The relative fuel consumption reduction strengths of multiple passenger car powertrains are investigated. These include [A] conventional compression ignition (CI) direct injection (DI) turbocharged (TC) diesel (D) [CI-DI-TC-D]; [B] Atkinson cycle charge sustaining (CS) “split-hybrid” electric vehicles (HEV) fueled by gasoline/petrol (G) [HEVG]; plug-in (P) hybrid gasoline/petrol [PHEVG]; and indirect fuel injected (IDI) spark-ignited (SI) internal combustion engines (ICE) fueled by gasoline/petrol [SI-IDI-NA-G]. When we use simulation to evaluate the behavior of PHEVG powertrains, the size is a four-to-five passenger car platform that would be regarded as “compact” in the U.S. and standard in Europe. A careful distinction between probable driving patterns for PHEVGs when in charge-depletion (CD) mode vs. charge sustaining (CS) operation is made. Effects of variation in the amount of kWh storage and the CD strategy, between PHEVs with varying km of electric-equivalent range are also investigated. The effect of electric drive (battery and motor) power (kW) on ability of a vehicle to operate all-electrically, relative to its ability to reduce oil use, is examined. Four degrees of hybridization are briefly examined, including stop-start (SS), integrated starter-generator (ISG), mild parallel (MP), and full parallel (FP). Each of the parallel PHEVs examined is an FP. Powertrain model simulations and limited dynamometer test results for such PHEVGs are compared to the other vehicle types for certification and “on-road” driving cycles from Europe and the U.S. It is illustrated that the conventional wisdom that HEVG has significant superiority over CG primarily in urban stop and go driving should not automatically be extended to PHEVGs. The driving cycle information is related to systematically varying consumer patterns of dwelling choice and vehicle use in cities, suburbs, and rural areas, as well as across nations. Effects of fuel taxation choices by nation — for gasoline, diesel and electric fuel — are investigated. The effects that residential location and type, driving cycle, and fuel cost have on the relative marketability of the studied powertrains, when initially entering the market, are summarized. The sequence of events leading to early emergence of original equipment automaker production and marketing of PHEVGs is discussed.

Keywords: Plug-In Hybrid Electric Vehicle, Parallel HEVs, Series HEVs, Energy Consumption, Vehicle Performance, Li-Ion Battery, Nickel Metal Hydride (NiMH), Zero Emissions Vehicle (ZEV)

1. INTRODUCTION: EMISSIONS REGULATION AND MARKET SHARE

Over the last 25 years, the key powertrain competition between conventional drivetrains for passenger cars has largely been between indirect fuel injected (IDI) spark-ignited (SI) internal combustion engines (ICE) fueled by gasoline [SI-IDI-NA-G] and conventional compression ignition (CI) direct injection (DI) turbocharged (TC) diesel (D) [CI-DI-TC-D]. In the United States, the SI-IDI-NA-G technology remains dominant, but only in light duty passenger vehicles. In commercial trucks, the CI-DI-TC-D technology is dominant. In continental Europe, however, the CI-DI-TC-D has now reached a position of dominance in all vehicle classes in new vehicles. At present sales rates (Figure 1), dominance of CI-DI-TC-D technology in the on-road fleet in Europe is simply a matter of time. On both continents, where emissions regulations have been favorable for the CI-DI-TC-D technology, it has, for years, taken market share from the SI-IDI-NA-G technology.
1.1 U.S. Light Duty Diesel and Hybrid Markets vs. Emissions Standards and Tests

In the United States, heavy duty vehicle emissions standards have been based on engine dynamometer tests, while light duty vehicle emissions standards for vehicles designed for 3856 kg Gross Vehicle Weight (GVW = vehicle mass plus maximum load) and less have been based on vehicle dynamometer tests. The CI-DI-TC-D technology has dramatically increased share in the U.S since 1982, for those vehicles above the 3856 kg GVW threshold and involved primarily in final urban delivery of goods [2]. At the lower end of this GVW range, where engine dynamometer emissions tests are used, a considerable amount of shifting upward in GVW, crossing this “vehicle dynamometer test” threshold, has occurred in the U.S. for pickup trucks. The group of vehicles between 3856 kg and 4536 kg GVW in the U.S. is called the “2b” class. As of 2004, a “Bosch study noted the enormous success of diesel engines in the larger (GVW class IIb) pick-up truck market, where they currently hold a 75% market share” [3]. Among pickup trucks 72% of those equipped with a CI-DI-TC-D engine used four wheel drive (4WD) in 2003, a feature that increases fuel consumption [4]. The vast majority of these CI-DI-TC-D engines are eight cylinder diesel engines [4].

The question of definition of a light duty personal use vehicle in the U.S. involves a decision concerning which GVW threshold is appropriate to use. If one uses 4536 kg GVW as the “cut-off” point for the definition of predominantly personal light duty vehicles, one includes these CI-DI-TC-D equipped pickup trucks and obtains a much different perspective on the success of the CI-DI-TC-D technology for personal use in the U.S. In 2003, about 2.6% of such vehicles used CI-DI-TC-D technology, up from 1.8% in 1999 [2]. However, below the 3856 kg GVW threshold, where emissions regulations are more difficult, the share from 1988 through 2007 model years varied from 0.0 to 0.4% [5]. In 2006 the share was at a high of 0.4%, but it dropped to 0.1% in 2007, the year that the new “Tier II” emissions regulations came into force.

For the latest full year, 2006, the share of HEVs sold in the 3856 kg GVW and below group was 2.2%, less than the diesel share in the larger 4536 kg GVW and under subset [6 and other sources]. This was up from 0% in 1999, thus a much faster growth rate than for the light duty CI-DI-TC-D in the 4536 kg GVW and below category. What has also happened as oil prices rose is a shift of share of hybrids away from light trucks (sport utility vehicles [SUVs]) with a recent acceleration of share of passenger cars (see Figure 2).

In summary, for recent decades in the U.S., the CI-DI-TC-D technology has increasingly dominated when the customer demanded high load carrying capability, and emissions regulations allowed such engines to be produced without aftertreatment. However, for those vehicles subject to the strict light duty emissions standards at 3856 kg GVW, as determined by vehicle dynamometers, this technology has not succeeded yet, while the HEV is rapidly increasing market share. Within the light duty vehicle market in the U.S., both hybrids and diesels have been expanding in share, but at opposite ends of the GVW range for light duty vehicles.
1.2 European Light Duty Diesel Market Shares vs. Emissions Standards

Historically in Europe, the CI-DI-TC-D technology has also been allowed to emit at a greater rate than the SI-IDI-NA-G technology. However, in Europe, the customer does not have to purchase a large heavy vehicle in order to enjoy the fuel consumption reduction benefits of the CI-DI-TC-D technology. The two different engine types have been subject to different emissions standards within the light duty vehicle category [7]. Diesels have consistently been allowed to emit nitrogen oxides (NOx) and particulate matter (PM) at a considerably higher rate than for petrol (gasoline) vehicles. However, proposed Euro VI standards for 2014 would nearly eliminate the difference between petrol and diesel passenger car emissions limits. The proposed near-term Euro V standard for 2009 would reduce allowable PM emissions by 80%, to a value identical to that of petrol cars. Allowable NOx emissions for diesels would remain three times as high as for direct injection petrol vehicles [7, 8].

Even if the proposed Euro V emissions standards are implemented in Europe, the allowable emissions of NOx will be over four times the allowable 2007 “Tier II” fleet average for vehicle dynamometer tested light vehicles in the U.S. At a recent General Motors presentation in August, C. Freese indicated that the much tighter U.S. NOx standards might prevent diesels that succeed in Europe from being introduced in the U.S. [9].

1.3 Emissions of a PHEV Conversion in “Blended Mode” Operation

While the new U.S. and proposed European standards will be difficult for diesels to meet, recent re-tests of a previously tested [10] but revised Hymotion Prius plug-in hybrid (PHEV) conversion at Argonne National Laboratory indicate that a “blended mode” (intermittent engine operation as the battery depletes its charge) control strategy has been developed that will allow this PHEV to meet California’s super ultra low emissions vehicle (SULEV) standard while charge depleting (Figure 3). While this test is not adequate to prove that the vehicle can be certified (such capability has to be demonstrated for 192,000 km), it does imply that PHEVs operating in blended mode can be developed to have emissions well below the U.S. Tier II fleet average requirements of 0.07 g/mi (0.044 g/km) of NOx.

Based on light duty vehicle emissions test results for 2008 the diesel and the hybrid are at opposite ends of the spectrum. The U.S. EPA Green Car Guide allows one to sort tested vehicles on the basis of multiple attributes, including an emissions score that varies from a value of 9.5 (best) to 1.0 (worst) [12]. The average score of 2008 hybrids is 8.3. For diesels it is 1.5. Thus, if diesels are to capture a market share of U.S. light duty vehicles comparable to Europe, they must reduce emissions considerably from present levels. If the emissions of PHEVs are close to those of the HEVs from which they are derived, perhaps a bit worse than the HEVs, the PHEVs could nevertheless easily meet existing U.S. standards. Since U.S. standards are more stringent than those in Europe, this implies that PHEVs could also meet European tailpipe emissions standards for traditional pollutants.

2. DIESEL, CONVENTIONAL PETROL, HYBRID, AND PLUG-IN HYBRID POWERTRAIN EVOLUTION

In a recent paper examining the life cycle emissions and energy use of the powertrain technologies under discussion, Gaines et al briefly examined the evolution of research on advanced powertrain concepts for the 1990s through the present [13]. They noted the importance of evolving and shifting priorities among GHGs, energy security, and what are called “criteria pollutants” in the U.S. (CO, HC, NOx, PM). Where the U.S. has stricter regulation for what are criteria pollutant emissions, Europeans have placed a higher priority on the reduction of carbon dioxide.

One of the pertinent questions of the period involved the desirability of shifting from the SI-IDI-NA-G technology to the CI-DI-TC-D, perhaps instead of [14], or temporarily in lieu of [15], the FCV to reduce carbon emissions. With regard to the FCV, in 2005, Brinkman et al [16] showed that if a FCV used hydrogen produced by electrolysis from electricity derived from today’s mix of fossil fuels, GHG emissions could be higher.
than for a CI-DI-TC-D using low sulfur diesel from petroleum (in Figure 4, compare LS Diesel DI CI CD below to Electro. GH2 FCV: U.S. kWh, and Electro. GH2 FCV: NA NGCC). However, this comparison also implicitly showed that if one chose the diesel instead of the FCV and depended on natural gas as the fuel feedstock once oil had been depleted, this would be a considerably worse long-term pathway, with regard to GHGs. Because the latter choice would eventually force use of Fischer-Tropsch diesel fuel production from natural gas (NNA NG FT Diesel DI CI CD) instead of use of hydrogen via reformation of natural gas for a FCV (NA NG Central GH2 FCV).

Brinkman et al did not consider the possible use of electric drive in either electric vehicles or PHEVs. The initial investigation of this option by Gaines et al indicates that combustion of natural gas in a natural gas combined cycle (NGCC) power plant to produce electricity to drive a PHEV in charge depleting mode would generate considerably less GHG per km than reforming the natural gas for use in a FCV. We italicize and underline “in charge depleting mode” because it is important to remember that a PHEV operates in two “modes,” charge depleting (CD) and charge sustaining (CS). CS operation is essentially like a normal hybrid. In this mode, the PHEV does not use electricity from the grid. Note also that it is possible to have a PHEV FCV.

Another extension beyond the Brinkman et al study by Gaines et al is additional examination of the effectiveness of use of renewable fuels, when comparing FCVs to PHEVs in CD mode. The last bar to the right in Figure 4 (GHG impacts) from Brinkman et al illustrates that there are no GHG emissions from fuel production or vehicle use if a non-cellulosic renewable — solar, wind, or geothermal energy — is used to produce H2. The same result applies for electricity for a PHEV in CD mode. (The bars with the green “net” note refer to use of cellulosic ethanol. Cellulosic ethanol differs from solar, wind, and geothermal in the sense that the fuel has to be collected and transported, using fossil fuels in the process. Thus, estimates for cellulosic ethanol, also a renewable, project non-zero GHGs). For the cases where solar, wind, and geothermal electricity are used, noting that the GHG results for both the PHEV and FCV can be zero provides no information about how much renewable energy is used in the respective cases.

As a part of standard LCA methodology, total solar and wind energy use was estimated by Gaines et al comparing the use per kilometer for a FCV using hydrogen produced via electrolysis to that used by a PHEV in CD mode. The implications of the calculation can actually be generalized to all electrical generation. Once any feedstock has been converted to electricity, use of that electricity will result in more than double the kilometers of service, if used in a PHEV in CD mode rather than in a FCV. Thus, for any low GHG source of electricity — wind, solar, nuclear, hydro, geothermal,
biomass – it will be considerably better to pursue development of PHEVs to use that electricity than FCVs.

2.1 Implications of Pathway Choices

In 2002, Owen and Gordon of Ricardo [15] recommended to the United Kingdom that there were two logical pathways to a possible eventual implementation of FCVs for purposes of reduction of GHGs. One – the hydrogen priority route - involved early adoption of hydrogen as a fuel, with use of hydrogen in internal combustion engines and use of limited hybridization up to about 10 kW of electric drive, until a last step in 2020, which involved the necessary jump to a series FC HEV with ~ 80kW electric machine and fuel cell. The second – the low carbon route - involved early adoption of CI-DI-TC-D engines in powertrains in the United Kingdom, where the vast majority of light duty vehicles were petrol fueled (Figure 1). The latter pathway involved a more aggressive rate of electrification of the vehicle, with 10 kW in 2010, 30kw in 2012, and 80kW in a series hybrid in 2015. At the 30 kW point in 2012, “ZEV mode” capability was to be included in the vehicle, but stating that at this stage these would be “self sufficient, grid independent vehicles that do not need electrical charging” [15, p. 30].

A key point is that the Ricardo alternatives involved a combination of CI-DI-TC-D technology and powertrain electrification. The steps from minimal electrification to the 80 kW series hybrids in the low carbon route were:

2. Stop/start with limited regenerative braking and launch assist. Using a belt starter/alternator of 3kW (2010)
3. Mild hybrid with torque assist. Using a single electric machine serving as starter/motor/generator, with 10 kW of capacity (2012)
5. Series hybrid presumably with more ZEV capability (unstated). Using electric machine of 80 kW

In the next two segments we address two questions: (1) if grid connected PHEVs can be implemented, where in the sequence above is it most logical to start? (2) is the switch to diesel fuel and CI-DI-TC-D engines a necessary combination, or would it be acceptable (or even desirable) to start the path with SI-IDI-NA-G engines?

