW ActiveHybrid 5 (535ih)**														403	520	112
P2	**Mercedes ML450h**												627	1	22	11	20
P2	**Mercedes S400**												801	309	121	64	10
P2	**Mercedes E400H**															282	158
Input powersplit	**Mazda Tribute**												570	484	90		
2-motor	**Chrysler Aspen**										46	33					
2-motor	**Dodge Durango**											9					
P2	**Subaru XV Crosstrek**																7,926
	Total Sales	**17**	**9,350**	**20,282**	**36,035**	**47,600**	**84,199**	**209,711**	**252,636**	**352,274**	**312,386**	**290,271**	**274,210**	**268,807**	**434,344**	**495,529**	**452,152**
	Number of models	**1**	**2**	**2**	**3**	**3**	**5**	**8**	**10**	**13**	**18**	**23**	**29**	**32**	**43**	**45**	**45**

1999 to 2013 sales: U.S. Department of Energy, Alternative Fuels and Advanced Vehicles Data Center. http://www.afdc.energy.gov/data/#tab/fuels-infrastructure/data_set/1030
2014 sales: http://www.hybridcars.com/december-2014-dashboard/

APPENDIX 3: HYBRID SYSTEM IMPROVEMENTS IN DEVELOPMENT

We are in the relatively early stages of a revolution in design and technology development that is impacting all aspects of the vehicle and of vehicle manufacturing. This breakthrough is due to computers. Computer simulations, computer-aided design, and on-board computer controls are revolutionizing every aspect of vehicle design.

Hybrids will benefit greatly from this revolution, as hybrids are still at a relatively early stage of development, especially the P2 and lower-cost hybrid systems. This section outlines some of the more promising improvements already in development: batteries with higher power density, design improvements for P2 hybrids, and lower-cost 48v hybrid systems.

Note that this is far from an exhaustive list, and there will be new developments that we are not aware of yet. For example, 48v hybrid systems are not in production and just a year ago were not widely considered to be a viable alternative to higher voltage hybrids. However, recent improvements and synergies with ancillary power demand and turbocharging have lead to intense development and widespread predictions by suppliers that 48v systems will be significantly more cost-effective than full-function hybrids in the long run.

HIGH POWER LI-ION BATTERIES FOR HYBRIDS

A major cost-reduction opportunity is to make Li-ion battery designs with higher power density. Batteries are a significant part of the cost of hybrid systems, on average about $1,375 for a 1.0 kWh Li-ion battery pack, based on the 2012 FEV cost report.

It is important to understand that current hybrid batteries are oversized, in order to provide the power needed for acceleration assist and regenerative energy capture without excessive deterioration. As long as they had to use oversize batteries, manufacturers made use of the excess energy to promote the ability to drive on the electric motor alone, with the engine off, as a customer feature. While it is highly desirable to turn off the engine during very low-load conditions, as the engine is very inefficient in that operating range, these conditions rarely last more than 5 or 10 seconds. Extending operation on the electric motor alone beyond such very low-load conditions offers little or no additional benefit. Unlike a plug-in hybrid, where you want to drain the battery because the battery is recharged by plugging in, a hybrid vehicle battery pack must be recharged from the engine. Thus, efficiency benefits are achieved only if the engine is operating in a significantly more efficient mode to recharge the battery than the mode in which it was turned off, as the difference in engine efficiency must be large enough to cover losses in discharging and recharging the battery pack. This does occur when the engine is turned off at very low loads, but turning off the engine during normal operation does not meet this criterion. Thus, storing a much smaller amount of energy in the battery pack will not significantly affect efficiency, as long as this does not affect the power output of the battery (i.e., the rate at which energy can be pulled out of or pushed into the battery pack).

Li-ion battery manufacturers sometimes claim to offer high-power batteries, but these are generally just high-energy batteries that have been modified to increase power output. What is really needed for hybrid vehicles are battery packs that have been designed for high power, with optimized cell chemistries. Such high-power batteries have been in development for several years and should reach the market as early as 2015 or 2016.

Higher power density will allow future P2 hybrid batteries to be much smaller—and therefore much cheaper—while still delivering all the power needed for acceleration and regenerative braking and the small amounts of energy needed to turn the engine off at very low load conditions. Instead of a 1.0 kWh battery, future high-power Li-ion batteries for typical P2 and input power-split hybrid applications should be only about 0.3 to 0.5 kWh.[31] Certainly these high power batteries will cost more per kWh than current Li-ion designs, but as illustrated in Table A-1 the cost savings should still be easily at least $500.

Table A-1. Current and future hybrid Li-ion battery power density and cost

	FEV 2010 teardown	2015 Production Sonata (Li-ion)	USABC targets	
			Min.	Max.
Power (kW)	25	47	25	35
Energy (kWh)	0.99	1.4	0.3	0.5
Power/Energy	25	33	83	70
Cost	**$1,375**	**—**	**$500**	**$800**

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[31] U.S. DOE Advanced Battery Development, FY 2013 Annual Progress Report, Table III—3: Summary of USABC performance targets for power assist hybrid electric vehicles.

