How to Use Life Cycle Analysis Comparisons of PHEVs to Competing Powertrains

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AABC Panel Sessions

SESSION 1 – Wednesday May 14, PM
Market Development of HEVs and their Batteries
Hybrid vehicles are increasingly attracting the attention of the general buying public, governments, and the press. While hybrids are migrating to the high-end car market, the debate about the level of hybridization, overall fuel efficiency, and other advantages of these vehicles against the increased cost is intensifying. In this session, automakers and industry observers will discuss market drivers and trends, and new vehicle introduction around the globe.

Chair: Menahem Anderman, *President,* Advanced Automotive Batteries
President of Advanced Automotive Batteries and founder of Total Battery Consulting, Inc. Dr. Anderman has led the development and commercialization of high-power Ni-CD batteries, Li Ion batteries, and ultracapacitors and spent the last eight years conducting assessments of energy-storage technologies for advanced vehicles.

1. **Technical and Market Challenges for Vehicle Electrification**
   John German, Manager, *Environmental and Energy Analysis*, American Honda Motor Co., Ltd.

2. **How to Use Life Cycle Analysis Comparisons of PHEVs to Competing Powertrains.**
   Danilo Santini, *Senior Economist, Section Leader, Center for Transportation Research,* Argonne National Laboratory

3. **Consumer Attitudes towards Advanced Propulsions and Alternative Fuels**
   Scott Miller, *Chief Executive Office,* Synovate Motoresearch, Inc.

4. **Li-Ion Introduction into the Automotive Market, When and How?**
   Menahem Anderman, *President*, Advanced Automotive Batteries

5. **Li-Ion Market Status and the Forecast for Automotive Applications**
   Hideo Takeshita, *Vice President,* Institute of Information Technology

How to Use Life Cycle Analysis Comparisons of PHEVs to Competing Powertrains

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Abstract

Life cycle analysis (LCA) techniques for evaluating the merits of advanced vehicle powertrains have been derived from the physical and engineering sciences. These techniques are contrasted to the economic project evaluation technique called cost-benefit (C-B) analysis. This paper examines the implications that C-B organizational principles could have on methods for designing future variations of LCA techniques to use for comparing hybridized powertrains to evolving conventional vehicle (CV; i.e., gasoline-fueled vehicle) powertrains. It recommends that future evaluations focus on the best market niche for various hybrid-based technologies rather than the average market for evolving CV technologies. Emerging powertrain options are numerous and complex. This paper focuses on three — full hybrid electric vehicles (HEVs), plug-in HEVs (PHEVs), and compression ignition, direct injection (CIDI) distillate-fueled vehicles. It argues that the separate "best niche" reference cases for daily driving behavior for these three powertrains involves a ranking of speed/distance combinations from lowest (HEVs) to higher (PHEVs) to highest (CIDI). Implications of the logic suggest that future LCA methods for evaluating these and other advanced powertrain alternatives be modified. Evidence is presented to support the argument that HEVs and PHEVs are, in economic terms, primarily complementary (mutually beneficial and positively reinforcing) rather than competitive with one another. For those using results from past evaluations, this conclusion implies that the proper LCA comparisons of HEVs and PHEVs should be to CVs and CIDIs and not to each other.

Given this context, we examine and discuss recent preliminary total energy cycle evaluations of charge-depleting (CD) operations of PHEVs made by using the GREET (Greenhouse Gas, Regulated Emissions and Energy Use in Transportation) model. These evaluations, which preceded the development of the logic here, did not precisely follow the recommendations of this paper. They did isolate the effect of CD operation of a PHEV, taking into account anticipated average speed during CD. However, they compared these results to simulated operation at the average (higher) speed operation of competing technologies rather than at the same speed as during PHEV CD operation.

Introduction

The umbrella term "plug-in hybrid electric vehicles" (PHEVs) covers a wide range of technological alternatives for powertrain development, involving many technological and economic choices and allowing varying degrees of substitution of electricity from the grid for refined products from conventional and unconventional petroleum. Alternative choices involve (1) battery chemistry (NiMH versus Li-ion), (2) level of capability to run all electrically (related to W/Wh capabilities of battery packs), (3) type of baseline hybrid powertrain (series, split parallel, pre-transmission parallel, dual-mode parallel, other), (4) type of vehicle model in which to implement the PHEV powertrain (sedan, crossover sport-utility vehicle [SUV], traditional SUV, pickup truck), and (5) fuel for the PHEV's on-board power unit (gasoline, diesel, ethanol, hydrogen).

The LCA method of comparing technologies is devoid of economic content. It is a method designed by engineers and scientists that is based on value systems with accounting procedures that have essentially no tie to economic methods of evaluation, such as cost benefit (C-B) analysis (Mishan 1976). For example, one variant of the LCA method is total energy cycle (TEC) analysis. In this method, as in the discipline of thermodynamics (Eastop and McConkey 1978; Burghardt 1982), the values assigned to units of "useful" energy are constant, regardless of the source or (generally) quality. In the construction of the Argonne National Laboratory GREET model (Brinkman et al. 2005; Burnham et al. 2006), principles of LCA were used to allow enlightened comparisons of advanced powertrains. We chose initially to construct a "full fuel cycle" variant, spun off of and inspired by LCA methods.

GREET has been sponsored by the U.S. Department of Energy (DOE) Office of Vehicle Technologies and its predecessors. It also benefitted from projects supported by General Motors (Brinkman et al. 2005). The interest of the primary sponsors of GREET was to be able to compare, on a consistent basis, numerous advanced technology powertrains, many of which are designed to use fuel derived from feedstocks other than petroleum. Accordingly, GREET was designed to separately report results for pathways that used different fuels, a key feature of the model. Though the model does not place any dollar values on the different fuels, as is done in economic evaluation such as C-B analysis, it does at least provide the distinction for those who might wish to apply C-B analysis in evaluating alternative vehicle technologies. For such practitioners, the differences in the costs of the fuels to be used by the powertrains being compared can be a critical determinant when they estimate net benefits to choose the "best" alternative.

Some simplifying assumptions were made in the initial versions of GREET, since prior research and development (R&D) had indicated the net effects would not be large. One exception was the simplifying assumption in the full fuel cycle version of GREET that the vehicle cycle could be neglected. The vehicle cycle includes raw materials extraction, processing, fabrication, assembly and disassembly, recycling, and disposal of the vehicle and its powertrain. Among simplifying deletions of detail, this one was the most desirable to add. Accordingly, the vehicle cycle has since been added to a recent version (Burnham et al. 2006). This latest version is the basis for the results presented and discussed in this paper.

Another important decision made when developing GREET was to use estimates of “on-road” fuel consumption of the compared alternatives, rather than the official corporate average fuel economy (CAFE) regulatory test certification values. This choice makes the output a step closer to the needs of C-B analysts, because good practitioners attempt to construct the best estimate of costs to the consumer. The importance of accurate on-road fuel consumption information caused those who publish fuel economy ratings (DOE and U.S. Environmental Protection Agency [EPA]) to twice modify and improve the estimates of fuel economy placed on new vehicle window stickers. The most recent of these changes was implemented last year (Jan.; EPA 2006). The changes involved an expanded, more costly set of tests, using four driving cycles (but five tests, one involving cold temperatures) instead of the two cycles and tests used for official CAFE certification, which remain unchanged. Effects of air conditioning in hot weather and operation in cold weather were incorporated in consumer information for the first time.

Still another important decision in GREET is to treat each powertrain as a universal competitor against each other powertrain, with the same annual miles of travel and the same mix of urban and highway driving. This default assumption needs reevaluation, as argued here, since the comparative advantage of emerging powertrains will involve a jumble of different niche markets, each with distinctly different driving patterns, rather than competition among powertrains for customers with the same driving patterns. In fact, it is easy to show that the implicit default GREET assumption of identical urban/highway splits is invalid for existing powertrains, because the contemporary diesel fueled CIDI powertrain is clearly driven many more miles per year than is the contemporary gasoline-fueled powertrain (Clement-Nyns et al. 2007). On the basis of the finding that the average hours per day spent in a vehicle in the United States are nearly invariant with respect to population density, while speed does increase significantly as density decreases (Vyas et al. 2007), if diesel light-duty passenger vehicles (LDVs) travel many more miles a year than do gasoline-fueled LDVs, they must do so at higher average speeds and thus do so more often in rural (low-density) locations or on suburban (less congested) roads.