2.2 The Step-In Evolution of HEV Electric Drive Where Grid Connection Can Begin

First, the nature of the ZEV mode capabilities is not specified. As Vyas et al [17], and Duoba and Carlson [18] discuss, the notion of zero emissions (ZE) or all-electric (AE) mode operation is meaningless without knowing the driving cycle for which the claim is made. With 30 kW, ZEV, or all electric range (AER) would surely be limited to urban driving with relatively low top speed and acceleration rates lower than many drivers demand. However, the testing of aftermarket conversions of Prius HEVs to PHEVs has shown that the power levels required to allow battery depletion with considerable reduction of petroleum consumption per mile are well below 30 kW [17]. So, whether or not the 30 kW level is capable of providing ZEV capability, it is certainly capable of providing blended mode charge depletion capability for a passenger car PHEV of the size of the Prius, allowing significant substitution of grid electric energy for petroleum energy in PHEVs. It appears that electric drive capabilities somewhere in the 10-30 kW range for world passenger cars could allow grid electrification of passenger travel to begin. Of course, as Owen and Gordon imply, that level of power and capability could well be exceeded over a longer period of time. The Chevrolet Volt, announced for a target date of 2010, is an electric drive dominant series HEV of the type hypothesized by Owen and Gordon for 2015.

2.3 Is a Shift to Diesel Desirable in a Transition to PHEVs?

Owen and Gordon implied that the path to electrification of drivetrains should be married to diesel fuel and CI-DI-TC-D engines. More recent work by Ricardo calls that implication into question. In a recent presentation by Osborne of Ricardo [20], the concepts of controlled auto-ignition (CAI) and homogenous charge compression ignition (HCCI) were discussed, in conjunction with the announcement of a petrol fueled engine concept, the 2/4SIGHT, to take advantage of CAI at low engine loads, combined with DI, using spark ignition for starting, idling, and high load. In addition, both a turbocharger and a supercharger (SC) are added, while the number of cylinders is dropped from 4 to 3. This engine was asserted to have the potential to exhibit the efficiency of a four valve high speed, direct injection (4V HS DI) diesel engine (undoubtedly turbocharged), though operating on petrol. In fact, it was asserted to be capable of realizing greater reductions in carbon dioxide than a 4VHS DI diesel meeting Euro 3 standards, at slightly lower cost. Osborne also projected that the Euro 4 standards would drive the cost of the
4VHS DI engine up, and the carbon dioxide reductions down, so that the 2/4 SIGHT would be a far more cost effective approach for the petrol dependent U.K. than would switching to CI-DI-TC-D engines meeting Euro 4 standards. Recall the earlier discussion that even more strict Euro V standards are under consideration, and that current U.S. Tier II standards are even stricter than the proposed Euro V standards. This engine concept shows the possibility for evolution of the petrol fueled engine toward and perhaps beyond the efficiency of the diesel fueled engine, when both have to compete equally, or nearly equally, under very strict emissions standards. The SI-IDI-NA-G engine evolves to the SI/CI-DI-TC/SC-G engine, and, for fuel consumption and particularly GHG emissions, petrol becomes as viable as diesel as a refined petroleum product for light duty vehicles.

Ricardo is not the only company touting the idea that an advanced petrol fueled engine of the “mid-term” future can be as efficient as today’s CI-DI-TC-D engines [21]. The recently displayed Mercedes Benz F700 concept car has an engine prototype called the “DIESOTTO.” This petrol fueled engine is said to obtain the “torque and consumption benefits of a diesel” [22]. It is a 1.8 liter engine with, direct injection, twin turbochargers, spark or controlled-auto ignition, variable compression ratio, variable valve timing, and hybridization. It might be called a SI/CI-DI-2TC-G HEV. This abbreviated acronym ignores the possibility of insertion of CAI for controlled auto-ignition, VVT for variable valve timing, and perhaps VC, for variable compression. This clearly makes the point that engines are becoming more and more sophisticated, as greater and greater fuel efficiency is demanded at the same time that tighter and tighter emissions standards are imposed. This engine is said to be capable of meeting “EU6” emissions regulations [22], a level of regulation we possible in 2014.

An interesting difference between the DIESOTTO and the 2/4SIGHT concepts is the absence of a supercharger in the DIESOTTO, but the inclusion of hybridization. According to Birch’s report “the DiesOTTO engine becomes even more economical if combined with a hybrid module — for which it was designed” [21, p. 17]. More broadly, the statement attributed to Mercedes Benz’s Herbert Kohler: “In future, Mercedes-Benz will only develop vehicles and engines which can be enhanced with hybrid technology” [21, p.18] is indicative that Mercedes Benz will soon begin a hybridization pathway. The hybrid motor linked with the F700 DIESOTTO engine concept is a 15 kW motor, on a touring sedan much heavier than a compact car, so this concept’s electric drive system may not be powerful enough to offer opportunities for significant all electric operation. Kohler was quoted as saying that diesel hybrid solutions are also being pursued, with expectations of overcoming the challenge of high costs.

Our point here is that the 2/4SIGHT engine concept implies that the long-term path to lowered carbon dioxide emissions no longer implies that a switch from the SI-IDI-NA-G to the CI-DI-TC-D is necessary to achieve carbon dioxide emissions reductions, and it may not be cost effective to do so. The DIESOTTO suggests that the evolution of the general combination of technologies touted by Ricardo for the 2/4SIGHT can be altered cost effectively to incorporate and benefit from hybridization, at about step 3 in the Ricardo 2002 low carbon pathway concept [15].

Varying, and recently narrowing, estimates of the degree of desirability of shifting from petrol to diesel fuel (and associated powertrains) as a means of reducing carbon dioxide emissions have also shown up in U.S. research at the Massachusetts Institute of Technology over the same time period (technological opportunities do not recognize national boundaries). In 2001 Weiss et al estimated that the life cycle reference case 2020 reductions of carbon dioxide per kilometer via a petrol to diesel switch for a conventional powertrain would be 7%, while for a hybrid the reduction would be 8% [24]. In 2003, Heywood et al estimated that a switch from an engine with SI-IDI-NA-G technology to one with a CI-DI-TC-D engine in a conventional powertrain would result in a GHG reduction of 15%, while in an HEV powertrain it would provide a reduction of ~13% [25]. However, by 2007, Kromer and Heywood had dropped the hybrid diesel from their investigation, and had increased the carbon benefit estimates for the petrol option, by including a turbocharged petrol engine alternative [26]. The technological details for the engines were not provided. For the vehicle alone, the Greenhouse Gas Emissions benefits of the diesel vs. the turbocharged petrol engine were now estimated to be only 4% [26, p. 48], while for the life cycle (well-to-wheels) the estimate was 8% [26, p. 115]. In striking contrast, the estimate of carbon dioxide reduction for a PHEV with 48 km of range was 38%!

Kromer and Heywood estimated the long-run incremental costs of several powertrains for the year 2030, including:

- NA-SI = naturally aspirated spark ignited petrol
- Turbo = turbocharged spark ignited petrol
- Diesel = advanced compression ignition, direct injection turbocharged
- HEV = hybrid
- PHEV = three of these, with 16, 48, and 96 km of all electric range on the UDDS cycle
- FCV = fuel cell vehicle, assuming successful R&D
They also estimated fuel consumption under several driving cycles, for electricity, refined petroleum products, and hydrogen. In Table 1 we use the vehicle cost and fuel cost values to construct benefit vs. cost ratios for vehicles operated ten years, evaluating the net present value of annual fuel cost savings at a discount rate of 10%, with different fuel cost assumptions, as noted. The “incremental” benefit versus cost ratio of purchasing any powertrain other than the Turbo is estimated in the sixth column, at gasoline and diesel prices of $3.00 per U.S. gallon and five cents per kWh of electric cost. The charger is assumed 92% efficient. We do not know whether the Wh/mile values reported by Kromer and Heywood are into or out of the battery. The rule of thumb with the benefit/cost ratio is that it should exceed one (1.0) if the evaluated alternative should be adopted. According to this rule of thumb, the only two powertrains that are more desirable than the Turbo are the HEV and the PHEV16. However, before purchasing a PHEV16, an astute consumer should redo the benefit/cost comparison for the PHEV16 against the HEV. The result of this comparison is shown in the seventh column, where the incremental benefits of adding more and more battery pack to PHEVs, then moving to an EV, are examined. In no case is addition of electric drive estimated to have a benefit/cost ratio exceeding 1.0. Each addition of more battery pack reduces the benefit/cost ratio. The last value in the column is a comparison of the FCV to the HEV, showing that at present U.S. gasoline price levels, even Kromer and Heywood’s estimate of success for FCV R&D does not lead to benefits exceeding costs.

In column seven we show the effect of increasing all fuel costs by a factor of two. In this case the PHEV with 16 km of range has a benefit vs. cost ratio in excess of 1.0. The PHEV with 48 km of range also has a benefit cost ratio close to 1.0, suggesting that PHEVs with range intermediate between 16 and 48 km could also have a positive benefit cost ratio.

The Turbo petrol vehicle, which we assume is inspired by the same technological trends that have caused Ricardo and MercedesBenz to tout significant potential improvements in efficiency of petrol burning engines, is estimated to be more desirable than the NA-SI engine (row 1 vs. row 2). Switching from the Turbo engine to the NA-SI engine has a benefit/cost ratio less than 1.0, indicating that the Turbo is superior. The worst switch that could be made under fuel price conditions shown in column 6 would be to switch to the diesel.

In Table 2 we illustrate, based on manipulation of numbers from Smokers et al [27], the near-term European perspective on carbon reduction effectiveness per Euro of manufacturer cost for anticipated improvements in petrol and diesel vehicles from 2002 to 2009, and contrast this to the implementation of different degrees of hybridization. We assemble a comparison based on kilograms of CO2 reduced per 100,000 kilometers per incremental Euro of cost to the manufacturer. A larger number is better in Table 2, as it was in Table 1. In its last row, Table 2 illustrates that from 2002 to 2009 more Euros per powertrain are anticipated to be spent on improving petrol powertrains

Table 1: Benefit/cost ratios of 2030 powertrains simulated by Kromer and Heywood [26]

<table>
<thead>
<tr>
<th>Powertrain</th>
<th>First cost difference</th>
<th>S/yr fuel cost @ 3.00/gal</th>
<th>fuel S/yr cost change</th>
<th>fuel NPV $ cost A per decade @ $3.00/gal, $0.05/kWh *</th>
<th>Benefit/ Cost Ratio @ $3.00/gal</th>
<th>Incremental Benefit/Cost Ratio @ $3.00/gal</th>
<th>Incremental Benefit/Cost Ratio @ $0.05/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA-SI</td>
<td>-$500</td>
<td>$1,000</td>
<td>$100</td>
<td>$614</td>
<td>0.81 b</td>
<td>0.81 b</td>
<td>0.41 b</td>
</tr>
<tr>
<td>Turbo</td>
<td>0</td>
<td>$900</td>
<td>$900</td>
<td>$900</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Diesel</td>
<td>$700</td>
<td>$650</td>
<td>$450</td>
<td>$246</td>
<td>0.35 b</td>
<td>0.35 b</td>
<td>0.70 b</td>
</tr>
<tr>
<td>HEV</td>
<td>$1,400</td>
<td>$1,600</td>
<td>$240</td>
<td>$2,089</td>
<td>1.49 b</td>
<td>1.49 b</td>
<td>2.98 b</td>
</tr>
<tr>
<td>PHEV16km</td>
<td>$2,500</td>
<td>$4,100</td>
<td>$590</td>
<td>$2,765</td>
<td>1.11 b</td>
<td>0.61 b</td>
<td>1.23 b</td>
</tr>
<tr>
<td>PHEV48km</td>
<td>$3,800</td>
<td>$5,350</td>
<td>$445</td>
<td>$2,849</td>
<td>0.88 b</td>
<td>0.45 b</td>
<td>0.90 b</td>
</tr>
<tr>
<td>BEV</td>
<td>$5,600</td>
<td>$6,600</td>
<td>$600</td>
<td>$3,687</td>
<td>0.66 b</td>
<td>0.19 b</td>
<td>0.38 b</td>
</tr>
<tr>
<td>FCV</td>
<td>$9,700</td>
<td>$200</td>
<td>$200</td>
<td>$4,301</td>
<td>0.44 b</td>
<td>0.15 b</td>
<td>0.30 b</td>
</tr>
<tr>
<td>PHEV96km</td>
<td>$3,100</td>
<td>$525</td>
<td>$375</td>
<td>$2,304</td>
<td>0.74 b</td>
<td>0.13 b</td>
<td>0.25 b</td>
</tr>
</tbody>
</table>

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Table 2: Powertrain carbon reduction cost effectiveness measures from Smokers et al [27]

| Kilograms of CO2 reduced per 100,000 km, per Euro added manufacturer cost |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                                 | Small Diesel    | Small Petrol    | Medium Diesel   | Medium Petrol   | Large Diesel    | Large Petrol    |
| 02 to 09 upgrade                | 2.2             | 2.8             | 2.3             | 2.7             | 3.1             | 3.4             |
| Start-stop                       | 2               | 2.2             | 2.3             | 2.7             | 3               | 2.8             |
| Start-stop + regeneration        | 1.5             | 1.6             | 1.9             | 2.1             | 2.3             | 3.4             |
| Mild hybrid (motor assist)       | 1               | 1.1             | 1.1             | 1.2             | 1.6             | 1.8             |
| Full hybrid (electric drive)     | 0.8             | 0.9             | 0.9             | 1.1             | 1.4             | 1.7             |

| Percent change in gram/km of CO2 and price increase to accomplish the improvement |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 02 to 09 % improvement          | -7%             | -19%            | -8%             | -20%            | -11%            | -22%            |
| 02 to 09 Euro cost increase     | 356             | 1,029           | 518             | 1,152           | 773             | 1,573           |

than diesel powertrains. Further, other rows illustrate that the estimated cost effectiveness of the spending on petrol powertrains will be greater than for diesels, particularly for the small and medium car. This is consistent with the optimism about the potential to improve the petrol based powertrain seen in previous publications cited. Further, one sees that the first stages of implementation of electric drive — stop-start, and stop-start with some regeneration — are often estimated to be as effective as other anticipated conventional drivetrain powertrain improvements (i.e., “02 to 09 upgrade”). For the larger passenger vehicles start-stop with regeneration appears as desirable as the conventional powertrain upgrades, while in small cars neither the stop-start nor stop-start with regeneration option is as desirable as the conventional powertrain upgrades. This difference would be consistent with the changes anticipated by Ricardo and MercedesBenz. For Ricardo, the discussion of the 2/4SIGHT (which does not include hybrid components) was for application to a Ford Escort, a much smaller car than the MercedesBenz F700 luxury sedan (which does include hybrid components).

If we assume that the effectiveness estimates developed from Smokers et al are correct, they imply that implementation of electric drive in petrol vehicles is more effective than in diesels, and that implementation of all technological improvements are more cost effective in larger vehicles. The implementation of full hybridization in the large petrol car is nearly as effective as stop-start in a small car, and more effective than stop-start with regeneration in a small car.

Ironically, Smokers et al only provides incremental costs of changing powertrains, and does not provide the base costs for the reference powertrain. Accordingly, it is not possible to develop an estimate of the 2009 incremental cost effectiveness of switching from a petrol powertrain to a diesel powertrain. We do know, however, that the percentage differences between the two types of powertrains are implied to narrow significantly, both in cost and carbon emissions. Consistent with Kromer and Heywood’s “2030” projection of a 4% difference in CO2 emissions between a turbocharged petrol engine and an advanced diesel [26, p. 48], the 2009 projections of Smokers et al are also ~ 4% for all three car size categories.