P2 HYBRID LEARNING OPPORTUNITIES

While the input power-split hybrid design used by Toyota and Ford is in its fourth generation of learning and development, P2 hybrids were only recently introduced. These first generation designs are at a much earlier point on the learning curve and have not been optimized. For example, all current P2 hybrids, including the P2 hybrids used by FEV in their tear-down cost assessments, install the motor between the engine and the transmission. This minimizes the amount of redesign required, which is important for first generation systems, but it requires a separate case, cooling system, oiling system, and clutch for the motor. It also compromises packaging of the powertrain, as extra space must be found to insert the motor.

The impact of learning is illustrated by Hyundai's recent announcement about its second generation P2 hybrid.[32] This system will fully integrate the electric motor and almost all of the hybrid powertrain components within the transmission. The innovations include:

- A new traction motor
- Replacement of the mechanical oil pump with a new electric oil pump, which reduces hydraulic losses and automatically optimizes the system according to all driving conditions.
- The torque converter has been removed completely.
- A lighter torsion damper.
- A new engine clutch, which features fewer clutch discs, reducing drag and contributing to a more efficient transfer and use of power.
- With few components, the new transmission is lighter than the previous version yet still delivers 280 Nm (207 ft-lb) of torque.

These improvements minimize energy losses, increase fuel economy, and reduce costs. As P2 hybrid systems progress to third- and fourth-generation systems, there will be many additional opportunities for major cost reductions due to learning, such as:

- Use a less expensive conventional manual transmission instead of an automatic or dual-clutch transmission, enabled by using the electric motor to fill in the engine torque gaps.
- Eliminate the synchronizer rings and, instead, use the electric motor to match the revolutions of the engine and transmission gear on each shift.
- Create multiple power flow paths in a manual transmission to increase the number of effective gear ratios without increasing the number of gears (similar to current 6+ speed automatic transmission designs).
- Use less expensive techniques to coordinate friction brakes and regenerative braking.
- Drive the air conditioning compressor off of the electric traction motor with a gear or belt drive, instead of using a separate electrically-driven compressor.

DEVELOPMENT OF LOWER-COST HYBRID SYSTEMS

It is difficult to assess hybrid costs and benefits in part because hybrid designs are multiplying. This is a positive trend, as it indicates that manufacturers and suppliers are searching for the right level of hybridization with the best payback for the consumer, although lack of cost data on these new systems makes it more difficult to understand what the true cost differential is for hybrids against ICEs.

One example of a lower cost system already on the market is General Motor's BAS design. The system is lower cost than hybrid systems with dedicated motors and minimizes packaging concerns by simply replacing the alternator. However, belt drives are not as efficient as the gear drives used in more advanced systems, and the maximum power is limited by the belt. GM's first system was introduced in 2007 in the Saturn Vue Green Line. It used a 36v NiMH battery pack and a 5 hp electric motor. A much improved system, called eAssist, was introduced in the 2012 Buick LaCrosse. It increased the voltage from 36v to 115v, used a 0.5 kWh Lithium-ion battery instead of a NiMH battery, and increased the motor power from 5 hp to 20 hp for regeneration and 15 hp for assist.

The first micro-hybrid system on the market is the Mazda i-ELOOP, available on the Mazda3 and Mazda6. This uses a variable output alternator and a double-layer capacitor to capture small amounts of regenerative braking energy and turn off the alternator during acceleration. The system improves the Mazda6 fuel economy label values by 2 mpg, or about 7%. The cost of the system is disguised by Mazda's decision to only offer it with a $2,080 GT Technology Package that includes a lane departure warning system, high beam control, radar cruise control, forward obstruction warning, a sport mode, and active grille shutters.[33]

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[32] Hyundai Motor Launches Motor Integrated Six-Speed Transmission For Latest Hybrid Models, October 28, 2014. http://www.hyundaiglobalnews.com/prCenter/news/newsView.do?dID=3653

[33] Mazda Announces Pricing, Fuel Economy of I-ELOOP-Equipped 2014 Mazda6, www.mazdausamedia.com/2013-07-05-MAZDA-ANNOUNCES-PRICING-FUEL-ECONOMY-OF-i-ELOOP-EQUIPPED-2014-MAZDA6.

Other types of low-cost hybrid systems have not been introduced yet, but there is a great deal of development taking place. Manufacturers are still sorting out the relative advantages and costs of the many different possible configurations, such as voltage level (12v–48v), energy storage (lead-acid, lead-acid plus ultracapacitors, NiMH, Li-ion), and drive type (BAS or P2 configurations). Another advantage is that a 48v system can be used to power an electric motor integrated within the turbocharger to reduce turbo lag and improve turbocharged engine efficiency and response. While there currently is no clear winner from among these low-cost hybrid options, all are in development. The companies developing mild-hybrid systems are generally claiming efficiency benefits of 15% to 20% and/or that they will be significantly more cost-effective than full-function hybrids. For example:

