Comparing Cost Estimates for U.S. Fuel Economy Improvement by Advanced Electric Drive Vehicles

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Abstract

Several U.S. studies, conducted from 1997 to 2002, have employed vehicle and powertrain simulation models to estimate energy equivalent fuel economy gains and have also estimated associated retail price increases for a variety of advanced electric drive powertrains. Many of those studies attempted to control for the comparability of performance between conventional and advanced electric drive vehicles, but different sets of performance goals and simulation models were used. This paper draws from recent reviews by some of the authors of the estimates of fuel economy gain (in km/L) vs. varying measures of performance change for a set of those studies. In addition, this paper adds and comparatively evaluates retail price increase estimates, discusses and selects a measure of cost effectiveness, and adjusts information from selected studies for the purpose of comparison. We examine the implied rank ordering of vehicle technologies in terms of cost effectiveness of reducing fuel consumption. Comparisons include diesel hybrids vs. hydrogen fuel cell vehicles. Cost effectiveness of dieselization and hybridization combined is compared to cost effectiveness if implemented separately. The paper discusses whether the studies provide evidence that there is a degree of fuel economy gain (and fuel cost) at which advanced electric drive technologies are more cost effective to implement than advanced conventional technologies. The information in the surveyed studies is based on U.S. driving cycles and, with one exception, passenger cars.

Keywords: diesel engine, fuel cell, gasoline engine, HEV (hybrid electric vehicle), hydrogen.

1. Purpose

The purpose of this paper is to search for common findings among several recent prominent studies of the trade-off of cost vs. potential for reduced fuel consumption in advanced automotive powertrain technologies that make partial or full use of electric drive. Technologies to be evaluated, whose cost effectiveness relative to one another and to advanced conventional vehicles, include:

- Parallel or series hybrid powertrains that use internal combustion engines (ICEs) for primary power.
- Hybrid and non-hybrid powertrains that use direct hydrogen fuel cell (FC) primary power units.

Among parallel hybrid powertrains, primary power alternatives including gasoline and diesel fueled engines are examined. Among all types of advanced vehicles, the effects of differing degrees of hybridization, starting with a base of none, are examined. Hybrid vehicles capable of all-electric operation using power from the grid are included in some of the studies, and are examined here as well. However, the only fuel consumption figure of merit that is examined in this paper is that of the primary power unit. Benefits of all-electric operation of grid-connected hybrids are not examined in this paper.

In addition to exploring the effects of implementation of advanced electric drive powertrains in place of conventional powertrains, it is important to examine the nature of the starting point. Some studies switch to an advanced electric drivetrain from a reference vehicle that is contemporary in nature,

while others assume significant improvement in the conventional vehicle and its powertrain before making the hypothetical switch to an advanced electric drive powertrain. Only one does both.

2. Methodological Issues

2.1. Ordering alternatives from most to least cost effective

In analyzing the cost effectiveness of technologies, there is an economic model that recommends adopting technologies in order of their incremental cost effectiveness. If such a procedure is followed, analysts often plot a curve of cost increase vs. gain in distance per unit volume of fuel, as in Figures 4-5 and 4-6 of the 2001 National Research Council (NRC) study [1]. This curve is composed of a series of technological steps ordered from most cost-effective step to least cost-effective step. One thereby obtains a steadily rising curve of cost vs. fuel economy gain. Another variant plots cost vs. percent gain in fuel economy such as shown in Figure 1. Such plots imply that the slope of the curve is a measure of the incremental cost-effectiveness of that step along the curve.