In our first attempt (Vyas et al. 2007) to address the market niche competition among conventional and advanced gasoline-fueled vehicles (CVs), hybrid electric vehicles (HEVs), PHEVs, and conventional and advanced compression ignition, direct injection (CIDI) diesel-fueled vehicles, we argued that there was a likely logical hierarchy of competitiveness as a function of average speed (and associated average daily distance driven). The ability to best compete with the CV as a function of speed and daily distance driven was argued to go from HEV at lowest average speeds to PHEV at higher speeds to CIDI at the highest speeds. The probability of this hierarchy being valid is examined further here, by taking into account some vehicle simulations of these powertrains that had been done subsequently (Passier et al. 2007). In effect, our perspective was that the “next best” powertrain to compete with the CV was not a single powertrain at all, but a mix of powertrains, each serving a different speed/distance niche.

Grid Electric Mix — GREET has long included pure electric vehicle (EV) pathways. For EVs it was important to decide, for default value purposes, what the mix of generating unit technologies and fuels should be “upstream” of the EV. Because this is a complex question, and because there are very different regional mixes of types of generators and fuels, the choice was not to use a single national value for the generation mix for EVs in GREET. Investigation of EVs in the 1990s raised issues with respect to use of coal-fired power, which was increasing its share of generation at the time (Passier et al. 2007). However, for California and the Northeast, where there was mutual intent to take advantage of the same set of regulations to promote low-emission vehicles (LEVs) and zero-emission vehicles (ZEVs), the electric generation mix included very little coal. Thus, California and the Northeast were separated in GREET to illustrate to users why there might be higher enthusiasm for EVs in these regions.

Average vs. Incremental Choices — For PHEVs, one can use the assumptions used to date; i.e., that one can simply construct an annual average with a linear combination of the estimated amount of ZEV mode (i.e., charge-depleting all electrical [CDE] mode) and charge-sustaining (CS) mode operation, or “HEV mode” operation. This is what is done for the default PHEV recently incorporated into GREET. However, as would have been the case if we had averaged electric generation across the nation for EVs, this simplification risks causing loss of some valuable details useful for the C-B analyst. In particular, to evaluate the merits of installing a PHEV option in an HEV, a C-B analyst might want to know precisely what happens to fuel consumption only during the time the battery is used. In a related analysis (Gaines et al. 2007), we did separate what happens under the assumption that PHEVs were operated all electrically. Unfortunately, the effort was not perfect, because we did not estimate the corresponding behavior of the foregone option (CS mode operation of the PHEV) nor for the operation of competing CV and HEV powertrains for the same pattern of driving. In other words, we did not report the gasoline use as if all competing options had been used at the same driving speed and distance as the PHEV in the CD case.

It would be easier if this was the only problem. The other complicating factor is that many early PHEVs are likely to use “blended” mode charge depletion (CDB), in which the engine comes on intermittently to assist the battery during charge depletion. This complication is more problematic for criteria pollutant emissions (hydrocarbons [HCs], carbon monoxide [CO], nitrogen oxides [NO_x], sulfur oxides [SO_x], and particulate matter [PM]) than for fuel use, greenhouse gases (GHG), and energy. Tests of a recalibrated Hymotion Prius showed promising results with respect to the ability of a PHEV operating in CDB to be cleaner than the average LDV in terms of tailpipe emissions (Passier et al. 2007). Among the results of our first effort to evaluate the TEC emissions of PHEVs via the GREET model, the most robust estimates are for fuel use, GHG, and energy. Accordingly, these will be the only results discussed in this paper.

Another "average" versus incremental choice is made with regard to reference gasoline. A mix of reformulated gasoline and conventional industry average gasoline, refined from crude oil, is used for the reference case. However, the "incremental" source of expanded feedstock for refineries is increasingly from oil sands in Canada. GREET allows a separate evaluation of this "incremental" pathway, which we include here.

Comparison Ground Rules — The C-B expert, working for a new company that wants to introduce a product into the marketplace, had better help that company find the best market niche for the product. If the product has to compete with a well-established competitor that produces many more units of product, the new company will initially want only a small part of the competitor's market. The market leader can lose sight of the fact that the competitor can succeed if it does its evaluations on the basis of the competitor's ability to take away its average customer. In effect, this could be a flaw imbedded in GREET by assumption, since GREET demands that the competitor be evaluated against the standards of the average CV owner, who is not the CV owner who is most likely to be won over by the advanced powertrain.

One fundamental question is: "Compared to what?" Various starting points can lead to different results. In GREET, to date, the CV has to be "beaten" at its own game (speed and daily distance driven). Suppose instead the reference was the CIDI powertrain. If so, the average speed and daily distance driven for the comparisons should, in principle, increase to match those of the reference average CIDI. Alternatively, note that HEV owners are disproportionately represented in major cities (e.g., Los Angeles, Washington, D.C., New York, Boston, San Francisco), where they drive in some of the most congested conditions in the nation. Then if one starts with the HEV's best niche, a relatively slow urban driving cycle should be used to see if the CV can keep the HEV out of this market.

Another fundamental question is "How should one think of the use of a vehicle?" Should the metric be kilometers of daily use or completed trips to necessary destinations? When we examined the U.S. patterns of driving as a function of population density, we found that the average number of trips per day is remarkably constant (Vyas et al. 2007), as are hours of driving per day. Some of the discussion in this paper was prepared on the basis of fuel consumption per day of service provided (at 1.25 hours of operation per day) rather than the present standard input in GREET, which is fuel consumed per mile of service.

The results are thought-provoking. For example, does the existence of the hybrid powertrain make moving to more dense urban locations more desirable? Since HEVs represent the lowest-emitting powertrains in the marketplace, the first places to use such vehicles to improve air quality should be the areas with the highest volume of LDV emissions per unit of volume of air, which are dense urban environments, where many tailpipes emit per unit of surface area. This use of the HEV will make the dense urban area cleaner in terms of criteria pollutants than it otherwise would be, making it more attractive to live in. An increase of urbanization, with more congestion, will reduce daily fuel consumption and GHGs if the LDVs used are HEVs. A look at the numbers per day (or hour) of use helps this relationship emerge more clearly. We ask, "Should a new version of GREET be constructed on the basis of anticipated emissions per day of usual operation, in order to get users to perceive relationships differently?" With regard to perception, the present use of miles per gallon (mpg) as the fuel use rating basis results in the risk of causing CV and CIDI consumers to perceive that urban driving is less economically efficient than highway driving, because the mpg is lower. However, according to estimates presented later, less fuel is consumed for an average day of U.S. urban driving than for an average day of U.S. highway driving. Is the ultimate measure of effectiveness of transport the number of trips needed to accomplish household tasks? Is the proper measure the fuel use needed to accomplish these trips?

Another measure is time to accomplish the day's needs. On this measure, there is a mild "U" shape as U.S. population density moves from lowest to highest density (Vyas et al. 2007). If time is the most valuable resource, this would suggest that, by a slight margin, an intermediate level of population density is best. This low point for time spent in the vehicle may be the best part of the market for PHEVs. At the lowest points, time per day was estimated to be about 1.2 hours per day, in detached single-family units rather than multi-family units, at speeds of 44–47 km/h and implied daily distances of 52–57 km. Such values include all vehicles in the household. Generally, newer vehicles are driven further per day than older vehicles, so these values probably understate speed and distance a bit with respect to new vehicle markets. As argued here, the best PHEV market is neither at the slow end or the fast end of daily driving in the United States.

Path Dependence — Some colleagues who worked diligently in the 1990s to make the EV a success seem happy (although sometimes grudgingly) to support the PHEV because it is the logical path to the EV. Their belief is that the ultimate universal vehicle of the 21st century is the EV. Another group that has been disappointed with progress on fuel cell vehicles (FCVs) is now beginning to consider the possibility of the gasoline-fueled PHEV as a first step in a path toward eventual success of fuel cells as on-board electric generators. A path advocated by yet another group of colleagues is the expanded use of the CIDI powertrain.