It should also be noted that the regulations to clean up the diesel are accompanied by regulations to clean up diesel fuel — primarily to reduce sulfur content so that aftertreatment devices can operate reliably. Thus, in addition to cost pressures on diesel powertrains, there are also cost pressures on diesel fuel as well. Figure 5 illustrates that the ratio of untaxed cost of diesel fuel relative to gasoline has risen over the last five years, as lower sulfur regulations have been imposed in the U.S., while the demand for diesel fuel has risen more rapidly than for petrol.

3. HYBRID POWERTRAIN TYPES

Thus far, the discussion of HEV powertrains has implied that there are four levels of hybridization, stop-start, stop-start and regeneration, mild and full hybrids. This is an extreme oversimplification. Presently, there are two types of mild hybrids in production. These are Honda’s Integrated Motor Assist (IMA) system, available in the Civic, and the General Motors Belt Alternator System (BAS), now available in three models [12, 30]. Among full hybrid powertrains there are numerous options. The “split hybrid”, developed by Toyota, (called the Toyota Hybrid System – THS)
is the most widespread at the moment. Versions of this powertrain have been implemented in the U.S. by Ford, in the Ford Escape, Mazda Tribute, and Mercury Mariner SUVs, and by Nissan, in the Altima mid-size passenger car. Toyota has implemented the technology in several models, including the front wheel driven Prius, Camry, Highlander and Lexus RX400h [12]. Each of the hybrids mentioned previously in this paragraph is a front wheel drive (FWD) vehicle.

Toyota has recently introduced two Lexus passenger car hybrids which use rear wheel drive (RWD). Among the vehicles mentioned, these two have the highest kW/kg ratio, and fastest acceleration times.

The jointly developed “2Mode” system, under shared development by GM, BMW, Chrysler, and Daimler, is not yet available, but will soon appear in several models [30, 32]. The 2Mode and split hybrids use two electric machines. Daimler has also developed prototype commercial trucks (the Sprinter) with a pre-transmission parallel hybrid, which has one electric machine between the engine and transmission [31]. Yet another two electric machine system, designed particularly for 4WD, has been developed by Magna Steyr, Magna Powertrain and Siemens VDO [33], for use in the Mercedes ML SUV series.

To this point, all hybrids discussed are petrol fueled. According to one recent announcement, a hybrid diesel passenger car will be introduced by PSA of France in its 308 model in 2010 [34]. This vehicle’s CO2 reduction is said to be “20% below a comparable diesel engine” [34] achieving a level of 90 g/km.

### 3.1 Effects of Hybridization with and without Engine Downsizing

#### 3.1.1 A EUROPEAN 4WD SUV CASE – NEDC CYCLE PREDICTIONS

Typically, though not always, the engine used in the hybrid is smaller in displacement than the largest available engine in the model line. When this is true, if the vehicle is compared to a conventional powertrain with a larger displacement engine, the hybrid engine is said to be “downsized.” When, for example, there are both four and six cylinder conventional powertrains available, while the hybrid uses a four cylinder engine, a comparison of the hybrid against the larger six cylinder engine allows us to examine the effect of downsizing, while a comparison with the conventional powertrain with a four cylinder engine can be thought of as a comparison without downsizing. The earlier discussion
of the future of the ICE engine indicated that downsizing (significant reductions of engine displacement) can be anticipated in the near to medium term future. For existing hybrids, the implementation of downsizing has already been a very important feature, enhancing petrol fueled powertrain efficiency now.

The conceptual issue can be illustrated by using data provided by Schffernak et al [33].

This table provides a general idea of the trade-offs that emerge when a competent full hybrid powertrain is implemented. Without the benefit of hybridization, if a consumer presently wanted to save fuel when purchasing a Mercedes ML series, the consumer would have to sacrifice generally, in terms of acceleration and top speed (though the consumer would pay less for the vehicle). However, if the consumer wants both improved fuel efficiency and improved performance, then a trade-off is made possible by the hybrid option. The anticipated optimized powertrain would provide much faster acceleration than the ML350, and somewhat faster acceleration than the ML500. The large sacrifice in start-up acceleration when purchasing the ML350 instead of the ML500 would be completely eliminated. Passing acceleration would be improved relative to the ML500. The consumer does have to give up sustainable top speed when switching from the ML500 to the hybrid. The fuel consumption reduction, if compared to the ML500, is predicted to be 29%. This is the case with engine downsizing. Fuel consumption reduction compared to the ML350 — the “no downsizing” case — is a respectable 18%.

In light of the differences in fuel consumption reduction comparisons that result, unless one knows the “with vs. without” downsizing assumption used, interpretation is very difficult. This problem exists for Table 2. While Smokers et al provide estimates for three passenger car sizes, they do not tell whether or not engine downsizing was assumed [27].

### Table 3: Projected attributes of three SUV powertrains, HEV vs. same and larger engine size [33]

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Units</th>
<th>ML 500</th>
<th>ML350</th>
<th>Change (%)</th>
<th>ML350H (E4WD HEV)</th>
<th>Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>kg</td>
<td>2175</td>
<td>2135</td>
<td>-1.8</td>
<td>2285</td>
<td>7</td>
</tr>
<tr>
<td>ICE Type</td>
<td>-</td>
<td>V8 (5.0L)</td>
<td>V6 (3.5L)</td>
<td>V6 (3.5L)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engine power (battery)</td>
<td>kW</td>
<td>225</td>
<td>200</td>
<td>-11.1</td>
<td>200 (50)</td>
<td>&lt; 25%</td>
</tr>
<tr>
<td>0-100 km/h</td>
<td>sec.</td>
<td>6.9</td>
<td>8.4</td>
<td>21.7</td>
<td>6.7</td>
<td>-20.2</td>
</tr>
<tr>
<td>80-120 km/h</td>
<td>sec.</td>
<td>6.7</td>
<td>7.1</td>
<td>6</td>
<td>6.1</td>
<td>-14.1</td>
</tr>
<tr>
<td>Top speed</td>
<td>km/h</td>
<td>240</td>
<td>225</td>
<td>-6.2</td>
<td>225</td>
<td>0</td>
</tr>
<tr>
<td>NEDC fuel use</td>
<td>l/100 km</td>
<td>13.4</td>
<td>11.6</td>
<td>-13.4</td>
<td>9.5</td>
<td>-18.1</td>
</tr>
</tbody>
</table>

3.1.2 U.S. CASES – CONSIDERING DETAILS OF DRIVING CYCLE EFFECTS

In Figure 6 we show a set of results obtained with hybrid powertrains available in the U.S., according to the latest “window sticker” rating of U.S. fuel economy [35]. We also show results for the latest diesels as well. Note that the results in Figure 6 are on a volume of fuel basis, not on a carbon content basis. Because diesel fuel has about 11% more energy (and more carbon), per unit volume, volumetric fuel economy comparisons look better for a diesel than carbon emissions comparisons. As a point of reference if one uses an 11% adjustment for volumetric effects, the Smokers et al report implies a 26% volumetric fuel consumption benefit in 2002 if switching from a comparable petrol engine to a diesel, but only 15% in 2009 (the year of implementation of Euro V standards). Note also that the comparisons discussed earlier are based on forthcoming technology, while the results in Figure 6 are for today’s technology. While more diesel models are available in the U.S. than in the past, the absence of the relatively high sales VW diesel powertrains due to problems in developing a reliable emissions control system [36] have caused the share of diesels in the U.S. to drop, at least temporarily, for vehicles of 3856 kg GVW and less [5].

Note also that the comparisons in Figure 6 are compiled in the same way as those in Table 3. The comparisons are for different engine options within the same make and model line. Generally, the comparisons are for pairs of hybrids with the number of cylinders equivalent to the smaller of two engines in the conventional powertrain offerings (no downsizing), and pairs where the hybrid has less cylinders than the larger engine in the conventional powertrains (downsizing). In Table 4 we provide the estimates of Smokers et al as a frame of reference.

What one can immediately see is that the reductions in fuel consumption attainable — for the city cycle
estimates — are consistently greater than the assumptions of Smokers et al for the split hybrid (full hybrid) and particularly the Honda integrated starter generator (mild hybrid) cases with engine downsizing and front wheel drive. Without engine downsizing, the results are also better, but are comparable. For the belt alternator systems with engine downsizing, the results are better. In some cases aerodynamic improvements are incorporated into the hybrids and not the models with conventional powertrains, so this can explain some of the difference. Nevertheless, these results imply that the benefits of hybridization are, to a degree, in the eye of the beholder. If the consumer wants high top speed and towing capability, then the proper comparison is the “no downsize case.” However, if the consumer is indifferent to the reductions in top speed for a given hybrid model, and does not plan to tow, then the proper comparison is the downsize case.

Estimates of cost effectiveness depend on the analysts’ implicit assumptions about how consumers will react. If one assumes that the majority of passenger car customers will forego towing capability, then the proper estimates of benefits of hybridization of passenger cars should be done on the basis of an assumption of engine downsizing. However, if one assumes that towing will be critical to the customer base for other vehicles — such as large SUVs and pickup trucks — then the proper comparison would be done on the basis of no engine downsizing. The latter case would diminish the estimated benefit to cost ratio for hybridization of larger vehicles, while the former would increase the estimated benefit to cost ratio for hybridization of smaller vehicles. Taking this into consideration, the decline in benefit to cost ratios estimated in Table 2, as one moves from large to small cars, might disappear.

Table 4: Smokers et al estimates of fuel consumption reduction effects of electric drive options

<table>
<thead>
<tr>
<th>Electric drive option</th>
<th>% decline Diesel</th>
<th>% decline Petrol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start-stop</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Start-stop + regeneration</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Mild hybrid (motor assist)</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>Full hybrid (electric drive)</td>
<td>18</td>
<td>22</td>
</tr>
</tbody>
</table>

Figure 6: Percent reduction in city vs. highway fuel-consumption, by HEVs and diesels, U.S.
Another perspective, which we discuss at length below, is that consumers may select and use HEVs in driving conditions for which they are particularly suited – city driving. If this happens, then the estimates of cost effectiveness of HEVs deduced from the estimates of Smokers et al are clearly understated.

### 3.2 Downsizing to Reduce Fuel Consumption vs. More Power with the Same Engine

For those cases in which a manufacturer offers two engine options in a given make and model, and funds for adding engine options are limited, then hybridization of one of the two existing engine lines is possible instead of producing a new engine line. In light of the possibility that the hybrid powertrain option is being developed as a hedge against future high oil prices, the changing patterns of consumption that occur when oil prices rise should be considered. Another possibility that might be considered is to produce HEV compatible downsized engines based on the same engine blocks and related parts to be used for advanced, downsized turbocharged petrol engines. Daimler’s Herbert Kohler may have implied such a plan when he stated that Mercedes-Benz will in the future only develop engines “which can be enhanced with hybrid technology” [21].

Figure 7 constructs a comparison of fuel savings obtainable for full split-hybrid vs. diesel powertrains, with or without downsizing, for 2008 U.S. model year vehicles. The comparisons tend to give the diesel more credit than it deserves because the diesel models are larger than the HEV models. However, the purpose is not an absolute comparison, it is a relative one. What is demonstrated is that in city driving the split HEV with a downsized engine saves the most fuel per hour of operation of the three options while the diesel saves the most fuel per hour of operation in highway driving. Another interesting nuance is that the hourly savings of the HEV drop by a higher percentage in the highway than city cycle for an HEV with a downsized engine, than for an HEV without engine downsizing. This certainly implies that downsizing provides the greatest benefit in highway driving. In city driving, the benefits of idle off, fuel cutoff during deceleration, and regenerative braking dominate over engine downsizing. Each of these fuel saving steps require frequent repeats of start, accelerate, cruise, decelerate, stop sequences of operation to be effective. A downsized engine can be quite effective during continuous cruising, at which time the other HEV features have no value.
4. ON DRIVING CYCLES, AVERAGE SPEED, AND HEV EFFECTIVENESS

One interpretation of Figure 7 is that, as average speed drops, the relative advantage of the HEV vs. the diesel increases. For the start, accelerate, cruise, decelerate, stop sequence to exist, there must be stop signs and/or stoplights. The more stops per km, the more repetitions of such a cycle. Figure 8 and 9 illustrate the relationship between average speed and stops, for a number of driving cycles [37, 38]. The blue diamonds are predominantly U.S. driving cycles, both for trucks and cars, also including the European (NEDC) and Japanese (Japan 10/15) official test cycles [37]. The orange circles are developed from on-road tests of more than 70 European passenger cars [38]. One can see a strong inverse relationship between average speed, percent of time stopped, and number of start, accelerate, cruise, decelerate, stop sequences per km of travel. Thus, it is not surprising that the regenerative braking and unpowered fuel flow cutoff features of mild and full hybrids offer increasing fuel savings benefits as congestion increases and average speed decreases.

Figure 10 presents, for U.S. data alone, the top speed as a function of average speed of the different driving cycles. For average speeds of less than about 25 km/h, this data suggests that an ability to operate all electrically up to about 80 km/h would suffice to allow PHEVs to run all electrically. Toyota has recently delivered its first two PHEV Prius prototypes to the University of California at Berkeley and Irvine [39]. These prototypes use two NiMH battery packs. They have been modified to be able to run all-electrically up to about 100 km/h, and have an all electric range of 11km. If and when acceptable Li-ion battery packs are developed, it can be anticipated that the range will at least double. Though only suggestive, Figure 10 implies that this top electric speed capability will be adequate to allow an eventual Prius PHEV to run all electrically in many low speed trips.

Figure 11, developed from U.S. data [40], indicates that as distance driven per day increases, average speed increases, but at a decreasing rate of increase. Note that the average speeds of trips remain well below the top speeds legally attainable on U.S. Interstate highways. This is because even trips that include significant segments on limited access highways and motorways also include segments at the beginning and end that involve travel on local streets and highways at much lower speeds. Further, Figure 11 is an average. Even limited access highways are often congested, with
Figure 9: Number of stops per km vs. average speed, U.S. and European driving [37, 38]

Figure 10: Peak speed vs. average speed, U.S. and European driving [37, 38]
traffic at speeds well below free flow design speed. The congestion would not occur unless a large fraction of drivers were on the road during hours when congestion occurs. In other words, a large fraction of drivers on urban limited access highways do not travel at the posted speed limit, drawing the overall average speed, even on longer trips, down.

5. POPULATION DENSITY INFLUENCES ON VEHICLE SPEED AND MODEL CHOSEN

5.1 Population Density vs. Average Speed

Figure 12 illustrates how average speed varies in the U.S., as a function of population density [40]. Figure 12 separates out dwelling unit type by “detached single” vs. “all other” because garages and carports – where PHEVs can be recharged from the house – are more often found with this type of dwelling unit. Average vehicle speed appears to be far more closely linked to population density than dwelling unit type.

An average speed of about 32 km/h is the average speed of the U.S. city cycle. Thus, the most advantageous circumstance for split-HEVs in the U.S., over the range of speeds that apply in Figures 6 and 7, is for population densities in excess of 9,800 persons per sq. km. However, only 1.1% of the U.S. population lives at that density [40]. About half of the U.S. population lives at a density between 390 and 9800 persons per sq. km, where average speeds vary from ~ 37 to 48 km/h.