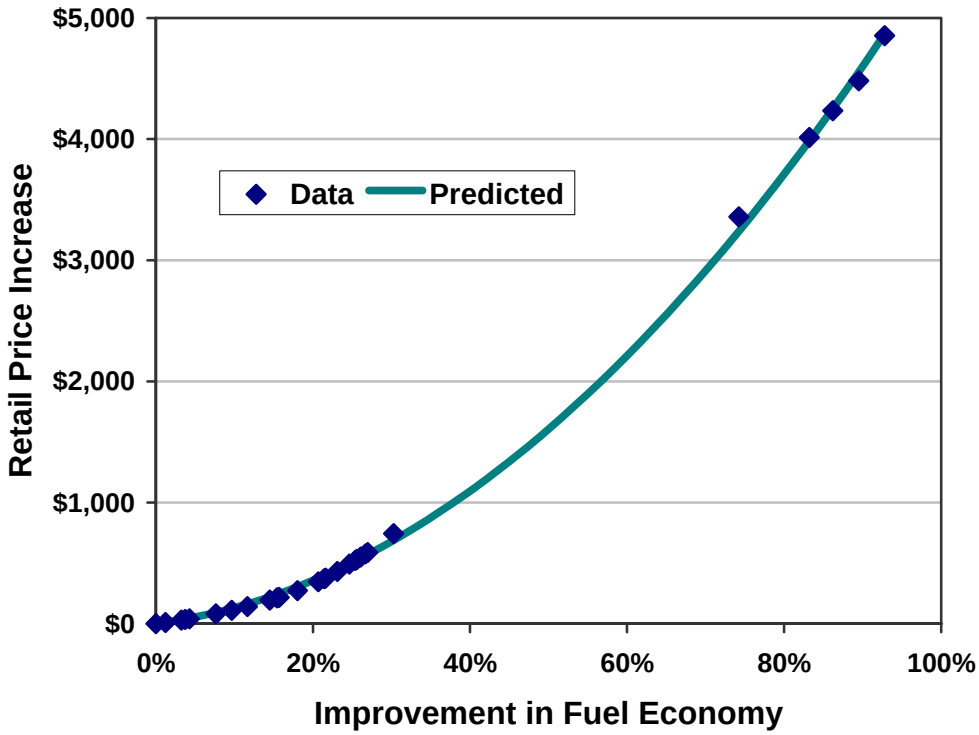

Figure 1: Passenger car fuel economy technology cost curve

However, despite the logic of this cost-effectiveness system, it is not necessary for engineering cost analysts to construct a hypothetical sequence of technological steps with this logical ordering. In fact, they generally do not.

2.2. Reasons for Ordering of Technological Steps Inconsistently

There are good and bad reasons for ordering of technological steps inconsistently with sequential increase in cost-effectiveness. Let us generally define "kilometers per liter cost effectiveness" (e-kpL) as unit change in cost per unit change in km/L for the technological step, and fuel saved cost

effectiveness as liters saved per dollar of incremental vehicle cost (e-liter). Call the variant in Figure 1 — change in cost per percent change in km/L — e-kpL%. The e-kpL approach is widely used, as the recent survey of the literature (Engineering-Economic Analysis of Automotive Fuel Economy Potential in The United States) by Greene and DeCicco shows [2].

Unfortunately, the e- kpL approach, as defined above, is often thought of loosely, in a generic fashion. Such thinking results in several different forms of this conceptual approach being used. Note that change in km/L could be defined either as percent change in km/L, or actual change in km/L. A change in cost could be defined as percent change in cost or actual change in dollar cost. There are four permutations and combinations of plots possible from these four variable definitions.

Table 1: Options for plotting cost vs. km/L trade-off curves.

	Change in cost	Percent change in cost
Change in km/L	Option 1 (e-kpL)	Option 2
Percent change in km/L	Option 3 (e-kpL%)	Option 4

In their comparison of studies, Greene and DeCicco [2] plot retail price increase vs. actual value of fuel economy for a specified model of vehicle (option 1). An, DeCicco, and Ross [3], reporting on work contributing to evaluations by the American Council for an Energy Efficient Economy, plot percent increase in retail price increase vs. percent change in fuel economy for multiple models of vehicle (option 4). Figure 1, drawn from an interim briefing of DOE sponsors on a draft Argonne National Laboratory (ANL) study, uses option 3. The NRC uses option 1 in its Figures 4-5 and 4-6 when comparing results.

The 2002 National Research Council (NRC) report, "Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards," in its detailed examination of technology pathways, also uses the fuel saved cost effectiveness (e-liter) approach and plots results on this basis (NRC Figures 3-4 through 3-13).

Some well-known studies provide examples of technological steps with a higher (lower) e-kpL or e-kpL% (e-liter) technical step adopted before a step with a lower (higher) value. These include the aforementioned 2002 NRC study, the 2001 study, "Assessing the Fuel Economy Potential of Light-Duty Vehicles," by An, DeCicco, and Ross, and the 2000 study, "On the Road in 2020," by Weiss et al. [4].

2.2.1. Time as a Consideration

There are multiple candidate reasons that the smooth, logical ordering implied by Figure 1 may not be followed. One is that the engineering analysts may regard the probability of near-term and long-term implementation of technologies to differ, but still wish to provide a summary of the potential represented by both sets. This is the case in the NRC study, where technologies are separated into "production-intent" groups and "emerging" technologies.