As recently as 2002, Owen and Gordon advocated a switch from CV to CIDI HEV technology (but not PHEVs) along a pathway to eventual use of hydrogen FCVs. In 2000, staff at MIT did not include PHEVs as an option (Weiss et al. 2000), estimating the CIDI HEV using petroleum distillate to be the lowest energy user and second best in GHG emissions, just behind the compressed natural gas (CNG) hybrid. A few years later, as is shown, the PHEV was included, and the diesel HEV and CNG HEV were deleted (Kromer and Heywood 2007). The perspective on CIDI technology appears to have changed over the last few years. CIDI technology is now anticipated to be penalized by the need for it to match CV and HEV technologies in criteria pollutant emissions, while the CV is anticipated to borrow advances from the CIDI (turbocharging and direct injection) and to adopt advanced combustion techniques at low engine load to increase the efficiency of gasoline combustion nearly to the level of future CIDI engines (Smokers et al. 2006; Osborn 2007; Birch 2007). Now that nations worldwide are demanding sulfur reductions to clean up petroleum-based fuels, distillate prices have been increasing relative to gasoline prices (Passier et al. 2007).

Thus, suggestions that further expansion of the petroleum-distillate-fueled CIDI engine be pursued as a long-term pathway are diminishing. The CIDI pathway is regarded here as problematic because of its long-term implications. In the short run, the adoption of CIDI might reduce energy use and GHGs by several percentage points. However, in the long run, if such engines represented a large part of an existing fleet, and if petroleum supplies peaked, continued growth of LDV services via use of this technology would require switching to liquid fuels processed from coal and natural gas. Such a switch would be very detrimental with respect to full fuel cycle emissions and rates of depletion of coal and natural gas, if compared to a foregone path that would have involved use of the same feedstocks to generate electricity for PHEVs instead.

For the PHEV path, one can imagine a long-term continuation of the evolution of battery chemistries and assembly techniques such that volumetric and gravimetric energy densities would increase, and costs per kWh would decrease. Recent significant improvements in Li-ion battery chemistry led to the discovery that low-power Li-ion packs in PHEVs with CDB are now technically possible at costs that could create a niche market by the time the needed refinements are made. Once the progress of Li-ion technology became apparent, two analysts (Deiml and Knorr 2005) suggested that the more-energy-dense, Li-ion option could be made available in the same vehicle platform, as an alternative to the NiMH pack used for a "full" HEV, thereby converting the vehicle to a PHEV and giving it the ability to operate electrically (the optimistic prediction being a CDE capability of as much as 30 km). A long-term but slowly evolving path involving an increasing share of LDV PHEV energy provided by grid electric kWh now seems far more plausible in the near term than a switch to hydrogen fuels for FCVs or a rapid jump to fully functional EVs. Nevertheless, if further (presently unanticipated) progress does occur, neither EVs nor FCVs seem to be precluded by focusing on this pathway. When the flexibility in the choice of an on-board power unit of a PHEV is allowed for, the CIDI PHEV is also possible.

HEVs and PHEVs: Competitive or Complementary? — Yet another question is whether or not HEVs and PHEVs are what economists call competitors or complements. If they are direct competitors, they serve the same market. If two products are pure competitors, when one gains, the other has to lose. If they are complements, the introduction of one can benefit the other. The argument here is that PHEV options to go with HEV powertrains will actually expand the total market for both powertrain options significantly. If this is the case, then one of the benefits will be to increase sales and thus production volumes more rapidly. Increase of production volume reduces component costs. Reduction of component costs reduces vehicle cost and increases the size of the market, and thus sales. This is what is known as a positive feedback loop.

The statements thus far suggest that HEVs and PHEVs are primarily complements. This means that both of them should be compared to CVs and/or CIDIs, not to each other. Although there will be some competition, for the most part, the calculations below imply that the HEV will carve out one niche of the present CV market and the PHEV another niche. The computations imply that the PHEV could reduce the competitiveness of the CIDI technology, except at the highest average speeds on rural interstate highways or uncongested European motorways.

Thus, the proper C-B *and LCA* comparison of the behavior of a PHEV during CD operation is against a CV operating on a driving cycle identical to that experienced by the PHEV. The comparison of an HEV to a CV should be done in the same manner and will involve a different (slower) driving cycle.

Urbanization

In 1974, the Federal Highway Administration (FHWA) reported that 55% of U.S. light duty (LD) vehicle miles traveled (VMT) were urban. This share rose to 65% in 2004. In principle, this should have reduced average speed. However, at the same time, travel shifted dramatically toward interstate highways, designed for high speed. The interstate share of total VMT rose from 16% to 23%. Nearly all of this growth was in urban areas. Essentially all the decrease in rural share of VMT was on roads and highways other than interstates. This should have increased average speeds in rural areas. Even though interstates are designed for high speed, the reality in urban areas is that in the congested traffic during morning and evening commutes, the average interstate/motorway speeds can be similar to those on urban arterials. In Belgium, while the reported average speeds for LD vehicles in "normal" congestion are 22 km/h for city traffic, 51 km/h for rural traffic, and 110 km/h for highway traffic, "dense" congestion resulted in values of 15, 25 and 25 km/h respectively (Smets 2007). Given reports of increases in congestion, it is reasonable to assert that the "full function" vehicle designer of today has a greater challenge now than 30 years ago with respect to the range of speeds over which such a vehicle must operate efficiently.

Table 1 shows that the share of time and km within three daily distance intervals in the United States had a low point at the intermediate speed and distance. This suggests either that universal powertrains have to be designed with great versatility, or that if a diversity of powertrains is offered in the future, the need for the slow and the fast may be greater than the need for those in the middle.

From the perspective of an analyst whose priority should be to help promote and develop technologies that save the nation the most fuel, the fastest and longest of these three categories carries more weight than either of the other two, because fuel consumption per unit of time in the vehicle rises over the speed ranges reported in Table 1. The two driving cycles used by the United States in its official testing for certification of fuel economy are the urban dynamometer driving schedule (UDDS), which averages 31 km/h (much the same as the average for the shortest distance grouping in Table 1), and the highway test, which averages 77 km/h, a bit more than the longest distance grouping.

Table 1 U.S. travel statistics as a function of daily distance driven

Daily distance (km)	0–32	32–64	>64	All
Trip share (%)	60.0	21.4	18.6	100.0
Share of time spent	40.8	23.5	35.7	100.0
Share of total km	28.1	23.3	48.6	100.0
km/h	34	50.4	68.1	50
km per trip	6.8	15.1	37.7	14.4

Source: Developed from U.S. Department of Transportation (2004)

In Table 2, for six powertrain options, the estimates of fuel consumption per km published recently by Passier et al. for five driving cycles spanning speeds of 22.5–93 km/h were converted to an estimated fuel consumption per day of driving, assuming that the specified driving cycle applies for the entire day and the time spent driving is 1.25 hours. The Argonne National Laboratory PSAT model was used to design the two PHEV powertrains to have about 32 km of CD range, with kW ratings of battery packs and motors sufficient to allow CDE operation on the slowest of the five cycles, the Artemis urban cycle.

In the European "Artemis" study (Andre 2004), real world driving was studied under three conditions — urban (22.5 km/h), rural routes (47.5 km/h), and motorways (98.2 km/h). In terms of the span of speeds covered, these European cycles nicely complement the two U.S. fuel economy certification test cycles. The acceleration and deceleration rates on the Artemis real world cycles (particularly the peak values) are considerably higher than for the two U.S. certification cycles.

Table 2 Estimate of daily fuel consumption (in liters) for advanced world car platform with alternative powertrains, by speed/cycle (Adapted from Passier et al. 2007)

Cycle Name	Cycle Speed (km/h)	SI ICE	CIDI	Split HEV	Split PHEV Medium	Pre-transmission HEV	Pre-transmission PHEV Medium
Artemis urban	22.5	2.71	1.98	1.06	0.42	1.47	0.76
U.S. UDDS	31.0	2.49	1.76	1.19	0.67	1.33	0.55
Artemis rural	47.5	3.20	2.37	2.01	0.92	2.35	1.06
U.S. highway	77.1	4.28	3.31	3.40	2.21	3.51	2.26
Artemis motorway	92.8	8.25	7.23	12.79	6.10	7.25	5.90

Gasoline consumption was simulated for short, medium, and long PHEV ranges (medium was selected for discussion here), and for HEV versions of the same powertrains. These vehicles were simulated to use a "split" parallel/series powertrain with two electric machines (split HEV cases), or a parallel powertrain using one "pre-transmission" electric machine (pre-transmission cases). In Table 2, the selected PHEVs are compared to HEVs with similar powertrain design, a reference petrol-fueled spark-ignited internal combustion engine (SI ICE), and a reference distillate-fueled CIDI (Passier et al. 2007). The same vehicle body is characterized across all cases. It is an advanced low-drag, reduced-mass world car (similar to the Prius but improved). Cold start and cold temperature effects are not addressed. In Artemis urban driving, the medium-range PHEVs can drive all electrically, depending on simulation assumptions about driver accelerator pedal manipulation. For the remaining cycles, the PHEVs do not have enough power to operate all electrically while operating CDB.