At the country level, the average density of European nations participating in this study is, aside from Sweden, greater than the United States. For continental European members, there are also as many or more cars, trucks and buses per populated square kilometer. Consequently, one might anticipate that traffic congestion would be worse, on average, in Europe than in the U.S., and average speeds would be lower.

Andre has recently examined real world driving in Europe, developing the “ARTEMIS” driving cycles [38]. The average speed estimated by Andre is 40 km/h, which is well below the value of ~ 48 estimated for the U.S. from the National Household Transportation Survey (Figure 12, “all population classes”). Another source, Barter, Kenworthy and Laube [42], provides data consistent with the data just discussed. “Urban density” is reported to be 14.9 persons per hectare in the U.S., but 54.9 in Western Europe. Given the higher population density in Europe, Figure 12 implies that the daily km of travel should be less in Europe. This is what the Barker, Kenworthy and Laube estimates imply, suggesting the annual km for vehicles in Western Europe are about 15,000 km/yr/vehicle, while for the...
In Table 7, based on manipulation of data in [40] we estimate the average speed, share of time spent, share of total trips, and average trip length for three different daily driving distance intervals. In the same way that average speed and cycle distance rise from urban to rural to motorway in Table 6, the average speed and average trip length rises from short to long daily travel distances in the U.S. As expected, the average speed and average trip length estimated for the U.S. from Table 7 exceeds the same averages estimated for Europe shown in Table 6. Although the comparisons are clearly approximate, it would appear that the average speed on a European motorway is faster than on a U.S. Interstate, since the longer trips in the U.S. average a much slower 68.1 kph vs. 92.8 on the European Artemis Motorway cycle.

Andre estimates that Europeans spend fully half of their time driving in “urban” conditions with an average speed of 22.5 km/h, well below the ~ 32 km for the U.S. city cycle. Given the pattern of savings estimated in Figure 7, this implies that the “real world”, or “in-use” savings via adoption of petrol full (split) HEVs in European cities would considerably exceed the savings achievable by further expansion of diesel powertrains. To the extent that literature reviews used by Smokers et al resulted in HEV fuel consumption reduction estimates biased on the low side because most literature was based on U.S. driving patterns, the
Table 6: European “ARTEMIS” real world driving cycles summary [38]

<table>
<thead>
<tr>
<th>Roadway</th>
<th>Trip share (%)</th>
<th>VKT share</th>
<th>Share of time spent</th>
<th>Average length (km)</th>
<th>Average speed (km/h)</th>
<th>% of time stopped</th>
<th>Stops per km</th>
<th>Average accelerate (m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motorway</td>
<td>2.8</td>
<td>27.6</td>
<td>12</td>
<td>92</td>
<td>92.8</td>
<td>4.3</td>
<td>0.08</td>
<td>0.63</td>
</tr>
<tr>
<td>Rural Roads</td>
<td>27.5</td>
<td>44.5</td>
<td>37.9</td>
<td>13.7</td>
<td>47.5</td>
<td>11.6</td>
<td>0.41</td>
<td>0.74</td>
</tr>
<tr>
<td>Urban</td>
<td>69.7</td>
<td>27.9</td>
<td>50.1</td>
<td>3.4</td>
<td>22.5</td>
<td>26.7</td>
<td>1.72</td>
<td>0.77</td>
</tr>
<tr>
<td>ALL</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>8.4</td>
<td>40.4</td>
<td>18.4</td>
<td>0.69</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Table 7: U.S. travel statistics as a function of daily distance driven
Source: Developed from 40

Table 2 benefits of HEVs are likely underestimated. It can also be noted that the top all electric speed of 100 km/h for the initial experimental Prius PHEVs sent to California Universities would likely cover a larger fraction of kilometers driven in Europe than in the U.S.

### 5.2 Hours of Use vs. Kilometers of Use Per Day

The common approach in thinking about the merits of switching from one powertain to another is to think in terms of fuel saved per km of service and estimate the km driven to determine fuel savings. The common wisdom is that costly technologies which reduce fuel consumption must be driven more km per year. However, note that, despite the fact that U.S. citizens drive considerably less km per day as population density increases (Figure 12), they are estimated to spend more hours per day in the vehicle. The overall average is about 1.25 hours per day (Figure 13). Thus, we have the counterintuitive observation that, as average speed declines (Figure 12), the hourly fuel savings of full split HEVs increases (Figure 7), and the hours of operations increase (Figure 13), thereby increasing the total savings obtainable by purchasing an HEV instead of a conventional powertain. In other words, as annual km of use (associated with population density effects) go down, the economic viability of the HEV goes up, on average. This is opposite conventional wisdom.

### 5.3 Model Mix vs. Population Density

Note that, as population density increases, the proportion of vehicles owned that are cars rises steadily (Figure 14). Since the fuel saving advantage of owning an HEV increases as congestion increases, and congestion increases with population density, this matches up with the tendency for a higher proportion of cars to be purchased. Smaller vehicles in congested areas are easier to park and maneuver.

At the other end of the scale is the dramatic decline in share of pickup trucks owned as population density increases. A manufacturer attempting to market HEVs in the pickup truck market has to deal with the fact that pickup trucks are driven at higher average speeds than passenger cars, therefore obtaining less benefit from the HEV powertrain. They also have to deal with the competition from the diesel, in a likely pattern of use where the diesel appears to have an inherent advantage (Figure 7).

We noted earlier that within the “2b” vehicle class with GVW category from 3856 kg and 4536 kg, pickup trucks dominate, and within pickup trucks, diesel engines dominate. Already, a diesel engine that meets the less strict new standards within this group has been introduced in all 50 states in the U.S. by Chrysler. This “medium duty” Dodge Ram pickup truck is allowed to emit NOx at 0.32 g/km, while diesel powetrains in vehicles 3856 kg GVW or less have to emit 0.11 g/km or under [45]. In addition to the diesel pickup truck already in the market, Mercedes and Audi earlier in the year announced that they would introduce diesels in SUVs in 2008. The latter two vehicles are to use selective catalytic reduction with urea, while the former does not [46]. Consumers contemplating purchasing SUVs may be anticipating the introduction of diesel engines in 2008, and may be waiting for those vehicles instead of purchasing HEV SUVs. This could be a contributing factor to the decline in HEV SUV sales. From a purely technical point of view – saving fuel – the decision may be a logical one for those intending to purchase for towing and normally driving at a relatively
Figure 13: Hours per vehicle per day vs. population density, U.S. [40]

Figure 14: Pattern of vehicle model shares owned as a function of population density
high average speed.

Our data source for Figure 14 does not allow us to distinguish the size of an SUV. However, based on the shift to cars as population density increases, one might expect that the size of SUVs purchased declines as population density increases. It would also be logical, though we have no data to prove it, that there would be a shift among SUVs toward smaller, more fuel efficient CUVs as population density increases.

Despite the patterns shown here, GM is introducing 2 mode HEV powertrains in a large SUV, the Chevrolet Tahoe, and in a pickup truck, the Chevrolet Silverado [47]. They do seem to realize that the traditional pickup truck customer may not be a candidate for an HEV powertrain. The image of the first Silverado 2 mode HEV in the recent GreenCar Congress article is of a six passenger pickup truck with a short truck bed — in other words, a version more suitable to hauling families and light loads in urban areas [44].

6. CHANGING MODEL AND POWERTRAIN DEMAND AS FUEL PRICES INCREASE

The U.S. market evolution of share of HEV powertrain types toward cars and toward powertrains with downsizing of engines has occurred as U.S. fuel prices rose rapidly — considerably more rapidly than in Europe (Figure 15). The increases in aggregate hybrid share in the U.S. have been boosted by government incentives that are now phasing out. Petrol prices have been moving in favor of more efficient powertrains such as HEVs and diesels, particularly in the U.S.

6.1 Fuel Price Effects on Interest in Diesels in Europe

Since European diesel prices have been rising faster than petrol prices (Figures 5 and 16) this should diminish the diesel interest arising from the general rise in price for refined petroleum products. In Figure 17 we see a clear 2004 “kink” in the ratio of retail diesel prices to petrol prices, with diesel prices rising. If we compare that relative price shift to the growth rate of share of diesels in Europe (Figure 1), it does appear that a 2004 kink to a slower growth rate of diesel share occurred as the upward shift in relative diesel prices began (Figure 16).

6.2 Shifting U.S. Choices within Models with HEV vs. Conventional Powertrains

To date, the only models that have full hybrid powertrains are SUVs and passenger cars. For the first wave of hybrids in the U.S., in Figure 2 one gets a hint that while the HEV market has been growing, there has also been a recent shift of mix from SUVs to cars.

![Figure 15: Movements of petrol and residential electricity prices, 2001-2006 [28]](image-url)
Figure 16: Movements of European retail diesel fuel prices, 2001-2006 [28]

Figure 17: Share of U.S. hybrids sold, with selected characteristics, 2005-2007
In 2006, it appeared that the growth of market share of hybrids had slowed. However, now that oil price concerns have re-emerged in 2007, growth appears to have resumed (Figure 2) and there has been a distinct shift of the mix of hybrid platforms from SUVs to passenger cars (Figure 17).

The shift away from SUVs within hybrid powertrains shown in Figure 17 is dramatic. To date, there has been no switch away from conventional SUV powertrains to passenger cars in the U.S., though there has been a powerful switch away from “traditional” SUVs to what are now called “Crossovers Utility Vehicles,” or “CUVs.” The CUVs are within the U.S. government’s official light truck category for purposes of fuel economy regulation (but most “light trucks” under 3856 GVW in the U.S. are actually passenger vehicles). As defined by J.D. Power, CUVs are front wheel drive SUVs within the U.S. government’s light truck category. The SUV acronym is now assigned by J.D. Power to those SUVs based on longitudinal powertrains — rear wheel drive platforms[6].

One interpretation of the CUV is that it allows powertrain and vehicle platforms to “cross” from the official U.S. government passenger car category, where FWD platforms dominate, to the official light truck category. The light truck category is subject to less stringent fuel economy regulation, so the CUV type allows manufacturers to defeat the intent of the fuel economy standards by moving the heavy front wheel drive vehicles out of the passenger car category, where they would reduce the official fuel economy regulatory rating, into the light truck category, where they improve the fuel economy regulatory rating. Nevertheless, this strategy can only succeed if consumers choose CUVs instead of passenger cars. From a marketing perspective this has been successful. In a year when overall vehicle sales are down, CUV sales are up 18.9%, while traditional SUV sales are down by 8.3%, and passenger car sales are down by 3.4%. Within the old SUV grouping, the CUV category has increased share from 46.3% in 2005 to 50.1% in 2006, and 56.3% in 2007 to October.

In contrast, U.S. hybrid powertrain customers, who were faced with a choice between CUVs and passenger cars, bought a lot of CUV HEVs when they were initially introduced, but since then have clearly been switching to car HEVs as petrol prices rise.

HEV buyers appear to be far more sensitive to fuel prices and perhaps GHG concerns, given the dramatic decline in share of SUV hybrids and power oriented hybrids (i.e. away from those HEVs with no engine downsizing). Note that the one passenger car that adopted the HEV powertrain to increase power and performance of the larger engine in the model line — the Honda Accord V6 hybrid — has been discontinued. Thus, the switch away from power oriented HEVs is not simply a switch away from SUVs. This pattern certainly has implications for early PHEVs. This seems to have been noted by GM. Both PHEVs under development by GM address the trends in the market toward somewhat smaller, less powerful and more fuel efficient vehicles. The planned Saturn VUE 2mode PHEV is a “Crossover” front wheel drive vehicle, while the VOLT PHEV is a relatively small (by U.S. standards) passenger car. Among HEV SUVs, the ones best holding share of the market are Ford’s powertrains, which implement the HEV with the smaller of the two engines available — in this case only among SUVs, the customer can choose to “downsize” from the V6 by purchasing the HEV. For the Ford hybrid powertrains, the new term CUV applies. However, the two Toyota light truck HEVs whose market share is dwindling are also FWD CUVs. They are not particularly large relative to traditional U.S. SUVs with longitudinally mounted engines. Thus, the reduction in hybrid powertrain SUV sales is not due to a switch away from longitudinally mounted rear-wheel to transversally mounted front-wheel drive, it is a switch among front wheel drive vehicles away from the power oriented hybrids that do not offer an engine downsizing option.

One possible explanation for this shift toward cars is a process of discovery and learning, along the lines presented earlier here. Potential customers across the U.S. have probably been studying the properties of the HEVs, and learning about their strengths and weaknesses in the context of their needs. As early as 2004, a survey later analyzed by Santini and Vyas [43,44] was indicating that consumers might behave in the fashion seen here. Those strongly intending to purchase HEVs also had a strong preference for small cars. A desire to purchase HEV powertrains in other models was weak. For the pickup truck, there was a tendency to prefer the diesel, and an allocation of theoretical dollars in a way that placed the highest dollar value on towing, for pickup trucks [44]. Further, among male respondents, there was actually an indication of increasing preference for HEV powertrains as annual miles driven decreased, and an increase in preference for diesels as annual miles increased [43]. Those intending to purchase HEVs tended to have a high level of education [43], so the notion of a careful evaluation seems logical. Those intending to purchase minivans or large cars did not have much interest in diesel or HEV powertrains. Those interested in SUVs were interested in both [44].
TRANSPORT FUEL PRICES VS. RESIDENTIAL ELECTRIC PRICES: IMPLICATIONS FOR THE PHEV

Figure 15 not only presents movements of oil prices, it also presents movements of residential electricity prices since 2001. At this point we begin to think about the desirability of PHEV powertrains, examining prices for diesel, petrol, and residential electricity. The assumption is that the first market for PHEVs will be in residences which have a garage, where the PHEV can easily be plugged in.

For most nations, the recent percentage increases in petrol prices have been considerably more rapid than residential electricity prices. In the U.S., Belgium, France, and Austria the movements of petrol and residential electricity prices favor the possibility of PHEVs. For Sweden and the Netherlands this is not the case. It should be noted, however, that Figure 15 shows changes of prices indexed to a value of 100 in 2001. It does not show relative prices of residential electricity. Figure 18 shows national average residential electricity prices, by nation. The Netherlands, Sweden, the U.S. and Denmark have all seen residential electricity prices rise in nominal terms, while Austria, Belgium, and France have had relatively stable prices. Italy has a high residential electricity price, but the remaining nations are, aside from the Netherlands, bunched together at a lower level, closer together than in 1996.

In Figure 19 we examine the ratio of diesel and petrol prices to residential electricity prices in 2006. After tax and before tax values are presented for diesel and petrol. Figure 19 illustrates the relatively high rate of taxation of motor fuels in Europe relative to the U.S. Vyas et al. have estimated the potential incremental cost of a PHEV, should the U.S. Department of Energy R&D cost and performance goals succeed (17). They also estimated the dollar value of fuel savings obtainable by operation of a PHEV, for various motor fuel and electricity prices. At present petroleum product prices, according to their estimates, even with a successful R&D program, the benefits of PHEVs may not exceed the costs in the U.S. For French prices, however, they estimated that the vehicle characterized might have benefits in excess of its costs. However, they did not adapt the vehicle characterization to French driving conditions. The average speed was higher than in France and the annual miles driven were higher as well. Nevertheless, for the moment, it seems logical to assume that the potential for PHEVs to save customers money in Europe is greater than in the U.S., both due to the likelihood of higher fuel savings per hour of operation, and due to the higher per liter retail prices of petrol. However, Figure 19 illustrates that the reason for Euro savings for the PHEV customer would essentially be
motor fuel tax avoidance. If one compares the “before tax” ratios, it is evident that Europe and the U.S. are not significantly different. Another point is that the before tax prices of petrol and diesel are consistently very close to one another. However, in each of the European nations, the taxes on petrol are higher than for diesel fuel, causing retail prices of petrol to exceed those of diesel, thus providing an incentive to purchase diesel fueled vehicles. In the U.S. motor fuel taxes are low, and are higher on diesel fuel than petrol, causing diesel to be slightly more expensive at the pump.