- Ricardo has built a prototype "HyBoost" engine, which adds a low cost 6kW BAS motor and an improved 12v battery plus ultracapacitors for recovering regenerative braking energy and stop/start.[34] It also augments the turbocharger with a Valeo 48v electric supercharger, powered by the energy from the ultracapacitors.[35]
- Valeo claims the electric turbocharger boost alone can reduce fuel consumption by 7% and that 20% reductions are possible when the device is combined with regenerative braking.[36]
- Valeo said they are working on all types of micro- and mild-hybrid systems, as all of them are more cost effective than full hybrids, diesels, or plug-in hybrids.[37] Slide 6 of their presentation showed that an optimized 48v hybrid system should be able to achieve more than 15% efficiency improvement at a direct manufacturing cost of less than $1,000. Slide 5 shows up to a 20% benefit if a 48v electric supercharger is included.
- Schaeffler Group North America is demonstrating a 48v hybrid system concept aimed at achieving a 35-mpg combined rating on a 2013 Ford Escape, which is a 45% improvement over the baseline vehicle with a 2.0L EcoBoost engine and 6-speed automatic rated at 24 mpg.[38]
- VW-Audi will put an "e-booster" system in production on their V6 diesel sometime in 2015. This integrates a 48v electric motor within the turbocharger system. This is a potential alternative to two-stage turbocharger systems and delivers boost instantaneously. The efficiency benefits are enhanced if the e-booster is integrated with a 48v hybrid system and regenerative braking. The major turbocharger manufacturers, including BorgWarner, Hitachi, Valeo, and Honeywell, have prototypes under customer evaluation.[39]
- Paul Naira of BorgWarner believes we will start to see a wave of 48v hybrid systems in the future, as they are more affordable, use conventional components, and have nice synergies with e-booster systems.[40]
- Matt Verschoor of BorgWarner presented the benefits of the e-booster system:[41]
  - Vehicle dynamics, 2x faster transient response
  - Faster response enables aggressive further engine downsizing and downspeeding
  - Enables improved (larger) T/C matching, driving fuel consumption reduction (lower backpressure P3)
  - Improved emissions control through true "boost on demand" (pro-active turbo lag, positive delta P possible at all times)
  - Easy packaging compared to other supercharging options).
  - 5-8 g CO_2 reduction with higher peak power and slightly improved low end torque
  - 12 V eBOOSTER: ~50% of 48V eBOOSTER CO_2 benefit
- Michael Omotoso of Eaton presented the advantages of 48v systems:[42]
  - 48v systems reduce CO_2 by 10%–20% (depending on test cycle), are 50%–75% cheaper than a full hybrid, and improve safety by staying below the 60v lethal threshold
  - Powertrain applications include e-boosting, electromagnetic valve actuation, and stop/start
  - 'Boost-on-demand' clutched superchargers reduce parasitic losses: up to 4% better fuel economy than existing superchargers

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[34] Ricardo, HyBoost – Intelligent Electrification, www.ricardo.com/en-GB/What-we-do/Technical-Consulting/Research--Technology/HyBoost---Intelligent-Electrification/.

[35] Don Sherman, "Blowing Your Way to Savings: How Electric Superchargers Boost MPG," *Car and Driver*, October 2014, blog. caranddriver.com/blowing-your-way-to-savings-how-electric-superchargers-boost-mpg/.

[36] Automotive News, "Electric turbocharger eliminates lag, Valeo says", August 4, 2014, p. 34.

[37] Mitti Vint, "Optimizing the Value Proposition of Low Voltage Electrified Powertrain Systems," presentation at The Battery Show, September 16, 2014, Novi, Michigan.

[38] "Schaeffler electrifies its fuel-efficiency demonstrator, aims for 35 mpg combined rating," Automotive Engineering Magazine, October 8, 2014. http://articles.sae.org/13592.

[39] SAE Automotive Engineering, "E-boosting for VW-Audi's 2015 V6 diesel", November 4, 2014, page 24.

[40] Paul Nahra, IC Engine Evolution and Effective Electrification, presentation at the 2015 SAE Government/Industry meeting, January 2015.

[41] Mart Verschoor, "Technologies for enhanced fuel efficiency with engine boosting," presentation at Automotive Megatrends USA, March 17, 2015.

[42] Michael Omotoso, Eaton, "Lighter, Better, Greener: Powering Tomorrow's Vehicles with Advanced Valvetrain and Engine Air Management Systems", March 17, 2015, Automotive Megatrends USA 2015.

  - Projected up to 3 million 48v units globally by 2020
- Karina Morley of Ricardo predicted 48v systems are coming to improve ICE system efficiency and reduce weight.[43]
- Alex Serrarens of Punch Powertrain stated 48v systems can provide further functionality, e.g., lower currents/losses; electric pumps, blowers, brakes and air conditioning; and e-boost for turbos.[44]
  - Mild hybrids can be moved to 48v at lower cost without much degradation in benefits
  - Choosing 48v hybridization instead of high-voltage hybrids is a cost-effective and scalable way to achieve CAFE/CO_2 targets

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[43] Karina Morley, "Trends: System Efficiencies of Advanced Propulsion Systems," presentation at Automotive Megatrends USA, March 17, 2015.

[44] Alex Serrarens, "Overview of 48V technologies, deployment and potentials," presentation at Automotive Megatrends USA, March 17, 2015.