Cost and Volume of Batteries for PHEVs

During the 1990s, the hypothetical PHEV technology option was allowed a partial ZEV credit by the California Air Resources Board (CARB) as a compromise (relative to EVs) to achieve limited zero-emission operation. Studies of the PHEV that have been done to date assumed that PHEVs would be capable of operating all electrically initially, while the PHEV charge depletes (Plotkin et al. 2001; Graham et al. 2001; Duvall and Knipping 2007; Knipping and Duvall 2007; Gaines et al. 2007). This assumption created a challenge for the PHEV battery pack designer, demanding battery cells with considerably higher W/Wh ratios than those for EVs.

Anderman (2007) argued that the need for power to accelerate a PHEV consistently without making the engine turn on means that resulting cooling requirements will make battery packs need more volume than most PHEV analysts assumed. This will cause the necessary packs to take scarce volume from the trunk of hybrid sedans (e.g., Camry), sharply reducing the value of such hypothetical PHEV sedans in the marketplace. However, recent tests of aftermarket conversion PHEVs show that gasoline consumption can be considerably reduced with no more battery pack power than is currently available in the Toyota Prius and Ford Escape (Carlson et al. 2007). In the tested hybrids, the engine comes on intermittently; thus, they operate in CDB mode. Both of these vehicles have considerably more storage volume than typical sedans. It also appears that the Toyota Camry sedan platform will soon add a crossover model that will have a Toyota hybrid powertrain option. Crossover vehicles (e.g., Escape and Saturn Vue) are capturing increasing U.S. market share, as is the Prius (J.D. Power 2008). Present plans for initial PHEVs include two crossover sport utilities, the

Escape and Vue, and the Prius. Selection of these HEV models to become PHEVs addresses the concern over luggage space volume but not the remaining issue of battery cost.

The CDB operations of the recent aftermarket PHEVs do not meet CARB's recent regulatory requirement that PHEVs be capable of operating all electrically on the UDDS cycle (State of California 2007). Note that the vehicle characterized in Table 2 is not able to meet this requirement, though it could operate all electrically in the slightly less demanding Artemis urban cycle. CARB is now responsible for GHG reduction as well as criteria pollutant reduction. CARB is evaluating a credit system for PHEVs that use relatively low-power batteries and CDB

The potential importance of the feasibility of PHEVs with low-power batteries is illustrated by the trade-off curves for estimated $/kWh versus W/Wh of battery packs (Fig. 1). The figure shows the results of two studies that have published their estimates of these battery attributes for multiple PHEV CD ranges. The estimates imply that, for a given amount of kWh, the less power required by the PHEV, the less costly the kWh will be. The 2001 EPRI study by Graham et al. assumed that Ni-MH would be the battery of choice for PHEVs, largely because Ni-MH was then about half as expensive as the Li-ion battery on a $/kWh basis (Duong 2007). However, since then, the $/kWh cost of portable Li-ion battery cells has dropped below that of NiMH cells, which have recently risen slightly in nominal cost. Thus, the more recent estimates of Li-ion battery pack costs for HEVs and PHEVs by Kromer and Heywood of MIT has $/kW costs very similar to the 2001 NiMH estimates in the EPRI study. In addition to the fact that the Li-ion $/kWh costs are now on par with or below NiMH, the specific energy of the Li-ion cells and packs (both volumetric [Santini 2006] and gravimetric [Fig. 2]) are very superior to those for NiMH. Significant improvements in these attributes not surprisingly coincided with reductions in $/kWh cell cost.

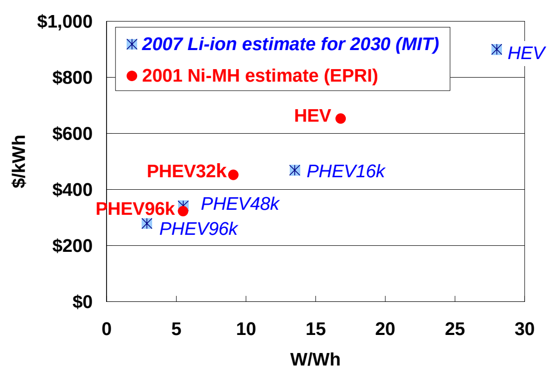

Fig. 1 Cost per kWh benefits of reduction in PHEV battery pack W/Wh, by chemistry

Incremental Cost of the Plug-in Option

The implications of Figs. 1 and 2 are that it is now possible to put more battery pack kWh into PHEVs by using Li-ion batteries than would have been possible with NiMH batteries, but the cost of adding the electric drive capability to an HEV is probably not much less than what was estimated in 2001.

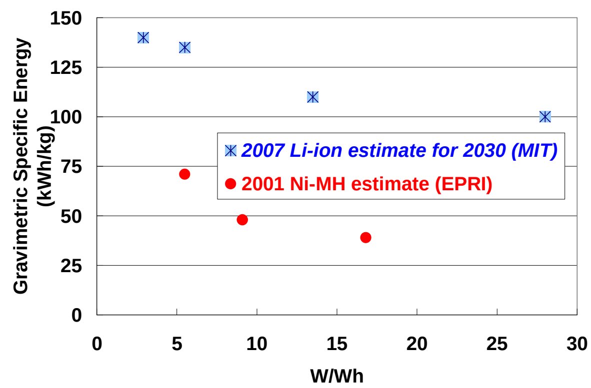

Fig. 2 Specific energy benefits of reduction in PHEV battery pack W/Wh, by chemistry

In principle, this means that the cost estimates of the 2001 EPRI study may still be reasonable. A relatively big difference in the recent Kromer and Heywood (MIT) study's estimates of 2030 HEV costs is a lowered increment relative to the advanced CV. The earlier study by Graham et al. (EPRI) did not attempt to develop an advanced SI ICE to compare to the future HEV. Kromer and Heywood include a turbocharged direct-injection SI ICE engine in their conventional powertrain alternatives (TC-DI-SI-ICE). As a result of the addition of a turbocharger, the advanced SI ICE is $500 more costly than the future naturally aspirated direct-injection spark-ignited (NA-DI-SI) engine — also more expensive than today's engine. The incremental cost of an HEV in 2030 is either $1400 (HEV versus NA-DI-SI) or $1900 (HEV versus TC-DI-SI-ICE).

In Table 3, the nearer-term incremental costs for HEVs relative to CVs and for PHEVs relative to HEVs are compared for two of the EPRI study mid-size vehicles with NiMH, versus the one 2030 mid-size vehicle from the recent MIT study. It can be seen that the EPRI base-case estimates are higher than (1) the EPRI estimates from using the Argonne analysts' methods and (2) the MIT analysts' estimates. In their Table 51, the latter estimates cite the EPRI study, but the quoted costs differ from those in Tables C-4 and C-5 of the EPRI study. Further, an engine downsizing credit is applied for the HEV and PHEV. This involves double counting, because the EPRI study had already included engine downsizing in the HEVs and PHEVs. The MIT analysts' 2007 decisions — if reevaluated — probably would place the HEV and PHEV cost estimates at a bit higher level, between the 2001 EPRI base case and the "Argonne method" case.

The results are that the largest difference in Table 3 is the higher incremental cost of the HEV in the EPRI base case. A relatively recent study prepared for Argonne by the Center for Automotive Research (Smith and Santini 2005) places the incremental cost of the split parallel HEV system at about $3400–$4140, assuming the HEV uses a four cylinder engine, replacing a V6. The "integrated starter generator" hybrid powertrain (comparable to the pre-transmission HEV in Table 2), with only one electric machine, has an incremental cost of $2550–$3200 under the same assumptions. A study by Greene et al. (2004) placed the full hybrid "incremental retail price equivalent" at $3320 for a small car and $3920 for mid-size and large cars.

From the Smith and Santini report, the incremental cost of a six-cylinder diesel engine replacing a six-cylinder gasoline engine (not an advanced version) was estimated to be $3138, due largely to an estimate of $1500 for "additional exhaust technology" to meet tightening emission standards. The Greene et al. study placed the 2012 (after emission-control tightening) incremental retail price equivalent of V6 diesels in a range from $2950 (smaller displacement V6) to $3250 (larger displacement V6). In the Kromer and Heywood (2007) case, the diesel cost was $1200 relative to a considerably higher-cost ICE engine. Osborne (2007) recently projected that the "Euro 5" emissions-compliant diesel for a small car would have more than twice the incremental cost of a TC-DI-SI-ICE engine that employs stratified combustion strategies, with very little improvement in carbon dioxide reduction relative to that advanced SI ICE engine. This 2007 estimate is very consistent with the Kromer and Heywood (2007) estimates of relative cost and fuel consumption for this pair of technologies.