8. THE EARLY MARKET – STARTING WITH A MODEST PHEV

Experimental Hymotion PHEVs based on the Prius platform [18] demonstrate charge depletion ranges that allow full depletion of a battery pack within the average 1.2 hours/day of driving done in the U.S. For the city cycle 63% savings per km traveled was demonstrated, while for the highway cycle 46-48% was demonstrated [48]. This was accomplished with about 12-15 kW of Li-ion battery pack power, from the supplemental Li-ion pack, installed in addition to the NiMH pack. The output power is less power than the peak power available in the Prius NiMH battery pack, which is as much as 25 kW (above the nominal 21 kW rating) for short durations [49]. However, this power level must be delivered on a sustained basis. The tests of the Hymotion Prius imply that, given enough energy and a “light foot” on the accelerator, the present Prius powertrain could likely run all electrically at speeds below 48 km/h [48], while Toyota’s first two experimental Prius PHEVs are designed for 100 km/h all electric operation.

Duoba and Carlson estimate that a peak power rating of about 35-40 kW would be needed to meet the U.S. city cycle “UDDS” speed vs. time trace, which requires a top speed of 91 km/h. We have estimated the power requirements for a European sedan, on four driving cycles (Figure 20).

Figure 20 illustrates that all of the energy requirements for the Artemis urban cycle could be met with approximately 35-40 kW of motor capability, which would require a slightly more powerful battery pack. It also illustrates that such power levels would be adequate to meet about 80% of the energy requirements for the rural and motorway cycles. Similarly, it shows that about 15 kW could meet about half or more of the energy needs of all driving aside from motorway driving. This makes the Argonne National Laboratory city cycle test results for the Hymotion Prius logical. The gap between the “Artroute” and “Artauto” estimates illustrate the relatively dramatic increase in power needed to replace petrol energy with electric energy as one moves from urban and rural driving to motorway (or Interstate) driving. Imagine that the goal were to
achieve 50% energy replacement. The kW required increases as the average speed of these cycles increase, moving left to right. In the neighborhood of 10-17 kW one can capture about 50% of the energy in urban and rural driving. But roughly a doubling of that is needed to capture 50% of energy in motorway driving.

In Figure 21 we illustrate the inverse of motoring power, braking power. For the Artemis Urban cycle it appears that about 35 kW will also be well suited to capture available braking energy. For the higher speed cycles, it appears that the costs, in terms of kW needed, to regenerate the last few percent of braking energy are quite high.

For a PHEV the needs in Figure 20 dominate. The purpose of a PHEV is to take energy from the grid and replace petrol based mechanical power with electrical power. The output power of the battery pack and motor dictate how completely this can be accomplished, for a given driving cycle. If one considers a PHEV battery pack option as an alternative to a pack designed for an HEV, then it will be likely that sizing of the electric machines will already have taken regenerative braking into account. A PHEV option in a vehicle otherwise designed to operate as an HEV will not notably increase the amount of regenerative braking, nor will it provide much additional savings for idle reduction, which should already be accomplished in the base HEV.
powertrain. The added benefit of such a PHEV option will be to allow electric cruising.

This will be the lowest cost way to accomplish early PHEV capability. Whether this will prove to be the strategy adopted by manufacturers remains to be seen.

Toyota is already investigating making changes to the full powertrain, not just a simple addition of a pack with a higher amount of energy.

The idea that a full hybrid might be offered with an alternative choice of a NiMH pack for an HEV version, and a Li-ion pack for a PHEV version is not new. In 2005, analysts from Siemens presented such a hypothetical case in a “paper study”[50]. Siemens analysts presented a systems evaluation of various hybrid vehicle types, from micro to mild to full hybrids. Their nominal full hybrids were examined with “hypothetical” NiMH and Li-ion battery packs of about 4 kWh each, in a mid-size vehicle. Each was rated at 40 kW discharge power and 25 kW charge power. The “best case” electric range was estimated at ~ 30 km, or 19 miles. Perhaps 12-15 miles would be more reasonable. Estimated pack weight of the Li-ion pack was 48 kg, the NiMh 85 kg. Pack volume in liters was 30 for the Li-ion vs. 60 for the NiMh. The present volume goal for the U.S. Department of Energy is 40 liters for a PHEV with 16 km of range, with battery pack discharge power output goals of 50 kW for 2 seconds and 45 kW for 10 seconds [51]. The experience with the Hymotion Prius tests, and the kW vs. energy trade-offs in Figure 20 imply that even if these goals are not met, PHEVs with significant capability for reducing petrol use could be produced, should reliability be demonstrated.

Vyas et al have examined the issue of battery cost per unit energy ($/kWh) as a function of W/Wh ratio. The literature implies significant cost advantages of lower ratios [17]. The trade-off curves in Figure 20 and the “on-road” driving investigations in Europe [38, Table 6] imply that the share of petroleum fuel energy replaceable by electricity in urban driving in Europe can be large at somewhat lower power levels than are currently being sought in the U.S. At the present time the state of California has codified a method [52] for defining a PHEV as qualifying for credits under the California Low Emissions Vehicle (CALEV) Standards [53]. This method requires the PHEV to match (or nearly match) the UDDS speed vs. time trace operating all electrically, thereby requiring a peak all electric operations speed of ~ 91 km/h. Aside from California, five Northeastern states in the U.S. have adopted the CALEV standards. This motivates manufacturers and battery design goals to focus on developing PHEVs that will meet this standard, even though 44 states do not require it.

Since there is no existing PHEV standard in Europe, those automakers focusing on the European market are at greater liberty to consider developing PHEVs with more modest battery and motor power levels. The ARTEMIS real world driving experiments concluded that the “urban” driving cycle in Europe should have a top speed less than 60 km/h, consistent with the ECE-15’s 50 km/h maximum. Further, because the ARTEMIS experiments also indicated that motorway driving in Europe often exceeds the 120 km/h top speed of the “Extra-Urban” portion of the NEDC, the futility of trying to attain all electric operations capability on Motorways in the near term is obvious.

Another point that could be made is that the development of a PHEV capable of meeting the ARTEMIS urban cycle’s requirements might result in a PHEV also suitable for many of the megacities of the world. A recent consulting report projected that 17 percent of the world population will live in megacities with 5 million or more population, spending three hours per day in the automobile, while traveling at an average speed of not more than 10 km/hr [54]. To date, few nations outside the U.S. and Continental Europe have adopted emissions and fuel economy tests similar to those of the U.S. China, in particular, has implemented an earlier version of the European tests. This is most likely because the driving patterns in most of the major cities of the world are better represented, at least in terms of average and top speed, by the European cycles than by those of the U.S. It is also possible that the development of such hybrid powertrains would lead to cheaper and more cost effective (in terms of liters of petrol saved per kWh used) PHEVs than developed with California standards in mind. If so, the 44 states in the U.S. that have not adopted CALEV standards might be a good market for such vehicles.

### 8.1 The PHEV as an Urban/Suburban Competitor to the HEV and Diesel

Let us examine the implications of development of a “modest” PHEV designed to allow the European urban driver to operate all electrically, as if it were driven in the U.S. As of the writing of this paper, such a vehicle has not yet been characterized. However, one can speculate on how it would test in the U.S., based on the Hymotion Prius test results. Such a vehicle should exceed the petrol displacement percentages of the Hymotion Prius, since its battery pack and motor would be somewhat more powerful, yet perhaps not powerful enough to match the UDDS speed time trace. Conservatively, let us assume that it has the ability to displace 66% (vs. 63% for the Hymotion Prius) of petrol use per km when driven on the UDDS speed time trace, and 50% (vs. 46% for the Hymotion Prius) when driven...
on the Highway trace. These percentages are relative to a stock Prius. For our purposes they are relative to the stock HEV in the cases we examined in Figure 7. The estimate of fuel saving of such a PHEV powertrain is shown in Figure 22.

Important differences concerning market potential arise from contemplation of this figure. First, note that the savings per hour for the PHEV option are consistently higher on the Highway cycle, despite the lower percent savings per km on the Highway. Assume that the kWh of the pack is set to allow depletion in about 1.2 hrs on the City cycle. This means that depletion would occur at a distance of about 40 km, which is the rated depletion distance of the Hymotion Prius [48]. For the Highway cycle the depletion distance of the Hymotion Prius is ~ 51 km. Since the Highway cycle is 77 km/h, this means that the time to depletion would be about 0.66 hours.

Rapid depletion is a significant advantage in terms of satisfying the market. Vyas et al have emphasized the importance of having the owner of a PHEV consistently drive further than the range of the vehicle [17]. If the customer does this, they get the most value from their investment in the PHEV instead of the HEV. For an expensive piece of capital equipment designed to reduce fuel use, the higher the utilization rate (load factor) the more cost effective the investment. If the customer returns to the garage most evenings with energy remaining in the pack, the customer has bought too large a pack for the purpose. In terms of market coverage more rapid depletion is also better. Consider the case where depletion takes 1.2 hours. Since this is the average number of hours spent in vehicles in the U.S., this means that half of customers could not fully utilize the pack on an average day. Vyas et al pointed out that customers whose daily driving distance is under the range of the pack available from the manufacturer will likely not purchase a PHEV instead of an HEV. Those whose daily driving distance is greater are the one’s who realize net benefits. The conceptual point is illustrated by Figure 23. The decline in benefits after twice the CD Range is due to our estimate that the PHEV in charge sustaining mode is less efficient than the HEV. However, this result has not been obtained in all simulations. The key point is that daily driving should exceed the CD range of the PHEV, and net benefits should be positive (the solid blue line should be

![Figure 22: Fuel savings of a “modest” PHEV, or HEV, or diesel vs. conventional petrol](image-url)
The Hymotion Prius results indicate that the time to depletion should decline as average speed rises. Since the average time in the vehicle in the U.S. does not vary with speed, this means that, for any UDDS range of a PHEV, a larger and larger fraction of customers will benefit as average speed rises (at least up to Highway cycle speeds). Thus, if the HEV benefits are greatest as speed drops, the opposite will be true for the PHEV.

Where does the diesel fit into this picture? For Belgium, Clement-Nyns, Van Reusel, and Driesen assume no change in driving pattern for petrol and diesel vehicles vs. PHEVs, assigning 2010 values of 30 km/day to the petrol fueled vehicle, and 59 km/day to the diesel. Based on the findings here about constant kilometers per day regardless of location in the U.S., these numbers do not necessarily mean that the petrol and diesel vehicles are driven different hours per day. The difference in speeds is comparable to the differences in speeds for the city and highway cycle in the U.S., both thought to be representative values under different circumstances. If inferences can be drawn from the U.S. example this may simply mean that more diesel powertrains will be found in rural areas than in urban areas, with the opposite for petrol vehicles. For the Belgian example’s petrol vehicles, in the event that the PHEV range were ~ 20 km, and the PHEV capable of driving all electrically in urban driving, then the PHEV could save over half of the fuel used by a typical petrol vehicle owner. For the Belgian case diesel owner, if we use the Hymotion Prius test results as a benchmark, it may take a bit more distance to deplete a battery pack of a given kWh capability (but less time). The added distance would be perhaps 30% more, but the km would not be all electric. For the person traveling 59 km/day, at a relatively high speed, the savings represented by purchasing a PHEV with the nominal 20 km range in ARTEMIS urban driving would likely be well under half of the total day’s consumption.

The reality is that the fuel savings potential of the PHEV vs. the conventional petrol vehicle is limited by the kWh of the battery pack, and the number of times per day that the vehicle can be charged. In this case we assume one charge per day. We have seen that once the PHEV depletes the battery pack, present day diesels will save more fuel than the PHEV operating in charge sustaining mode. Thus, for kilometers beyond the PHEV’s range, the diesel will be the fuel savings winner. The more miles driven per day, the better the diesel will look relative to the PHEV. On the other hand, for those whose choice of the diesel vs. petrol

Figure 23: Conceptual match of daily driving distance to PHEV capabilities

above the dotted brown line).
vehicle was difficult because the miles driven per day only barely made the diesel worthwhile, the PHEV may be a better option.

Without working out examples, we assert that the PHEV is a powertrain option that will straddle the boundary between petrol and diesel powertrain choices. In the most congested conditions, the HEV will compete best against the petrol vehicle, so long as the owner drives a lot of hours per day. The PHEV option will be attractive to petrol vehicle owners who travel at a higher average rate of speed than the average petrol vehicle owner. In contrast, it will be most attractive to diesel owners who travel at a lower rate of speed than average diesel owners. In other words, it will fit in the middle of the market between HEVs and diesels.

Unlike Clement-Nyns, Van Reusel, and Driesen [55], who assert that “there is no reason to assume that HEVs will drive fewer or more kilometers compared to conventional vehicles,” we see a very systematic set of reasons that HEVs, PHEVs, and diesels will split the advanced powertrain market in comparison to petrol vehicles. HEVs will be most advantageous in the most congested conditions, realizing the highest fuel savings per hour there. Diesels will be most advantageous to those customers driving long distances per day, far in excess of the range of available PHEVs. PHEVs will fit in the middle of these two markets. We expect this market to be on the outside of the most dense center cities, in residential areas where higher income residents are found, and where the highest percentage of single family detached dwelling units are found. In the U.S. these are called suburbs. In Europe they may simply be areas where newer dwellings have been built, after the advent of the passenger car.

8.2 The Importance of Garages and Carports, Heat and Cold

We would expect that PHEV customers will be more like HEV customers than diesel customers. One would expect the PHEV customer to be far more comfortable with an automobile dealer seen to have expertise in sales and repair of HEVs than of diesels. We have argued that the spatial breakout of HEV customers vs. diesel customers should be spatially distinct, with the HEV found advantageous for use in congested urban conditions, while the diesel will be most advantageous for low density rural customers. The early PHEV market is seen as a spin-off of the HEV market. Customers who first become comfortable with an HEV, or whose neighborhood is occupied by HEVs would be most likely to consider PHEVs. We have essentially argued, for Europe, that the development of an HEV market would have to precede the development of a PHEV market. The early PHEV is seen as a powertrain option to be offered after the HEV has been mastered by a manufacturer.