2.2.2. Logical Failure

Another reason to abandon apparently logical ordering is simply a failure to follow the discipline implied by the cost effectiveness system, perhaps intertwined with intuitive considerations of more probable and less probable technological steps. This is a particular concern in this paper. Rather than accept an implicit or explicit judgment by paper authors, we attempt to consider the proper ordering of mass reduction vs. hybridization in terms of the e-liter effectiveness measure. When an ordering is decided upon, or implied in the studies reviewed here, it has generally been assumed that mass reduction should precede hybridization.

2.2.3. Technically Logical Ordering

Still another reason may be a logical technical ordering in the thinking about the technologies. Before technologies can be reliably ranked in terms of cost effectiveness, their technical attributes have to be understood and the cost vs. fuel economy "space" vs. technology level has to be mapped out. In this paper, we are particularly interested in degree of adoption of battery storage relative to primary power from an ICE or FC.

Here we discuss how a logical ordering of thinking about evolution of electric vehicles appears to have resulted in misleading results and terminology, temporarily pushing research on hybrid vehicles down a path that was not cost effective. Technical analysts concerned with making electric vehicles acceptable to consumers have done most historical analysis of electric vehicles (EVs), for which electric energy is not produced on the vehicle, only stored in it. Due to the fact that the lack of range of EVs is one of their most significant problems, early analyses of hybrid electric vehicles involved creating "series hybrids" by adding a small engine to a series electric drive vehicle with no conventional mechanical drive whatsoever. The engine was considered a range extender intended only for infrequent use. For these analysts, the term auxiliary power unit (APU) seemed appropriate to describe the intent of their use of an engine in a hybridized electric vehicle. This terminology stuck, and has been improperly carried over to parallel hybrid-electric-vehicles (HEVs) for which the electric drive is actually the "auxiliary" system, while the ICE or FC is the primary system. For the most part, the papers reviewed in this paper evaluate vehicles that use electric drive, but do not use electricity generated from the vehicle to provide any energy of motion. In this paper, we do not use the term APU, and instead use the term PPU to describe the true primary power unit — either an ICE or FC.

2.3. Other Factors Affecting Ordering or Inclusion in a Package of Technologies

2.3.1. Mutual Exclusivity

In a list of options to improve technology, not all members of the list can be adopted in the same vehicle. For example, a continuously variable transmission (CVT) and an automated manual transmission are included in the NRC study's list of options, but in any vehicle only one of the two can be adopted.

2.3.2. Inseparability

One of the rules adopted in the majority of these studies states that a pair of compared vehicles should have comparable performance. If a vehicle body (glider) is reduced in mass, but the powertrain technology and size is unaltered, then the vehicle will accelerate more rapidly. A rule of comparison that requires the pair of vehicles to have comparable acceleration capability will require powertrain downsizing when the mass of the glider is reduced. Those studies that followed this rule combined glider mass reduction and powertrain downsizing in the same step. A study should provide separate estimates of the cost of the glider mass reduction and the resulting credit for powertrain downsizing. For a constant powertrain technology, the powertrain effect will always reduce costs. For the glider, however, costs will generally rise, since more expensive materials such as aluminum or magnesium would be required.

2.3.3. Path Dependence

In some cases, the adoption of a specified technology may not be likely until another enabling technology is adopted. Of particular interest here is the adoption of electrical systems with higher than 14 volts, to allow use of more electrical power. Higher voltage systems are likely to accompany a technology called integrated starter generator (ISG). ISGs are likely to be found in conjunction with 42V (or higher) electrical systems, though it is not absolutely necessary that a 42V system accompany an ISG. Similarly, electric power steering is more likely to be found in a vehicle with ISG and 42V electrical system.

Another particularly interesting technology is camless valve actuation (CVA). This technology is also likely to use electrically actuated valves, and therefore is dependent on a more electric vehicle. In principle, this technology overlaps with several valve control technologies listed separately in the NRC study (Table 2).

Table 2: Technologies that take advantage of sophisticated valve actuation (NRC 2002).

Technology	Percent km/L gain	Low price increase	High price increase	e-liter† estimates
Multivalve, overhead camshaft	2-5	$105	$140	158-288
Variable valve timing	2-3	$35	$140	47-176
Variable valve lift and timing	1-2	$70	$110	120-151
Cylinder deactivation	3-6	$112	$252	220-190
Intake valve throttling	3-6	$210	$420	117-114
Camless valve actuation	5-10 vs. VVLT up to 15 vs. 4V	$280	$560	144-137

† e-liter is computed as liters saved over 10,000 km per thousand dollars by a 11.8 km/L (27.8 mpg) car. We assume low km/L gain to match with low price increase (and high with high).