Table 3 Estimates of incremental costs of HEVs Versus CVs and of PHEVs Versus HEVs

	ICE	HEV	PHEV 16 km	PHEV 32 km	PHEV 48 km
EPRI study team base-case estimates (2001)					
Total retail price, base	$18,984	$23,042	NE	$24,966	NE
Cost increment over NA SI ICE		**$4,058**	NE	$5,982	NE
PHEV cost Increment over HEV				**$1,924**	NE
Alternative EPRI study estimates based on Argonne analysts' methods					
Total retail price, Argonne method	$18,980	$21,373	NE	$22,971	NE
Cost increment over NA SI ICE		**$2,393**	NE	$3,991	NE
PHEV cost Increment over HEV				**$1,598**	NE
Kromer and Heywood (2007) (MIT) estimates					
Total retail price	NE	NE	NE	NE	NE
Cost increment over NA SI ICE		**$2,400**	**$3500**	NE	**$4300**
PHEV cost increment over HEV			**$1100**	**NE**	**$1900**

NE = not estimated and/or not able to be estimated from data provided.

The bottom line is that there are expectations that adoption of direct injection, turbocharging, and advanced-combustion strategies will allow SI ICE engines to close the gap with diesel engines, which will be penalized by more stringent emission-control requirements.

The implications of the Kromer and Heywood cost and fuel consumption estimates for the various powertrains by using standard C-B methodology are shown in Fig. 3. Fuel cost reductions are converted to net present value (NPV) over a 10-year life, assuming a constant 24,000 km/yr of operation. The NPV fuel savings at different fuel prices are computed and compared to various measures of incremental cost. Results are presented as the benefit-cost (B-C) ratio. The criterion is that the B-C ratio should exceed 1.0. The results imply that the HEV technology is the most highly desirable among those evaluated. The next notable result is that although the B-C ratio for PHEVs is less than 1.0 at present fuel prices, it exceeds the ratio for the diesel vehicle, full-function battery electric vehicle (BEV), and FCV. When compared to a conventional TC-DI-SI ICE, the PHEV with 16 km of CD range appears to be cost beneficial. However, if one examines the incremental cost of adding the 16 km PHEV option to an HEV, the ratio drops to about 0.6. If fuel.

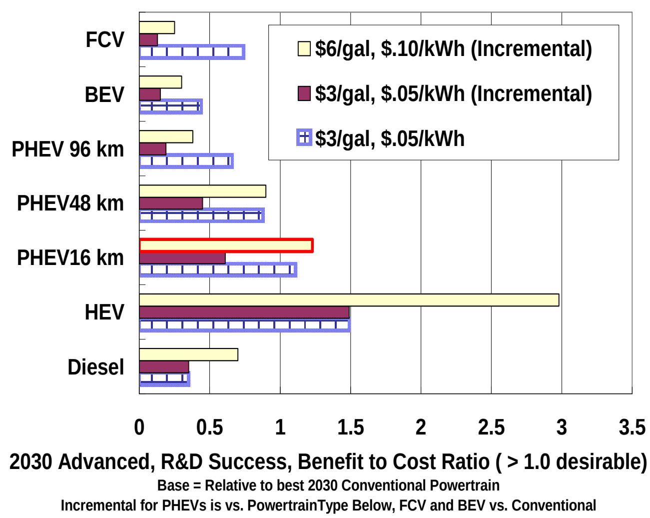

Fig. 3 Benefit to cost ratio for multiple PHEVs, relative to other powertrain options (Adapted from Kromer and Heywood 2007)

One property of the chart is that the B-C ratio drops steadily as the electric range is extended. The range of the BEV is 320 km and of the FCV is 624 km. Cost of kWh remains an issue for the full-function BEV. However, the "city electric" (not evaluated by Kromer and Heywood) could be enabled by the increased energy density of Li-ion batteries

An important point is that the HEV looks very desirable, and the PHEV looks more desirable than other options but seems too costly. However, there are two ways that the Kromer and Heywood estimates could be too pessimistic. First, recall the point about evaluations for average driving being potentially misleading.

In Fig. 4, the EPRI 2001 PHEVs, whose incremental costs are similar to those in the MIT study, are evaluated. The EPRI base-case costs are used, but the HEV and PHEV are evaluated as if they are driven exclusively on the UDDS driving cycle or the highway driving cycle. The B-C ratio of the HEV is considerably lower than it is for the MIT case because of the higher first cost for the HEV. For the higher-speed highway cycle, the HEV has a very low B-C ratio and is not desirable. In this case, however, the *incremental* B-C ratio of the PHEV versus the HEV behaves very differently from that of the HEV versus the CV. The ratio is nearly 1.0 at present fuel prices (assuming inexpensive off-peak electric rates) for both the urban and highway cycles. On the urban cycle, the incremental B-C ratio of the PHEV is less than it is for the HEV, while on the highway cycle, the incremental B-C ratio is significantly greater than it is for the HEV.

The proportion of time or miles driven all electrically can have a bearing on the viability of a PHEV battery pack, from a B-C perspective. When the share of km driven is raised to 50%, at $6.00 per gallon and 10 cents per kWh, the B-C ratio of the HEV remains very low, but for the PHEV it is raised to 1.0. This occurs because the incremental effect of the addition of the PHEV feature has a very high B-C ratio, pulling the average for the powertrain up considerably.

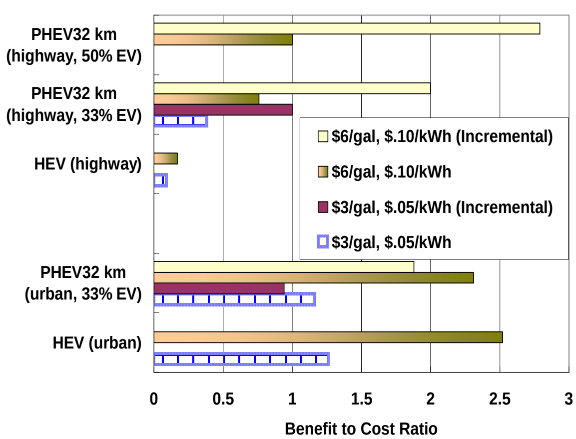

Fig. 4 Benefit-to-cost ratio for HEVs versus PHEV 32 km at urban and highway speeds

It can also be seen that the incremental B-C ratio of the PHEV option is slightly higher on the highway cycle than in urban driving.

This illustrates the misleading nature of averages and supports the earlier contention that the relative advantage of the HEV will be greatest during the slowest driving, while the relative desirability of the PHEV will increase as speed increases.

The results in Fig. 3 and 4 are for PHEVs designed to be capable of all electric operation on more aggressive driving cycles than recently simulated with PSAT by Passier et al. There is a theoretical reason that the B-C ratio of the EPRI base case should be less than it is for the MIT analysis. The reason is that the W/Wh requirements should nominally have been higher in the EPRI case than the MIT case. The EPRI case used the aggressive US06 driving cycle to size batteries, while the MIT study used the UDDS. The Passier et al. analysis used the even less demanding Artemis cycle, while the prototype PHEVs tested by Carlson et al. had even less battery pack power available. However, this is a theoretical difference at this point because the MIT cost estimates appear to be too rough to have isolated the costs of this effect. There is also the problem that the two studies simulated different battery pack chemistries.

What remains to be determined is how cost effective blended-mode PHEVs (such as those characterized by Passier et al.) can be. The trade offs across a range of power capabilities and W/Wh ratios remain to be evaluated consistently with the same model, for the same battery chemistry. Until these trade-offs have been carefully investigated, it is too early to conclude that U.S. fuel prices will have to rise to $6.00 gallon before PHEVs can be competitive. On the other hand, current petrol and diesel prices in much of Europe are at the $6.00 level and higher.

Fig. 4 illustrates an important effect of driving behavior on relative desirability of HEVs and PHEVs for two of the five driving cycles evaluated by Passier et al. Fig. 5 illustrates the estimated daily change in fuel consumption achieved by substituting a CIDI, or two kinds of HEVs, and two kinds of PHEVs for a CV, over five different driving cycles, spanning a wide range of speeds.