Having a garage to park a PHEV in is seen as a particular advantage as the market first develops. To enhance the market potential for PHEVs, plans are to make chargers compatible with the existing residential infrastructure. In the U.S. this means 110/120 V 15 to 20 amp chargers compatible with standard residential wiring[56], with chargers using ~ 1 kW rating. Chargers may be designed to be compatible with the standard U.S. residential wiring and standard European wiring, which can operate at ~ 3 kW. However, even if the residential wiring is capable of operating at 3 kW, it may still be desirable to start with ~ 1 kW chargers due to the cost of the charger itself. In 2002, analysts working for the U.S. Electric Power Research Institute “estimated the cost of installing an additional 120V, 20 A circuit and outlet near the electrical panel of a residential or commercial building (or upgrading an existing 15 amp circuit) at $200 and the cost of adding a 240V 40 A circuit at $1000” [57]. The high cost, high rate charger was deemed necessary to fully charge a large SUV PHEV96 overnight. Thus, we can see another advantage to starting PHEVs with modest range in smaller models. The kWh needed to fully charge the vehicles are less, and an inexpensive 1 kW charger will suffice.

The long-run visions for PHEVs have to date assumed all-electric operations capability [56, 57, 58] for 32km and up. Such a result is certainly possible. However, as the Owen and Gordon pathway investigations illustrated, one has to get from here to there. A modest start, with expanding and improving capabilities over time was suggested in that case, and is suggested here as well. Failing to see evidence that this result was soon coming, the California Air Resources Board modified earlier credits for PHEVs with 32 km of range, and set up credits for 16 km [52]. Now, PHEVs seem technically possible, and perhaps economically attractive within several years, if progress on batteries continues. Even so, the blended mode Prius PHEV conversions now make the basis for a case that a different mix of capabilities than sought by CARB (less power, more range) might be the basis for a marketable powertrain option within a few years.

How does this relate to garages and vehicle power? The efforts to introduce EVs in the 1990s involved intensive efforts to develop fast charging capability, because of range limitations of EVs. It was thought that charging times to compete with gasoline vehicles were necessary to success of EVs. Charging power far greater than assumed here was assumed necessary. Based on the
quote above the cost implications had to be significant. We stress that the EV experience is not instructive for PHEVs, since fast refueling via existing gasoline stations is readily available. To make the economics of the PHEV attractive, it needs to take advantage of the fact that the vehicle sits parked overnight near an existing plug. Batteries generally like the same temperatures that human beings do. They perform poorly in very cold and very hot temperatures. These problems can be addressed. However, for early PHEVs they can also be avoided when those vehicles are parked overnight in a garage attached to a house. Exposure to temperature extremes would be reduced.

The typical car owned by a household has the property that it is driven between one and two hours out of 24 per day. Compared to an electric generator, the “load factor” is extremely low. Perhaps half or more of the idle time will be parked at the residence. For the PHEV this means that one can take several hours to fill the battery pack with energy, and deplete the pack considerably more rapidly. Approximately 1 kW is sufficient to charge overnight with the needed kWh for PHEVs with 40 kW or less, designed for 16 to 32 km of range, in smaller vehicles. When running, the peak kW rating of the pack will be used only intermittently, so the average kW output will be much less (see Figure 20). Nevertheless, the fact that the average continuous battery power output capability is far in excess of the intended overnight power input from the charger provides theoretical long run opportunities for faster charging at locations with higher power plugs, should the initially installed charger be capable of ~3 kW rate charging. Should a customer opt for the higher expense of a 240 V, 40 amp capable charger, the customer would have the opportunity in the long run to charge reasonably rapidly during the day, should chargers become available. On the other hand, the economical solution of a charger capable only of 110/120 V, 15 amp would nevertheless have the advantage of readily available residential charging opportunities, at most plugs outside houses. Charging during visits to friends and neighbors would be possible, in addition to overnight charging.

Although far fewer Europeans have garages than do U.S. citizens (20% in France, according to [58]), it is still probably desirable to start the market by targeting those households with garages. These household are likely higher income and better educated occupants than average, both attributes associated so far with interest in HEVs, as well as a greater tendency to purchase new vehicles. While the U.S. does have the benefit of a much higher proportion of residences with garages, it also has wider temperature extremes than most of Europe, making winter and summer outdoor parking more problematic in the U.S.

The decline of performance of batteries in extreme temperatures is yet another reason to start with PHEVs with relatively modest power levels. If the engine has the capability to provide a large fraction of the performance expectations of the consumer, with the battery acting as a relatively modest supplement, then occasional deterioration of battery performance in extreme conditions will be more acceptable, and the fundamental functionality of the vehicle will still exist.

While garages are already common in the United States, the trend in housing construction has been for them to become yet more common. The 2005 American Housing Survey (AHS) provides a summary of housing units that have a garage or carport [59]. The AHS data showed that 76% of the occupied housing units were single family structures and 63% of all occupied housing units had access to a garage or a carport. Newer housing units, built in the last four years, were even more likely to have a garage or a carport. The 2005 AHS showed that 5.5% of the housing units were built in the last four years.

As nearly as possible, we divided the data in the AHS into center city, suburbs and rural areas. Table 8 provides the results. Within the U.S., the majority of dwelling units with garages and with multiple car households are found in the suburbs. Garages and multi vehicle dwelling units are also found in the highest percentage in the suburbs. Combined with our opinion that the type of driving most suitable for PHEVs should take place in the suburbs, this clearly suggests that the target geographical market for early PHEVs within the U.S. be the suburbs.

### 9. EFFECTS OF EMISSIONS CONCERNS

#### 9.1 Air Quality Trends: Implications for Tailpipe Emissions Standards

As has been noted, the U.S. has stricter emissions regulation in place than does Europe, making the expansion of diesel powertrains more difficult there. One issue raised here is whether or not the projections of increased cost and perhaps diminished fuel economy for diesel powertrains, due to tightening emissions control will continue to be problematic for this powertrain. In the U.S., at the present time, seven states have adopted the CALEV standards, which are even tighter than the Federal “Tier II” standards. For those states, at the present time, no diesel powertrains in the less than 3856 kg GVW weight class category are available [60]. As noted, for the remaining states, when sorted by air pollution score, hybrids are best and diesels worst.
This is not to imply that diesels are not now much cleaner than many gasoline vehicles used to be, nor that they cannot be made clean enough to become available in all 50 states. Evidence is that they will. However, the question is how much diesels will cost, what size of vehicles they will be installed in, and will their efficiency gains diminish relative to petrol vehicles, as projected by studies cited here. One issue for Europe is whether or not to expect more tightening of emissions standards. In the U.S., we are slowly succeeding in improving emissions and have a track record that documents it, with records in excess of a decade and a half [61].

For Europe the track record is shorter and is less encouraging to date (Figure 25 and 26). What the record implies is that no progress has been made since 1999. In truth, that is not really the implication. The problem is that emissions controls have to be so strictly monitored that they overcome the effects of economic and population growth. In light of the fact that European regulation has consistently given the diesel easier standards to meet than the petrol vehicle, the emissions standards collectively have to offset the effect of fiscal policy that encourages purchase of the dirtier of the two technologies. The fact that Europe has shown no deterioration since 1999 is actually an accomplishment. Nevertheless, this is unlikely to be considered satisfactory.

Thus, it is probably reasonable to assume that stricter and stricter Euro 5 and Euro 6 emissions control regulations are on the way. Those making such an assumption appear to be betting that the resulting pressures will make the petrol vehicle relatively more attractive, since it remains easier to control petrol emissions than diesel — particularly NOx. Taking one step further, the U.S. experience seems to show that hybridization can also allow further improvement in emissions. Thus, because of existing and anticipated tightening of emissions control regulations, there seems a likelihood of a changing balance in favor of petrol as a fuel and hybrids as a fuel-consumption and emissions reducing powertrain option. European cities and nations may exert the same pressures on the European Union that the block of states adopting CALEV standards puts on U.S. manufacturers, where the diesel has had great difficulty making inroads into

<table>
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<tr>
<th>Housing Unit Type</th>
<th>With garage/carport (millions)</th>
<th>Units with 2 or more vehicles (millions)</th>
<th>Percent units with 2 or more vehicles</th>
<th>Percent units with garage vehicles</th>
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<tr>
<td>Center city</td>
<td>16.7</td>
<td>14.5</td>
<td>52.70%</td>
<td>45.90%</td>
</tr>
<tr>
<td>Suburb</td>
<td>35.4</td>
<td>33.4</td>
<td>70.20%</td>
<td>66.10%</td>
</tr>
<tr>
<td>Rural</td>
<td>16.1</td>
<td>17.6</td>
<td>60.20%</td>
<td>65.80%</td>
</tr>
</tbody>
</table>

Table 8: Garages and vehicles, by dwelling unit location, U.S.
Figure 25: Population weighted annual mean concentration of PM10; Europe [28]

Figure 26: Population weighted yr sum max. 8-hour mean ozone concentrations > threshold [28]
light duty vehicles tested on vehicle dynamometers.

9.2 The HEV to PHEV Path – Reducing Exposure to Air Pollution

To the extent that zero emissions, all electric operations capability is developed by PHEVs, several positive population exposure effects can be expected. First, the need for frequent stops, causing low average speed, is generally because frequent pedestrian crossing at intersections is anticipated. The two flows of traffic – street and sidewalk – must be managed, with intermittent flow for both. For the automobile stream, nonreactive tailpipe pollutants tend to build up to much higher concentrations at intersections than at mid-block locations [62]. Present hybrids cannot “clear” an intersection in normal driving without an engine start. While such starts are very low emissions and in most cases the U.S. full HEV emissions are less than the typical conventional vehicle at an intersection, it is nevertheless true that complete clearance of intersections in all electric operation would be even cleaner. Since sidewalk and vehicle queues build up at intersections, zero emissions at intersections should provide the highest value in terms of human exposure reduction. The next level of benefit would occur when PHEVs can operate all electrically within entire neighborhoods where light pedestrian traffic on sidewalks is the norm.

The next level of benefit is displacement of the location and time of emissions. PHEVs charged overnight will cause powerplant emissions at night rather than in the day. For ozone, this can provide a benefit because chemical reactions in the presence of sunlight are the primary cause of ozone. Morning emissions on a sunny day are generally the most likely to create afternoon peaks in ozone downwind. Thus, the ability of a PHEV to travel in zero emissions mode during the morning should be more valuable than in the afternoon for ozone reduction purposes. Since the plan is for first introduction to be based on overnight charging, this effect is thus promoted. In the estimates of air quality impacts of PHEVs in the U.S. in 2030, the study sponsored by the Electric Power Research Institute and Natural Resources Defense Council estimated that a larger fraction of the U.S. population would experience ozone reductions than would experience particulate matter reductions (the vast majority benefitted in both cases) [63].

In truth, at least in the U.S., light duty motor vehicles tested on dynamometers are already extremely clean. It has been found that over and over again that the amount of electric demand by PHEVs will inevitably be very small [13]. Because of this, even when the Electric Power Research Institute simulated the introduction of a very large fraction of zero tailpipe emissions PHEVs into the U.S. 2030 fleet, simulating air quality impacts, the effects were small. Nevertheless, the effects were consistently positive. The study implies that even if coal is a dominant source of generation, if in the long-run PHEVs can operate all electrically for 32 km per day, then ozone and particulate air quality in nearly all of the U.S. would be improved as a result of the PHEVs [63].

The Knipping and Duvall study of the year 2030 [63] shows that, under current emissions control regulations in the U.S. it is necessary to invest both in cleaner new coal fired power plants, and to retrofit existing coal fired power plants with emissions control devices such as scrubbers and flue gas desulfurization if PHEVs increase electrical demand. Shelby and Mui of the U.S. Environmental Protection Agency [64] got essentially the same result for the generation mix in 2030 – an increase in coal generation, accompanied by construction of new coal power plants. However, this effect was not immediate. In 2015 the change in generation was dominated by an increase in natural gas. Since idle natural gas power plants are much cleaner than idle coal fired power plants, Shelby and Mui project that initial load increases due to PHEVs (~2015) are more likely to be provided by natural gas, until investment plans can be made to develop new clean coal powerplants and retrofit existing coal power plants [64]. The Knipping and Duvall study and the Shelby and Mui study projected increased utilization of existing natural gas power plants, many of which have been built in the last decade.

The two simulations mentioned above did not assume carbon constraints on the U.S. electric industry. For a separate study of a carbon constrained case, the Electric Power Research Institute and Natural Resources Defense Council [65] did predict that advanced combined cycle natural gas plants — a very clean technology with respect to ozone precursors, and approximately neutral vs. a conventional vehicle on total particulates [13] — would be added.

Perhaps the most important observation with respect to air quality is that in the U.S., when a very detailed study was done, it estimated very small improvements in air quality arising from replacement of petrol fueled conventional vehicles with HEVs and PHEVs, even if the dominant electric generating fuel remains coal. In part the study implies that one cannot make strong arguments in the U.S. for or against PHEV technology based on anticipated changes in air quality.

For Europe, at this time, there is very little information
to draw upon. However, we note that the estimates of Gaines et al (who include emissions from the vehicle assembly and disposal/recycling cycle, including the battery) imply that the use of natural gas and wind to generate electricity for PHEVs operating in all electric charge, depleting mode implies significant percentage reductions in total life cycle emissions of the three ozone precursors, volatile organic compounds (VOC), carbon monoxide (CO), and nitrogen oxides (NO\textsubscript{x}). With respect to particulate matter, the present estimates of Gaines et al imply similar emissions of fine particulates (PM\textsubscript{1.0}) and sulfur oxides (SO\textsubscript{x}). These latter two are only two of four of the above set of pollutants that contribute to fine particulates in the atmosphere. Secondary formation of fine particulates also arises from VOC and NO\textsubscript{x} emissions.

In the analysis by Knipping and Duvall, the atmospheric concentration of (and population exposure to) fine particulates in the U.S. in 2030 was reduced by PHEVs that operated all electrically, despite the fact that primary PM\textsubscript{1.0} emissions were projected to increase slightly due to the expanded burning of coal \cite{63}. There were at least two major reasons this result was obtained. First, the level of control of coal power plants was improved significantly, and many new clean coal power plants were built due to U.S. requirements for the electric utility industry to keep total NO\textsubscript{x} and SO\textsubscript{x} under a cap. The second reason that this was true was the reduction of secondary fine particulate formation from VOC and NO\textsubscript{x}.

9.2.1 U.S. LIFE CYCLE ANALYSIS RESULTS (EXPOSURE INDEPENDENT)

Allowing for the fact that PHEVs using electricity generated by natural gas can significantly reduce emissions of NO\textsubscript{x} and VOC, the aggregate implications of the Gaines et al estimates with respect to natural gas are, in total, probably consistent with a reduction of average atmospheric particulate loading and/or a change in the pattern of particulate loading contributing to population exposure (Figure 27). The PHEV case shown in Figure 27, the charge depleting emissions represent the best case for fossil fuels, combined cycle natural gas power. For the HEV and this PHEV substitution for a conventional vehicle, there is a trade-off involved, with SO\textsubscript{x} emissions increasing due to battery manufacture, but the four other pollutants decreasing. In the U.S. it is assumed that future diesel engines will have tailpipe
emissions as clean as petrol engines. Interestingly, the life cycle estimates have the near future CI DI engine using low sulfur diesel fuel refined from oil as consistently slightly cleaner than the petrol vehicle on a life cycle basis. Thus, if the CI DI engine can meet the tight U.S. standards it may be cleaner than the average petrol vehicle. Cost and technical feasibility are the only issues.