The question is, how much of the effects of the above functions can be replicated by a CVA system? Clearly the cost of the CVA is less than the cost for the full set of technologies that involve various types of valve control. An electromechanical CVA system may become desirable after a degree of hybridization (such as ISG) has been adopted, with a higher voltage system. The importance of CVA achievement of a "soft landing of the valve against the seat during idle and low-speed, low-load operation" (NRC, 2002, p. 37) would be far less in a hybrid, where the engine does not idle or operate at low load. There is a question of how sophisticated valve actuation will have to be in a hybrid vehicle. Note that one advantage of a hybrid is to make certain engine operating regimes relatively unimportant. Thus, in a hybrid it should not be necessary to have as complicated a valvetrain as in a conventional engine. For example, the Honda Civic hybrid uses a two-valve engine with limited cylinder deactivation, with a simpler mechanical valvetrain than in its conventional four-valve per cylinder VTEC engines. The Civic HEV does use "variable intake- and exhaust-valve tuning and lift." It should be noted that appropriate valve control for hybrids is probably very important for engine restart vs. normal operation. Engine restart was one of the major question marks about hybrids in 1995. The Civic HEV also uses more sophisticated injectors and two spark plugs per cylinder. As far as valve control technologies from the NRC study are concerned, it did appear in the NRC study that intake valve throttling was incorporated into the CVA system, since these two options were treated as mutually exclusive.

2.4. Variability of Cost Effectiveness as a Function of Position in Order

2.4.1. Pure Ordering Effects, Independent of Variation of Technical and Cost Effectiveness

One relatively straightforward mathematical property of fuel consumption is: if a constant e-kpL% is assumed, the later in a sequence of steps a given technology among a set of technologies is implemented, the less e-liter cost-effective it will be. The mathematical properties are illustrated by Figure 2, which assumes a set of 13 independent, non-interactive technologies, each capable of improving fuel economy at a constant e-kpL% of $62.50 per percent increase in km/L, and each capable of improving km/L by 6% regardless of sequence of placement. This e-kpL% is representative of the six technologies in Table 3-1 of the NRC study estimated to be capable of maximum gains in fuel economy of 6% or more. The ordering does result in a steadily declining e-liter measure (consistent with decreasing cost effectiveness), consistent with the intent of the ordering system. However, the e-kpL% measure is constant, even though less and less fuel savings is obtained at each step. Perversely, the implication of the e-kpL measure is that the implied cost

effectiveness improves as each step is added, since the estimated cost per unit gain in fuel economy drops. This illustrates the clear inferiority of the e-kpL and e-kpL% measures of cost effectiveness when a sequence of steps is evaluated.