Fig. 5 shows an anomaly for the split HEV on the Artemis motorway driving cycle. While this dramatic increase in fuel consumption may seem intuitively incorrect, it cannot be dismissed as invalid. When testing the Toyota Prius, Duoba et al. (2005) found that the Prius exhibited a sharp drop in fuel efficiency at high speeds. While five other vehicles were tested at speeds up to 129 km/h, no Prius tests were done at this speed (a coincidence, not a technical limitation). The top speed attained by the Prius in these tests was 113 km/h. The split HEV simulation model in PSAT was calibrated to the tests done in Argonne's Advanced Powertrain Test Facility. Those tests indicated sharp increases in fuel consumption as the speed rose to 113 km/h. Thus, it is not necessarily surprising that the simulation of the fuel consumption of a split HEV rose sharply on the Artemis motorway cycle, where speeds above 113 km/h and even above 129 km/h are frequent. Perhaps more interesting is the simulation of a sharp improvement on the motorway cycle when the split HEV was converted to a PHEV.

Consistent with earlier assertions, the patterns of predicted fuel savings vary significantly by powertrain technology and average cycle speed. The CIDI volumetric fuel savings improve steadily as speed increases, while the opposite is true

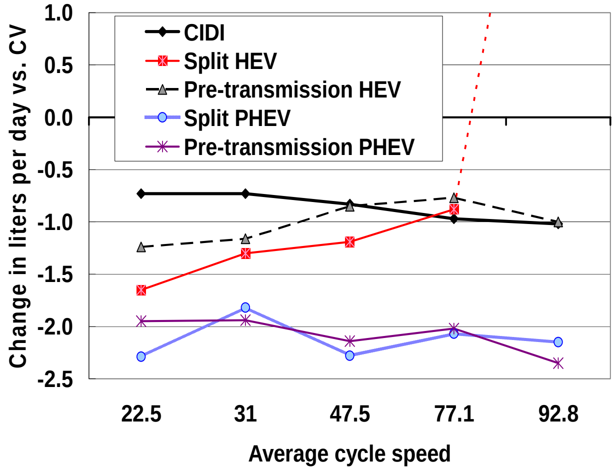

Fig. 5 Estimated daily fuel use change if alternative powertrains are chosen to replace a conventional powertrain (Developed from Passier et al. 2007)

for the split HEV. The pre-transmission HEV, like the split HEV, exhibits its greatest daily fuel saving for the European and U.S. urban driving cycles. However, its advantages in urban driving are less pronounced than for the split HEV. In fact, its fuel-saving advantages are consistently less up to the motorway cycle. This HEV system, however, is less costly to implement than the split HEV, as previously noted. Given the tendency of Europeans to spend a reasonable share of their mileage driving at high speeds, this implies that the pre-transmission HEV would be more probable in Europe.

This initial set of simulations implies that the split and pre-transmission power trains, when converted to PHEVs, would provide about equal fuel savings. All other things being equal, this would favor the pre-transmission powertrain, which is less expensive. However, in a sequence of introductory steps, if the HEV is to precede the PHEV, starting with the split HEV powertrain may provide more benefits. Note the pronounced advantage of the split HEV at the lowest speeds. Such speeds are typical in Japan, where the split HEV was initially implemented. Accordingly, the HEVs that are now being converted to PHEVs in the United States start with the split HEV.

At highway and motorway speeds, assuming that the price of diesel fuel is equal to or less (as in Europe, due to tax choices) than gasoline, Fig. 5 implies that the CIDI would have a higher B-C ratio, given the somewhat higher HEV first cost. Of course, recent trends involve increases in costs of diesel fuels relative to gasoline (Passier et al, 2007), as sulfur content is being reduced. The relative savings of fuel when the simulated PHEVs are implemented for average daily driving duration appear to consistently be much higher than those for a diesel vehicle or HEV at higher speeds.

At lower speeds, the fuel-saving advantage of the HEV is pronounced relative to the diesel. Thus, in urban driving, the HEV seems likely to be superior to the diesel. However, it is also true that the HEV accomplishes a significant share of the savings that can be accomplished with a PHEV, without the additional cost. As Fig. 4 also illustrates, the comparative advantage of the PHEV option is less in urban driving than in higher-speed driving.

Oil Crisis Resiliency

Another feature of the specific 32-km, blended-mode PHEVs being discussed in this case is the general increase in distance to depletion as the average speed increases. Ironically, however, the rate of the increase in speed across the five cycles overall outpaces the rate of increase of CDB distance to depletion. As a result, the time it takes to deplete is considerably less for the two highest-speed cycles. While this effect means that the fraction of daily fuel use reduced by the PHEV option is less for those PHEVs that deplete a charge quickly, it also means that they have the ability to charge more than once per day. Assuming that such PHEVs are normally charged only once a day, if there was a really serious shortfall of world oil supplies due to political turmoil or wars in oil-producing regions, those customers whose daily driving allowed use of two charges could step up their charging away from home and save themselves (and the nation) additional oil in such an emergency. Of course it is also true that more battery pack power allows more rapid depletion, as well as the technical capability to charge faster, which could expand the ability for multiple charges per day. However, more power, faster depletion, and faster charging all cost money, working against commercial success.

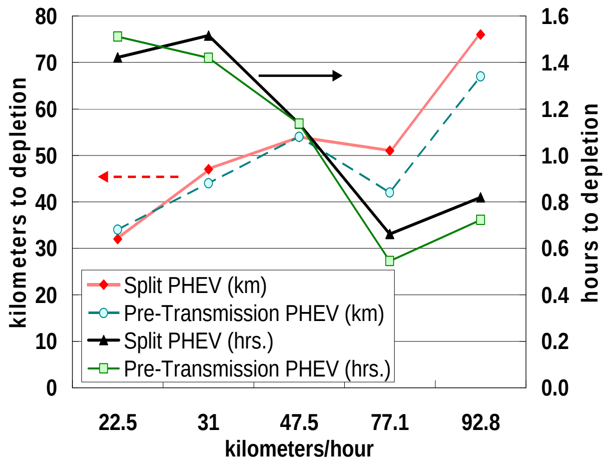

Fig. 6 Distance and time to charge depletion of the chosen PHEVs, by driving cycle

Another point that Fig. 6 illustrates is that the time to depletion for the two urban cycles exceeds the normal amount of time spent in the vehicle. In other words, the chosen vehicles have more range than many urban customers would use. To maximize the NPV benefits of a battery, the more it is used, the faster it pays for itself, so this is a drawback. The problem can be addressed by providing an option to purchase lesser amounts of kWh than the amounts used in the PHEVs discussed here, but this has another catch. Reducing kWh for a given cell design would also reduce power, which reduces time to depletion, all other things equal. The net effect would likely be positive economically, but the elusive goal of operating all electrically would slip away. If a higher W/Wh cell design was used instead, it might require two cell and battery pack production lines, reducing the production cost efficiencies arising from standardization.

Implications for Evaluation of LCA Results

These computations and illustrations make it clear that the markets for HEVs and PHEVs are complementary rather than competitive. HEVs will be the best choice for those driving at low speeds in congested urban environments. PHEVs will be the best choice for suburbanites driving at higher speeds. This is fortuitous, since it is in suburbia where garages are found — the desirable locations for plugging in overnight. The PHEV option has the potential to expand the market for the fundamental HEV powertrain further into suburbs and small towns. The HEV is best for replacing the CV in urban areas with multifamily dwelling units and an absence of garages, while the PHEV is best for replacing the CV in the suburbs.

Implications of Recent LCA Estimates for the Split PHEV Discussed Here

Gaines et al. (2007) examined PHEVs similar to those discussed here. The simulated PHEVs were designed to operate all electrically on the UDDS cycle. This assumption requires re-examination in light of the analysis in this paper. However, experiments reported in Passier et al. support the contention that the amount of fuel saved per kWh of electricity used is relatively constant, regardless of driving cycle. The fuel saved per day by using the chosen PHEVs instead of a CV is relatively constant, regardless of speed driven (Fig. 5). The share of fuel savings, however, does decline as speed increases, because overall consumption increases with average speed (Table 2).