For the clean diesel case using low sulfur diesel produced from natural gas via the Fischer-Tropsch process, emissions trade-offs are implied. Total life cycle emissions of CO and VOC decrease, but NOx, SOx and PM2.5 increase.

Table 9 presents numerical results for the reference vehicle, the HEV case and PHEV combined cycle natural gas case from Figure 27, as well as six other methods of producing electricity to meet requirements of charge depleting (CD) operation. Note that the estimates assume all electric operation during charge depletion, which is not necessarily what is anticipated in 2015. The italicized, bold numbers are cases where the results for the PHEV operating in CD mode are worse than the reference vehicle. We can see that coal has an apparent (the word “apparent” is discussed in the next section) problem with respect to PM2.5 life cycle emissions, exhibiting about three times the emissions of the reference vehicle and hybrid.

Knipping and Duvall note that, in the U.S., there are regulatory caps on NOx and SOx emissions from power plants. Accordingly, their position is that there can be no increases in emissions of these pollutants from power plants, because tighter emissions controls and/or cleaner new power plants will have to be implemented. Accordingly, where the coal options increase pathway emissions, we also present a pathway case in which the powerplant emissions of NOx and SOx are set to zero. The results suggest that if the U.S. NOx and SOx caps are to be met, the increases of generation required to meet the needs of PHEVs will have to be met by a combination of tighter emissions controls and choice of non-coal generation technologies such as natural gas and wind. In the event of a carbon control regulation or tax, the mix of power plants would move away from coal. Even so, the estimates shown in Table 9 imply that life cycle primary and secondary PM emissions could increase due to all electric operation. This result is consistent with the estimates of Van Mierlo for the Belgian case, for an electric vehicle [66]. He estimated an increase of PM emissions for an electric vehicle relative to the reference petrol vehicle, but significant reductions for a hybrid.

9.2.2 LOCATION OF EMISSIONS

We underlined “emissions” above and stressed the words “apparent problem” when discussing the potential PM emissions increases for all electric vehicle operation. Measures of emissions are not measures of air quality, and estimates of changes of air quality are not estimates of changes of population exposure to pollution. The population exposure benefits, in terms of estimated damage per kg of emissions, via displacement of particulate emissions from vehicle tailpipes near streets to remote power plants have been made explicit in both Europe [66], and the U.S. [67]. Rural emissions of nonreactive primary PM2.5 and CO have been estimated in Europe to cause one fourth the damage of urban emissions [66]. Findings for the U.S. were similar [67]. The damage costs per kg of reactive pollutants’ rural emissions (VOC, NOx, SOx) are also lower than for urban emissions, but not as significantly so, since the formation processes involved are more likely to cause rural emissions to result in downwind urban concentrations. Based on use of the damage factors selected by Van Mierlo, the damages from pollutants in Table 9 are dominated first by PM2.5. For all cases other than renewables, estimated damages from primary PM2.5 exceed those of SOx by a factor of five or more, while for renewables the factor is under four. The estimated effects for VOC, CO and NOx are far less. Thus, reduction of exposure to primary

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PM appears the most important effect to be sought by substitution of advanced powertrains for existing powertrains.

The estimates shown in Table 9 include one battery replacement, increasing SO\textsubscript{x} emissions for the HEVs and PHEVs relative to a case where no replacement occurs. Thus, R&D to increase cycle life for batteries can contribute to reduced battery emissions effects, as can increased recycling. The estimates are the first made for the Li-ion battery chemistry. While the effects are not large, neither are they small. Thus, further R&D on battery life cycle effects is desirable.

Even though the total PM\textsubscript{2.5} concentrations for the life cycle pathways are comparable, the locations and timing of the emissions are not. For the PHEVs the estimates assume all electric operation, so there is a displacement of emissions from urban to rural areas. Further, atmospheric chemistry at night will differ from that in daylight. The earlier emissions have more time to be deposited on the ground overnight before urban populations are exposed the next day. Concentrations immediately following the generation of the energy will occur at a time when populations are more likely to be indoors, further reducing exposure.

The GREET model has long recognized the importance of the distinction between urban and rural (and upstream) emissions [16]. However, the development of the vehicle cycle portion of GREET is more recent. Thus, Gaines et al did not have confidence in completion of the urban vs. rural breakout at this time. Interpretation of the pathway emissions results shown in Figure 27 and Table 9 must take this shortcoming into consideration.

The European approach explicitly recognizes population exposure as the appropriate criterion (Figures 25 and 26). Urban roadway network level analyses of air pollutant concentrations are being prepared, demonstrating clearly the high concentrations of particulates along roadways, as well as the build-ups at intersections and in urban "canyons" [68, 69]. However, the life cycle analysis methodology apparently does not yet attempt the simple urban vs. rural dichotomy that GREET has explicitly recognized [66].

Another issue is the fact that, considering U.S. regulations, Table 9 assumes diesel powertrains are as clean as petrol powertrains. However, U.S. vehicles are considerably more tightly controlled than in Europe. The U.S. light duty diesel has no exemption in the U.S. to emit higher levels of NO\textsubscript{x} or PM\textsubscript{2.5}. In other words, if the petrol and diesel conventional powertrain vehicles in the Gaines et al analysis had been European, the tailpipe emissions would have been estimated to be considerably higher. This difference shows up distinctly in the recent estimates for Belgium by Van Mierlo. According to his estimates, the particulate emissions of the diesel are more than four times those for the petrol vehicle, under Euro IV standards [66]. The implications are that the introduction of electric drive via petrol fueled PHEVs in lieu of diesels should, on the basis of a per km or per hour of use basis, far more significantly reduce fine particulate formation than in the U.S.

Considering the emissions rates of contemporary vehicles in Switzerland (much higher than future emissions rates should be [68]), Sommers recently estimated annual health costs for light duty passenger vehicles to be 0.83 U.S. cents per kilometer. These costs are not large relative to the costs of fuel. However, neither are they negligible. In light of the low fraction of diesels in Switzerland (Figure 1), the estimate by Van Mierlo that diesels emit more than four times the particulates of petrol vehicles [66], and the World Health Association plot of estimated health effects, by nation [69] the motor vehicle induced air pollution damages per km in the dense urban areas of the more diesel dependent nations is likely considerably greater.

A note of caution is that the PHEVs discussed in this section were assumed to run all electrically when charge depleting. This may be possible in the long-term future, such as 2030. However, our focus here is more on the near term. We believe that the initial PHEVs will operate in blended mode and will not be zero emissions. Yet, they are anticipated to be capable of being very clean among light duty vehicles, particularly so in comparison to diesels in Europe.

In summary, the early evaluations of PHEVs are promising with respect to the long-term ability of the PHEV technology to provide at least small improvements in air quality in the U.S., small to significant improvements in Europe. Nevertheless, at this time, the means of providing improvements and degree of improvements in air quality cannot be asserted to provide a compelling reason to pursue this technology. Rather, it is the absence of evidence of any significant difficulties, in light of the great opportunities for reductions of GHGs and petroleum use that provide motivation for pursuing this technology. In the meantime, research on how to maximize the potential air quality and population exposure benefits with respect to ozone and particulate matter is clearly warranted.
9.3 The HEV to PHEV Path – Reducing Oil Use and GHGs

9.3.1 POTENTIAL OF 23 FUEL TO POWERTRAIN-OPERATION PATHWAYS TO REDUCE OIL USE AND GHGs

Figure 28 presents the Gaines et al [13] life cycle pathway estimates of total energy use, petroleum use, and GHG emissions for the 23 cases that they examined. An important distinction between these estimates and those of Duvall and Knipping [65] is that separate estimates are provided for the energy, oil and GHG emissions of PHEVs during all electric charge depleting mode. In the PHEV cases presented, either CD mode operation or CS mode operation estimates are presented in Figure 28, but not an annual average of the two. In fact, the estimation of the mix of CD and CS mode for PHEVs is an area of significant uncertainty. Thus, these estimates do not presume to predict the annual CD/CS mix that will emerge, since that is itself an area of considerable uncertainty [17]. However, a shortcoming of these values is that, at this point, they present an annual average for conventional powertrains. Accordingly, they do not present comparable driving fuel consumption estimates for conventional powertrains. The average speed for CD mode is less than for CS mode for PHEVs. For conventional powertrains a single estimate is presented where the average speed is intermediate between CD and CS mode. Future estimates should isolate the fuel consumption of the conventional powertrains under comparable driving conditions for patterns of driving associated between CD and CS mode. It is anticipated that this correction will improve the estimates of the relative benefits of PHEV CD mode operation relative to conventional powertrain operation, but not relative to HEV operation. The hybrid technology characterized is the split hybrid in a Prius type vehicle body with improvements in aerodynamic drag and tire rolling resistance. The CD range of the simulated PHEVs is 32 km.

The values in Figure 28 are ordered from lowest GHG case at the top to highest GHG case at the bottom. One can see that energy use fluctuates considerably, in a very different way from GHGs. The lowest GHG case among fossil fuel pathways is a plug-in hybrid (PHEV) in charge depleting (CD) operation using electricity generated via a natural gas fueled combined cycle power
plant (NGCC). Among renewables the lowest GHG case is wind electric power for a PHEV in CD mode. In general, the use of an alternative fuel — coal, natural gas, wood, wind — reduces petroleum use dramatically. Among these options, wood uses the most oil. Wood represents the least concentrated energy among the four alternatives to petroleum. Thus collection and transport of the wood uses petroleum fueled trucks. Wood has been estimated by Doornbosch and Steenblik [68] to have production costs from two to five times the recent range of petrol prices. However, these biomass critics cite a 2007 study by Zah et al estimating that the total environmental impact of wood biomass ethanol is less than petrol and diesel, and considerably better than many less expensive biomass sources for ethanol fuel (rye, potatoes, corn, sugar cane, sugar beets, sorghum). Thus, according to this source, wood is an expensive, relatively environmentally benign source of ethanol fuel, with very significant GHG benefits.

It can be deduced from inspection of Figure 28 that the combination of a flex fuel (FFV) plug in hybrid (PHEV) running on E85 in charge sustaining mode, combined with wind or solar power in charge depleting (CD) mode is estimated to be superior, as of 2015, to a gaseous hydrogen (GH2) fuel cell vehicle (FCV) using electrolysis to produce hydrogen from wind or solar. On the other hand, the GH2 FCV wind/solar electrolysis path is superior in GHGs to any fossil fuel alternative.

Figure 28 shows that there are many ways for the combination of PHEVs and electric generation pathways to reduce GHG emissions during CD mode operation. Figure 29 shows a prediction that the cleaner options that would reduce GHGs are quite probable in the event of carbon policy. Most important is the prediction of reduced coal generation under such a policy. Studies of the magnitude of electricity demand increase possible with early market PHEVs suggest that PHEVs will not by themselves have much influence on the future mix of generation in the U.S. The future mix of generation in the U.S. in the 2015 time frame will be determined by a much broader policy perspective than the potential effect of PHEVs. Theoretically, in the long-term, the effects of PHEVs might be relatively significant, and have a significant effect on the mix of generators. But this would be true only after a very great market success by PHEVs, which simply cannot occur in the near term. Consequently, our perspective is that the technology represents great potential to reduce GHGs in the U.S., should the U.S. choose to alter its mix of generation capacity in order to reduce GHGs.

9.3.2 AVERAGE VS. INCREMENTAL GENERATION

One method of estimating the GHG effects of PHEVs in CD mode is to take the average mix of generation in a given nation or region. This has been the historical method of evaluating electric vehicles in the U.S. in

![Installed Capacity Chart](image-url)
the GREET model. In the 1990s, studies of EVs used this perspective. The greatest enthusiasm for electric vehicles was in regions with very little coal generation, California, and the Northeastern U.S. However, national studies in the late 1990s brought up the issue of increases of particulates and sulfur oxides emissions [72, 73]. At the time, the share of coal in U.S. generation was increasing slightly, natural gas decreasing slightly, so it also appeared that electric vehicles would mean more coal fired power. However, since that time, coal's share of U.S. generation has dropped, and natural gas share has risen steadily (Figure 30). The share of natural gas in U.S. generation since 1996 has risen by 7.2%. To give an idea how large this change is relative to the potential demand by PHEVs, note that Short and Denholm, projecting 50% market penetration of PHEV60s for the total light duty fleet in 2050, estimated that the increase in generation caused by these PHEVs was 7.3%. Kintner-Meyer, Schneider and Pratt found that the current underutilized overnight generation capacity in the U.S. as a whole was dominated by natural gas generating units [74]. Hadley for one generating region in the U.S. found that either coal or combined cycle natural gas could dominate, depending upon charge rate and time of initiation of charge [75]. Thus, it appears that the U.S. as a whole could easily set policy and/or adopt technical strategies to make combined cycle natural gas powerplants the dominant source of generation for early market PHEVs. Combined cycle natural gas power plants in the U.S. operate at a 38% capacity factor [76]. Planned capacity in the U.S. continues to be predominantly natural gas, though expansion of coal's share in out years is evident. Admittedly, if natural gas is the source of power, the fuel operations cost for the utility will be considerably higher [76], and the inclination to provide low off-peak rates would be diminished. Further, natural gas would be imported, while coal is domestically produced.

Relative to a conventional petrol powertrain, a mix of 20% or more combined cycle natural gas, with inefficient existing coal, would be “carbon neutral” or better. To outdo the simulated full HEV, about 75% or more of generation would have to be combined cycle natural gas. As we have emphasized, the best market niche for PHEVs is likely to be different than for HEVs. This is an argument for comparison to the conventional petrol powertrain. In any case, in the United States, the GHG effect of PHEVs could be either negative or positive, depending on evolution of public policy during the time the technology develops.

For Europe as a whole, the odds in favor of reduction of GHGs by use of PHEVs are far better than in the...
U.S. (Figure 31). Coal constitutes only 20% of the EU generation mix, and is more rapidly declining than in the U.S. The share of natural gas generation has been rising more rapidly than in the U.S., and wind is also growing rapidly in Europe. Goal for rapid expansion of renewable energy generation have been set [28].

Among European nations participating in this study, only the Netherlands has a coal generation share in excess of the European average (Figure 32). For the other four nations the share of coal generation is less than 10%. The share of natural gas generation among the participating nations is highly variable (Figure 33). Natural gas generation share is higher in all nations than in the mid 1990s. Wind power is also increasing in all participating nations, sharply in the Netherlands and Belgium (Figure 34). The U.S. Energy Information Agency reports expansion of share of non-hydro renewables (presumably incorporating wind) is also expanding rapidly (Figure 35) in Europe, but is stagnant in the U.S., and growing slowly in Canada.

Although nuclear power was not included in Gaines et al, due to the fact that its capacity factor is highest of all generators in the U.S. and it is shrinking in share in the U.S., if Gaines et al had included nuclear it would have had nearly zero GHG emissions and oil use. In at least two European nations — France and Switzerland — nuclear power has been increasing share for over a decade (Figure 36, 37). If these nations claimed that PHEVs would be fueled in significant part by nuclear generated electricity, they would have a credible argument. Canada and Sweden have resumed expansion of nuclear generation, but still have a lower nuclear share than in 1994. Otherwise, in North America and the EU as a whole, nuclear power has relatively consistently lost share over the last dozen years, and should not be anticipated to be the source of power for early market PHEVs. Hydro power (clean) shares are generally stagnant or shrinking (Figure 38).