Fig. 7 presents estimates of total energy use and GHG emissions, by fuel type and powertrain technology. (A list of acronyms is found in the appendix.) The fuel/powertrain pathway combinations are ordered from highest to lowest energy user within fuel types. The ordering within fuels is consistent for both energy and GHGs. Across fuels, this is not the case. For example, processing of farmed trees requires a lot of energy in the collection and conversion steps, but since the carbon is assumed to be recycled, the GHG emissions are very low.

The case on the far right side shows the construction of an example annual average case for the best (for an energy perspective) CS pathway (i.e., gasoline) for the PHEV and for the best CD pathway (i.e., wind). The reference value is for 50% of km in each mode, while the high energy use point is 33% CD operation and the low point is 67% CD operation. For GHGs, the best combination would be different, combining CS operation via ethanol (E85) from farmed trees with CD operation from wind.

One key finding is that, within each fuel type other than oil, the best pathway is the PHEV operating in CD mode. In fact, if the combined-cycle generating technology had also been included in the oil pathways evaluated, then PHEV CD operation would also have been best in the oil case. Combined-cycle technology is more easily implemented with oil than coal. However, in the United States, there are no plans to install any new power plants that use oil.

For the CIDI diesel, if petroleum was no longer available and natural gas or coal was used to produce liquid fuel for the CIDI engine, considerably more fuel would be needed to provide km of service than if the dollars invested had gone into PHEVs that could rely on that same fuel used to generate electricity efficiently in combined-cycle power plants.

The estimates imply that it could be better to gasify farmed trees and use the resulting gas in a combined-cycle power plant to serve PHEVs operating in CD mode than to convert the farmed trees into ethanol and run an HEV or PHEV in CS mode using that E85. The generating technology to do this is in experimental stages (as is ethanol production from woody biomass).

Once wind is used to produce electricity, more km of service could be provided if that electricity was used for PHEVs operating in CD mode than if the electricity was used to produce hydrogen via electrolysis to fuel an FCV.

The estimates made imply that, on average, a PHEV operating on gasoline in CS mode and an HEV could use less oil and create less GHGs than would a CIDI engine.

If the arguments in this paper are correct and PHEVs should be compared to CVs and not HEVs, then the initial estimates presented here indicate that building new coal-fired power plants that would, in part, provide electricity for PHEVs operating in CD mode would generate slightly less GHGs per mile than would expanding production of gasoline from oil sands to serve CVs.

More certainly, building efficient coal-fired power plants that serve PHEVs in CD mode would be vastly superior to adopting CIDI technology and fueling it with coal-to-liquid (CTL) fuels from the same coal fields. Similarly, building efficient combined-cycle natural gas (NG) power plants that serve PHEVs in CD mode would be vastly superior to adopting CIDI technology and fueling it with NG-based Fischer-Tropsch diesel (FTD) from the same NG reservoirs.

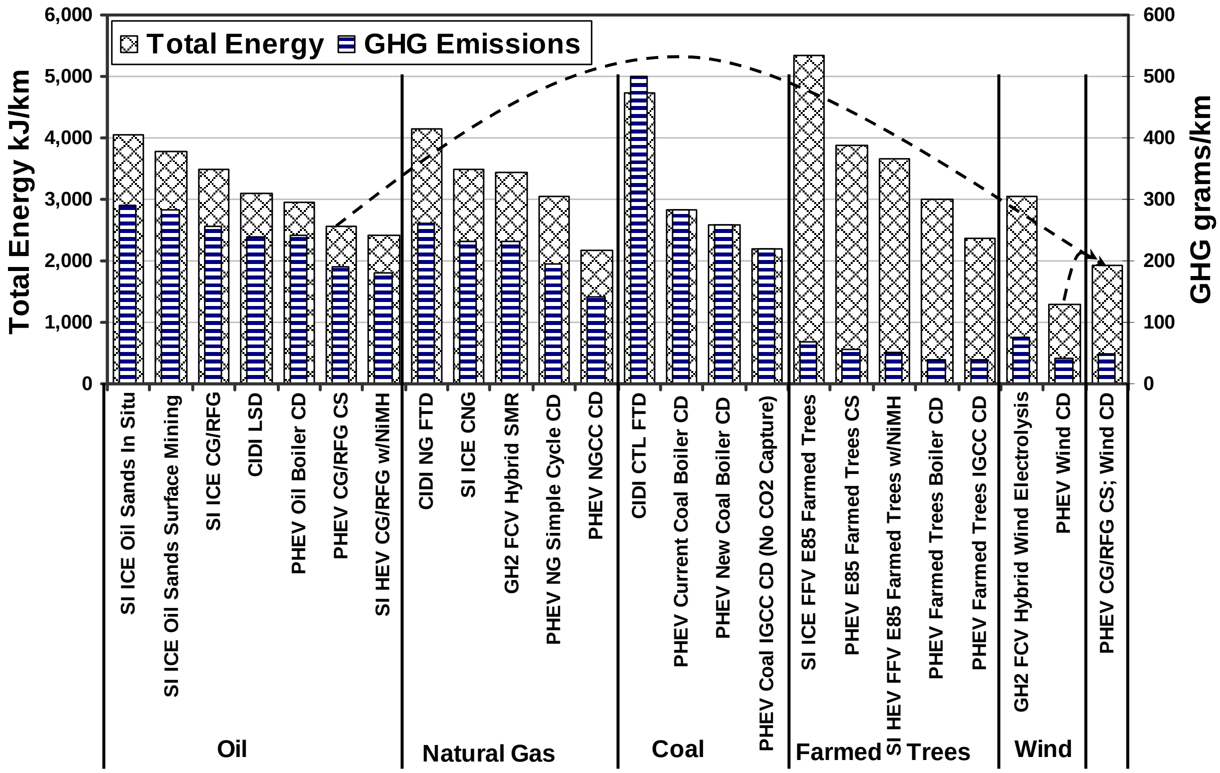

Fig. 7 Energy use and GHG emissions per km of travel for different pathways and selected vehicle technologies (conceptual flaws and caveats for these early estimates, along with suggestions for methodology revisions, are discussed in the text)

Caveat Relative to Fig. 7

Table 4 shows comparisons in Fig. 7. The speeds assumed in the Gaines et al. analysis are listed in the top row. The cases that were estimated are shown by an "X." This paper argues that comparisons should be made vertically, for the single average speed deemed most appropriate for the conditions being evaluated. If this suggestion is followed, the numbers in Fig. 7 will change in future investigations. Instead of one figure, perhaps multiple figures for each of the three columns in Table 4 will be presented for each PHEV evaluated (recommended speeds will vary by CD range of the PHEV).

Table 4 Speeds estimated to be appropriate for the cases estimated for Fig. 7 by Gaines et al.

	31 km/h	48 km/h[a]	52 km/h[b] (50.5)[c]	60 km/h[d]	77 km/h
	UDDS	CD = Slow	CV Average	CS = "Fast"	Highway
CV			X		
CIDI			X		
HEV			X		
PHEV medium		X		X	

[a] Average speed for first 32 km of daily driving of all NHTS households driving more than 32 km/day (developed from data in U.S. Department of Transportation 2004).
[b] Average speed assuming 55% of time at UDDS speed, 45% of time at highway speed
[c] Average speed for occupants of detached single-family houses (Vyas et al. 2007)
[d] Average speed for remainder of daily driving beyond 32 km, for all NHTS households driving more than 32 km/day (developed from data in U.S. Department of Transportation 2004).

Implications for Future Research

PHEVs are complementary to HEVs. They offer an opportunity to expand the market for significantly electrified powrtrains well beyond what might otherwise be captured by HEVs alone. HEVs and PHEVs both compete against CVs in different market niches. Accordingly, to evaluate past LCA results and restructure future LCA analyses, comparing each of these vehicles to CVs (in each case, evaluation of patterns of driving most advantageous for the HEV or PHEV) is far more appropriate than comparing one to the other.

PHEVs appear to be a very promising technology for the 21st century. When they operate in CD mode, they can provide transport services with less fuel use and GHG emissions than any other powertrain competing for R&D and demonstration dollars. One challenge is to determine the most cost-effective way to use this capability, bringing the technology to the market sooner rather than later.

It appears that there will be no universal alternative to the conventional gasoline fueled powertrain (CV). A combination of HEVs, PHEVs and advanced CIDI powertrain technologies is likely to compete with the CV in different segments of the market. Analysis done here and elsewhere indicates that the most advantageous applications of HEVs will be at the lowest average speeds and daily driving distances, probably where the highest proportion of multifamily housing is located and the lowest portion of single-family homes with garages or carports is found.

The emergence of the HEV could help prevent rising urban congestion from increasing fuel consumption. Estimates here imply that fuel consumption per hour of driving steadily drops for a split HEV as congestion increases and average driving speed slows.

Fortuitously, the estimates indicate that the comparative advantage of the PHEV technology will be in suburbia in the United States and generally in upper-income nations and communities with low densities where single-family homes and garages are relatively common.

For those who travel long distances per day at relatively high speed, the emerging clean CIDI technology may be more desirable than PHEVs.

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Appendix: Additional acronyms used in Fig. 7

Fuel types
RFG = reformulated gasoline/petrol
CG = conventional gasoline/petrol
LSD = low-sulfur diesel
GH2 = natural gas converted to gaseous hydrogen
SMR = steam methane reforming (for GH2 production)
E85 = 85% by volume ethanol, 15% hydrocarbons

Electric generation types
Simple cycle = combustion turbine
CC = combined cycle
IG = integrated gasification

References

Andre, M. (2004). "The ARTEMIS European Driving Cycles for Measuring Car Pollutant Emissions," *Science of the Total Environment* 334–335, pp. 73–84.

Anderman, M. (2007). "Power Distribution and Energy Storage Configuration, Requirements, and Management," presented in the Advanced Vehicles Session, Advanced Automotive Battery Conference, Long Beach, CA (May).

Argonne National Laboratory, *PSAT (Powertrain Systems Analysis Toolkit)*, http://www.transportation.anl.gov/.

Birch, S. (2007). "M_DiesOtto: A Diesel-Gasoline Technology Blend," *Automotive Engineering*, pp. 17–18, Oct.

Brinkman, N., et al. (2005). *Well-to-Wheels Analysis of Advanced Fuel/Vehicle Systems — A North American Study of Energy Use, Greenhouse Gas Emissions, and Criteria Pollutant Emissions*, Argonne National Laboratory, Argonne, IL, www.transportation.anl.gov/pdfs/TA/339.pdf, May.

Burghardt, M.D. (1982). *Engineering Thermodynamics with Applications*, Second edition, Harper and Row, NY.

Burnham, A., M. Wang, and Y. Wu (2006). *Development and Applications of GREET 2.7 — The Transportation Vehicle Cycle Model*, ANL/ESD/06-5, Argonne National Laboratory, Argonne, IL, Nov.

Carlson, R., et al. (2007). "Testing and Analysis of Three Plug-in Hybrid Electric Vehicles," SAE 2007-01-0283, presented at SAE World Congress, Detroit, MI, April.

Clement-Nyns, K., K. Van Reusel, and J. Driesen (2007). "The Consumption of Electrical Energy of Plug-in Hybrid Electric Vehicles in Belgium," presented at EET-2007 European Ele-Drive Conference, Brussels, Belgium, May 30–June 1.

Deiml, M., and R. Knorr (2005). "DLC, NiMH, or LiIon: Proper Storage Systems for Hybrid Vehicle Applications," *Proceedings of the Fifth International Advanced Automotive Battery and Ultracapacitor Conference,* Honolulu, HI, June 15–17.

Duoba, M., H. Lohse-Busch, and T. Bohn (2005). "Investigating Fuel Economy Robustness of Conventional and Hybrid Electric Vehicles," *Proceedings of the EVS-21, The 21st Worldwide Battery, Hybrid and Fuel Cell Electric Vehicle Symposium and Exposition,* Monaco, Apr. 2–6.

Duong, T. (2007). "Update on the U.S. Department of Energy PHEV Activity," presented at the Advanced Automotive Battery Conference, Long Beach, CA, May.

Duvall, M., and E. Knipping (2007). *Environmental Assessment of Plug-in Hybrid Electric Vehicles,* Vol. 1, *Nationwide Greenhouse Gas Emissions,* Final Report 1015325, Electric Power Research Institute, Palo Alto, CA July.

Eastop, T.D., and A. McConkey (1978). *Applied Thermodynamics for Engineering Technologists,* Third edition, Longman, London, England.

Gaines, L., et al. (2007). "Sorting through the Many Total-energy-cycle Pathways Possible with Plug-in Hybrids," *Proceedings of the Electric Vehicle Symposium 23,* Anaheim, CA, Dec. 2–5.

Graham, R., et al. (2001). *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options,* Final Report, Electric Power Research Institute, Palo Alto, CA, July.

Greene, D.L., K.G. Duleep, and W. McManus (2004). *Future Potential of Hybrid and Diesel Powertrains in the U.S. Light Duty Vehicle Market,* Report ORNL/TM-2004/181, Oak Ridge National Laboratory, Oak Ridge, TN, Aug.

J.D. Power, *The Sales Report,* various issues.

Knipping, E., and M. Duvall (2007). *Environmental Assessment of Plug-in Hybrid Electric Vehicles,* Vol. 2, *United States Air Quality Analysis Based on AEO-2006 Assumptions to 2030,* Final Report 1015326, Electric Power Research Institute, Palo Alto, CA, June.

Kromer, M.A., and J.B. Heywood (2007). *Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet,* Publication LFEE 2007-03 RP, Massachusetts Institute of Technology, Cambridge, MA, May.

Mishan, E.J. (1976). *Cost-Benefit Analysis:New and Expanded Edition,* Praeger, NY.

Osborne, R.J. (2007). *Automotive Gasoline HCCI and CAI Engines: Future Combustion Systems for Ultra-Low NO_x Engines,* ATC Lustrumcongres, June 26.

Owen, N., and R. Gordon (2002). *Carbon to Hydrogen Roadmaps for Passenger Cars: A Study for the Department for Transport and the Department of Trade and Industry,* Report RD 02/3280, Ricardo Consulting Engineers Ltd., West Sussex, U.K., Nov. 8.

Passier, G., et al. (2007). *Status Overview of Hybrid and Electric Vehicle Technology(2007):Final Report Phase III, Annex VII, IA-HEV, IEA,* TNO Report MON-RPT-033-DTS-2007-02955, Delft, Netherlands, Dec. 6.

Plotkin, S., et al., 2001. *Hybrid Electric Vehicle Technology Assessment: Methodology, Analytical Issues, and Interim Results,* ANL/ESD/02-2, Argonne National Laboratory, Argonne, IL, Oct..

Santini, D. (2006). "Two Industry Developments That Justify Optimism about Potential for PHEV Success: Powertrains and Batteries," presented at the Electric Drive Transportation Association Conference, Washington, DC, Nov. 28–30.

Smets, S. (2007). e-mail communication to D. Santini (Argonne National Laboratory, Argonne, IL) from Smets (VITO, Belgium), downloaded Oct. 22.

Smith, B., and D. Santini (2005). *The California Greenhouse Gas Initiative and Its Implications to the Automotive Industry* Report ANL-06/05, prepared by Center for Automotive Research, Ann Arbor, MI, for Argonne National Laboratory, Argonne, IL, Sept.

Smokers, R., et al. (2006). *Review and Analysis of the Reduction Potential and Costs of Technological and Other Measures to Reduce CO_2 Emissions from Passenger Cars,* Final Report, TNO Science and Industry Automotive Business Unit, Delft, Netherlands, Oct. 31.

State of California (2007). "The California Low-Emission Vehicle Regulations for Passenger Cars, Light-Duty Trucks and Medium-Duty Vehicles," including all or portions of Sections 1900, 1956.8, 1960.1, 1960.5, 1961, 1961.1, 1962, 1962.1, 1965, 1976, 1978, 2062, and 2101, Title 13, *California Code of Regulations,* as of Oct. 11.

U.S. Department of Transportation (2004). *2001 National Household Travel Survey: Compact Disk and User's Guide,* Washington, DC.

U.S. Environmental Protection Agency (2006). *Fuel Economy Labeling of Motor Vehicles: Revisions to Improve Calculation of Fuel Economy Estimates*, Report EPA420-D-06-002, Office of Transportation and Air Quality, Ann Arbor, MI, Jan.

Vyas, A., et al. (2007). "Plug-In Hybrid Electric Vehicles: How Does One Determine Their Potential for Reducing U.S. Oil Dependence?" *Proceedings of the Electric Vehicle Symposium No. 23,* Anaheim, CA, Dec. 2–5.

Weiss, M.A., et al. (2000). *On the Road in 2020: A Life-Cycle Analysis of New Automobile Technologies,* Report MIT EL 00-003, Energy Laboratory, Massachusetts Institute of Technology, Cambridge, MA, Oct.