In the aggregate, and in detail for the nations participating in this study, it appears that PHEVs operating in CD mode in Europe would be considerably cleaner than conventional vehicles, and probably cleaner than HEVs, in terms of GHG emissions. Expanding use of natural gas, wind, and other renewables is a common feature of the participating European nations in this study. With the exception of the Netherlands, coal is also used less than on average in Europe by participating nations, and its share is...
Figure 32: Share of European Union coal electric generation [28]

Figure 33: Share of European Union natural gas electric generation [28]
Figure 34: Share of European wind electric generation [28]

Figure 35: Share of non-hydro renewables in electric generation [40]
Figure 36: Share of nuclear in electric generation [40]

Figure 37: Change in share of nuclear generation by time period, nations with nuclear [40]
shrinking. Primarily due to extensive, expanding use of nuclear power, France has the cleanest mix of power among all participating nations. PHEVs in France would unquestionably reduce GHGs, perhaps very significantly, dependent mostly on the capability of the PHEV and its pattern of use.

10. OBSERVATIONS/INFERENCES

10.1 Power vs. Energy Batteries (HEV vs. PHEV vs. EV Batteries)

As the kWh rating is increased relative to kW, as done to increase PHEV range when holding electric acceleration capability constant, the cost per kWh drops and both the volumetric and gravimetric energy density increase. Put another way, the $/kWh costs of power batteries for HEVs are far higher than needed for PHEVs. These changes make PHEVs much more feasible than implied by estimates simply extrapolating characteristics of existing HEV power batteries.

It has been demonstrated in converted Prius passenger cars that batteries with power to energy ratios suitable for EVs (i.e. energy batteries) can be used to achieve reductions in fuel consumption of 45-65%, with the reductions increasing as the degree of congestion (number of stops per km and time stopped per km) increases. Such PHEVs are said to operate in “blended mode,” where the engine frequently assists the battery during acceleration and high speed cruising.

10.2 Battery Chemistry and Energy Density

Li-ion batteries have demonstrated considerably higher volumetric and gravimetric energy density than NiMH batteries. Accordingly, in existing and soon to be introduced full HEVs, replacement of NiMH battery packs with Li-ion packs of approximately the same volume, but higher energy content, is a relatively inexpensive way to introduce the first wave of “modest” capability PHEVs.

10.3 Appropriate Range and Residential Placement for Early PHEVs

Cost estimates by Kromer and Heywood (for a PHEV16) and Vyas et al (for a PHEV32) imply that, at European petrol and residential electricity prices, a PHEV with ~ 16-32 km of charge depleting range could be economically attractive to consumers with garages or carports with electric service, within a few years,
should U.S. Department of Energy goals for battery development be met.

10.4 PHEVs Are Less Cost Effective than HEVs

Cost estimates by Kromer and Heywood imply that, at present U.S. petrol and electricity prices, the PHEVs would not be marketable on the basis of value of fuel savings alone. In Europe the frequent lower taxation of diesel fuel will make it more difficult for HEVs and PHEVs to compete with the diesel powertrain. On the other hand, the generally high road fuel taxes in Europe provide more incentive for future consumer interest in PHEVs than do road fuel taxes in the U.S.

10.5 Diesels’ Cost Effectiveness Will Drop Due to Tightening Emissions Controls

Recent studies that consider the effects of tightening emissions controls on the cost and efficiency of the diesel powertrain suggest a significant shift in the relative merits of the diesel vs. petrol powertrain, in favor of the latter, in 2009 (Smokers et al) in Europe and in the future in the U.S. (Kromer and Heywood).

10.6 Hybridization of Petrol Powertrains is More Desirable than Diesel Hybridization

Estimates of the effectiveness of various steps of hybridization (Smokers et al) indicates that hybridization of petrol-fueled powertrains is more cost effective than diesel-fueled powertrains.

10.7 Today’s Coal Generation Causes PHEVs Using Coal Electricity to Emit More GHGs than Conventional Vehicles

Total life cycle analysis indicates that the greenhouse gas risk in implementing PHEVs involves cases where coal is the primary fuel used for generation.

10.8 Early PHEVs Should Generally Reduce GHGs, Sometimes Sharply

In both the U.S. and Europe over the last decade there has been a significant increase in the amount of generation of electricity by natural gas, a very positive trend for full fuel cycle GHGs if the recently constructed combined cycle natural gas power plants are used to generate electricity for PHEVs. The dominant technology of the last decade for new capacity has been the combined cycle power plants, which are highly efficient, intermediate load plants. “Intermediate load” means that the combined cycle plants cycle increase in power during the day and are throttled back or shut down at night. This means that these plants, in particular, are available to charge the first PHEVs on the market, when those PHEVs are charged in the evening and overnight.

10.9 U.S. Electric Generation Could Either Improve or Worsen Air Quality with PHEVs, but Any Effects Would Be Very Slight

Planned capacity in the U.S. continues to be predominantly natural gas. Studies attempting to examine a plausible number of PHEVs introduced into the marketplace consistently conclude that there is far, far more overnight generation capacity than would be required over the next couple of decades. In the U.S., during the time that PHEVs are developed, public policy focusing far more widely than on PHEVs will determine the marginal source of electric generation (next units to be built, next existing units to be turned on). If public policy so dictates, natural gas from combined cycle power plants could easily (from a capacity to provide services basis) be the primary generator for PHEVs. The combined cycle natural gas pathway was estimated to lead to reductions of about 40% relative to a diesel powertrain, and about 45% relative to a conventional petrol powertrain. Relative to a conventional petrol powertrain, a mix of 20% or more combined cycle natural gas, with inefficient existing coal, would be “carbon neutral” or better. To outdo the simulated full HEV, about 75% or more of generation would have to be combined cycle natural gas. In the United States, the GHG effect of PHEVs could be either negative or positive, depending on evolution of public policy during the time the technology develops.

10.10 In Europe, if Petrol Fueled HEVs and PHEVs Replace Conventional Petrol, Significant GHG Benefits Should Result

The current mix of average coal generation in Europe is 20% hard coal, and this share is shrinking. Every other method of generation is cleaner than coal, most by significant margins. In Europe, with strong trends away from coal and oil generation, and towards natural gas and wind, the effect of PHEVs on GHG emissions would be very positive. Nuclear and hydro are very clean, and have significant shares of the European market, but those shares are shrinking. Present public policy in Europe sets targets for sharply expanded renewable generation, reinforcing the positive trends toward natural gas and wind in the past decade. It seems very likely that PHEVs would have a strong positive effect on GHGs in Europe.
10.11 In Europe, if Petrol Fueled HEVs and PHEVs Replace Diesel, Significant Particulate Emissions Benefits Could Result

10.12 FCVs and PHEV CD Mode Operation Are both Clean, but PHEV CD Mode Will Squeeze a Lot More Miles from Feedstocks Converted to Electricity

Once any feedstock has been converted to electricity, use of that electricity will result in more than double the kilometers of service, if used in a PHEV in CD mode rather than in a FCV. Thus, for any low GHG source of electricity – wind, solar, nuclear, hydro, geothermal, biomass – it will be considerably better to pursue development of PHEVs to use that electricity than FCVs. Although this observation appears to make the FCV far less logical, one must remember that the PHEV can only operate in CD mode for a limited number of kilometers. Once the CD mode has been exceeded, comparisons must be done on a different basis. This is an area where future investigation is desirable.

10.13 Consequences of Choices – Fossil Fuels Will Get Worse in Quality, Are Dirtier if Liquefied than if Electrified

10.13.1 NEXT GENERATION COAL ELECTRIC VS. NEXT GENERATION PETROL – U.S.

It was pointed out that the use of existing U.S. coal boilers to generate electricity for PHEV operation in CD mode was estimated to increase GHGs compared to continuing to use petrol in a conventional powertrain (much less a HEV). However, consider the future. The U.S. obtains a higher and higher fraction of its petrol from oil sands in Canada. Construction of a new coal boiler in the U.S., then serving a PHEV, was estimated to generate 258 g/km of GHGs, essentially the same as a conventional petrol fueled powertrain. Oil sands to serve the conventional petrol vehicle were estimated to create 283 to 290 g/km, depending on method of mining. The market arguments in this paper essentially amount to an argument that the PHEV would likely compete in a different market window from either the HEV (short daily distances at low average speed, but a lot of time per day), or the diesel (long daily distances at high average speed). In effect, the argument was that the proper comparison is the one we have done here, conventional petrol vs. PHEV, in the market in between that for the HEV and diesel. Research does exist to make the coal to electric pathway much more efficient, using combined cycle technology with coal gasification (218 g/km). However, it is also true that research to improve the petrol powertrain can offset the increases in GHGs caused by greater dependence on oil sands.

10.13.2 NEXT GENERATION COAL ELECTRIC VS. NEXT GENERATION DIESEL – U.S.

The short term switch to low sulfur diesel and diesel powertrains is estimated to allow a reduction of GHGs of about 8%. What happens once oil supplies diminish? One technology that is already successful is the production of Fischer-Tropsch diesel (FTD) from natural gas. This pathway is roughly equivalent to the reference petrol pathway (261 g/km). So long as natural gas is the feedstock for FTD, there is no strong GHG related reason to avoid a switch to the diesel, especially for the market for which it is best suited. A concern for the U.S., however, is increasing imports not only of oil, but also natural gas. Suppose the U.S. and IEA goal were to use at least some coal for transport for its energy security benefits. Then if one considers converting coal to a form of fuel for the diesel (CTL/FTD) vs. the PHEV (electricity), the PHEV wins hands down. Consider a hypothetical diesel using Fischer-Tropsch technology to produce diesel fuel from coal (coal-to-liquids – CTL). Compare this to generation of electricity using a new boiler for a PHEV. The latter vs. the former reduces coal use per km by 50% and GHGs by almost as much. If successful, advanced IGCC technology could improve the coal-to-electricity result in the future.

10.14 Designing HEVs (then PHEVs) for Efficiency or Performance

The Chevrolet VOLT approach notwithstanding, the majority of early PHEVs will likely be adaptations of parallel HEVs, especially if oil prices rise. HEVs have yet to be implemented in a significant way in Europe. With respect to PHEVs this may be an advantage. New HEV powertrain types remain to be tested in both the U.S. and European markets. If the early PHEVs will be adaptations of HEVs, it follows that success of HEVs is imperative if PHEVs are to succeed as a “spin-off” powertrain technology. As HEVs are developed, it is suggested that automakers consider the possibility of creating a PHEV capability during the life of the HEV powertrain, taking the PHEV alternative into account in HEV electric machine and component design.

The PHEV is a technology that is very promising but is also very expensive. If oil supplies do fall short of demand, and prices rise, then the PHEV could become the next best option for many customers. Auto manufacturers should track consumer behavior with respect to HEVs as oil and petrol prices rise. Recent market share shifts for HEV powertrains suggest that implementing HEVs in the most powerful engine may be very risky if competitors choose to implement HEVs tied to less powerful, smaller engines. If early PHEV purchasers have the same preference for fundamental
efficiency that U.S. HEV purchasers appear to be demonstrating, then developing PHEVs which use smaller engines may be the best strategy. This strategy will also benefit from extra engine compartment volume for electric machines and components, when the base vehicle has been designed to also accept larger engines than to be used for the PHEV.

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APPENDIX

Acronyms and Terminology

According to the given text, the following acronyms and terms are used:

- **NG kWh** = electricity production from natural gas combined cycle power plants
- **Renew. kWh** = renewable power delineating either wind, solar, or hydro power

Figure 28 (additional to Figure 4):

- **FTL** = coal to liquids
- **FTD** = Fischer-Tropsch diesel
- **ICE** = internal combustion engine
- **CD** = charge depleting (not conventional drivetrain in this figure)
- **CG** = conventional gasoline/petrol
- **IGCC** = integrated gasifier combined cycle power plant
- **NiMH** = nickel metal hydride

**UDDS** = urban dynamometer driving schedule (used in U.S. new vehicle certification tests)

**FTP** = by FTP here we mean the federal test procedure used to measure emissions, from which an estimate of “city” fuel economy is also constructed. The FTP involves running a complete UDDS, waiting ten minutes, then running the first 505 seconds of the UDDS again. The running time for the UDDS is 1372 seconds. The running time for the FTP is 1877 seconds (ignoring the ten minutes between bag 2 and bag 3). The average weighted speed of the FTP is 34 km/h, while the average speed for the UDDS is 31 km/h (see Plotkin et al, 2001).

**HWY** = Highway driving cycle, lasting 765 seconds, constituting 16.3 km, and 77.1 km/h.

**CV** = conventional vehicle

**HEV** = hybrid electric vehicle

**PHEV** = plug-in hybrid electric vehicle

**SOC** = state of charge, in percent. Though batteries are typically rated as if they can be completely discharged to 0% SOC, in practice in EVs and PHEVs the battery is discharged to between 30% and 20% SOC.

**Charge sustaining (CS)** – the state of charge of the battery pack fluctuates in a narrow range, around an average value. HEVs always operate CS, between approximately 50% and 70% SOC.

**Charge depleting (CD)** – used to convert electric charging of the battery pack into vehicle motion. The battery’s energy (kWh) is used to run the motor to drive the wheels, and the battery pack is discharged. From the point of charging PHEVs would typically depart in CD operation until depleting the battery, then operate in CS mode. A difference between CS mode in an HEV and PHEV is that the average SOC “window” is much lower for the PHEV. This may have detrimental effects on battery life.

**Blended mode** = a CD operations strategy in which the engine is run intermittently to provide added power when the battery is not able to provide enough power.
for PHEV movement.

\[ \text{CDB} = \text{Charge depleting in blended mode} \]

\[ \text{Electric mode} = \text{a CD operations strategy in which only} \]

\[ \text{the battery provides power and energy to move the} \]

\[ \text{PHEV.} \]

\[ \text{CDE} = \text{Charge depleting in electric mode} \]

\[ \text{EV} = \text{electric vehicle} \]

\[ \text{PHEVXX} = \text{where “XX” is filled in by a number of kilometers} \]

\[ \text{all electric range nominally obtainable on a certification test.} \]

\[ \text{California has specified a test for certification of all} \]

\[ \text{electric range capability which requires that the vehicle be able to} \]

\[ \text{operate all electrically while meeting the speed and acceleration} \]

\[ \text{requirements of the UDDS. This is not an official} \]

\[ \text{terminology, but has become common practice in the} \]

\[ \text{U.S. “XX” defines the distance that can be traveled} \]

\[ \text{when a battery is discharged from full to a selected} \]

\[ \text{SOC. Simulations for this research assume 30%.} \]

\[ \text{This research investigated by simulation PHEV16, PHEV32} \]

\[ \text{and PHEV64 vehicles. The electric range requirement} \]

\[ \text{is based on the ability to run the UDDS.} \]

\[ \text{PHEVXXB} = \text{for a PHEV not capable of running the} \]

\[ \text{UDDS all electrically, blended mode is used. Such} \]

\[ \text{vehicles will be identified with a “B”.} \]

\[ \text{The “XX” will refer to the distance traveled during CD operation,} \]

\[ \text{during UDDS tests.} \]

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