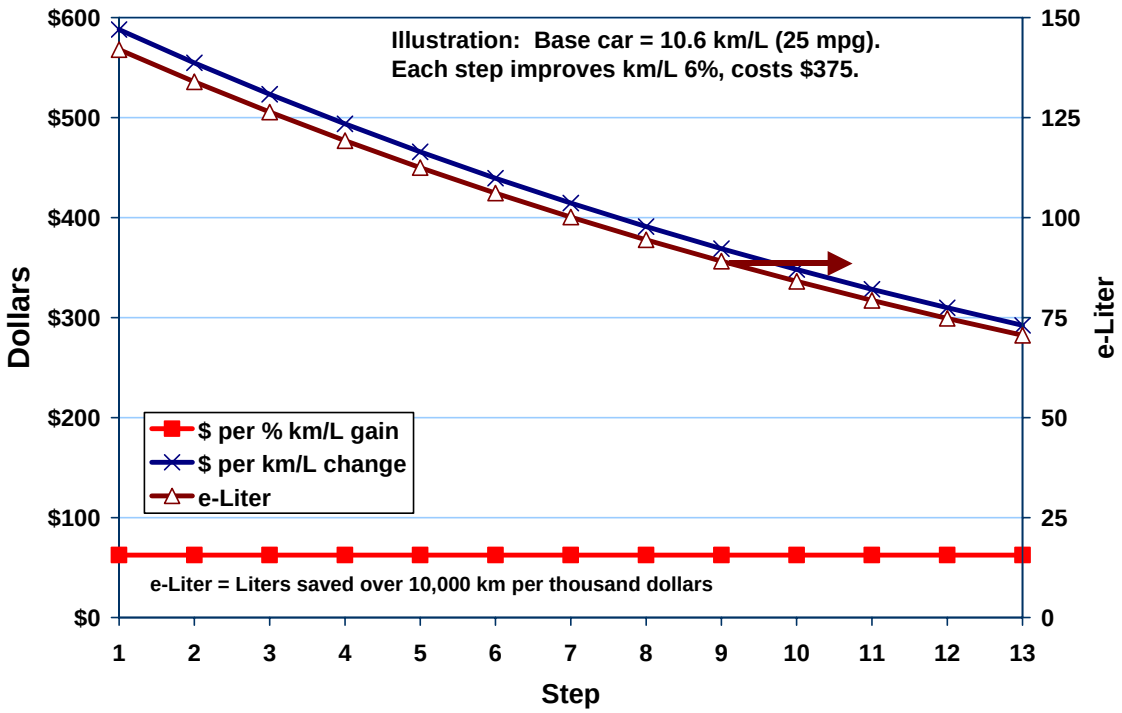

Figure 2: Plot of e-kpL, e-kpL%, and e-liter measures for an illustrative sequence of steps

This point has been made because we found concrete examples for mild vs. full hybrids (discussed below) for which use of the e-kpL% plot incorrectly implied that full hybridization should be more desirable than mild hybridization. Illustration here is beyond the scope of the paper. To assure correct results, the measure of cost effectiveness that is used here is e-liter.

There is another important illustration of this exercise. If two technologies are otherwise identical in terms of e-kpL%, then their e-liter cost-effectiveness is a function of the order in which they are analyzed. If the fuel economy gains obtainable for each are entirely independent of the other (a very unlikely condition), then the technology that is selected to go second in the order will incorrectly be determined to be less cost effective. The problem of incorrect diminution of estimated cost effectiveness for a technology could be severe if less cost-effective technologies were adopted earlier in a sequence of technical steps. The Weiss et al. study provides an example of this type of error.

2.4.2. Decline of Technical Effectiveness if Implemented Later in Order

The discussion in the prior section assumed that if a technology were implemented first among thirteen technologies, or thirteenth among them, it would still return the same % change in km/L. This led to declining incremental effectiveness in terms of liters saved per step. However, reality can be worse than this. The basic problem is that many of the candidate technologies compete with one another to save the same unit of fuel.

2.4.3. Competing to Reduce Fuel Used in Low-Load ICE Operation

As noted above, an example is the competition between hybrid technologies and technologies designed to vary the actuation of valves in order to save fuel at low engine loads. By their nature, hybrids eliminate engine operation at low load, and replace it with efficient high-load operation (though suffering losses involved in storage in the battery and retrieval of the energy). One might expect variable valve timing and variable compression ratio engines to remove opportunities to save fuel through hybridization. So, if these technologies are chosen first, a hybrid advocate might correctly claim that the steps would be unnecessary in the event of hybridization. Unfortunately, among the studies examined, there are no concrete examples that attempt to quantify this type of competition. However, as noted, the Honda Civic hybrid appears to use a less complex valvetrain than Honda VTEC engines for conventional vehicles.

A concrete simulation example was found that examined negative interactive fuel economy (but not cost) effects of reducing vehicle mass and hybridizing. Most studies cited do not have a "clean" analysis of the cost effectiveness or technical effectiveness of mass reduction before and after hybridization, but several do include technological steps that combine significant mass reduction with other changes. The one paper that did examine the effects of mass reduction before and after hybridization concluded that the fuel economy effectiveness of mass reduction in a gasoline ICE hybrid had an elasticity of about –0.5, vs. an estimated –0.8 for a conventional vehicle (Santini, Vyas, Anderson, and An, 2001) [5]. Note, however, that glider mass reduction (the glider is the portion of the vehicle excluding the powertrain) also allows reduction in size and cost of the powertrain.

2.4.4. Increase of Technical Effectiveness if Implemented Later in Order

While the only study to examine mass reduction estimated that mass reduction *after* hybridization was less technically effective in improving fuel economy, another study that examined hybrids after several load reduction steps had been taken *before* hybridization estimated that the technical effectiveness and cost effectiveness of hybridization improved. In the study by Graham et al. [6], two glider types were evaluated, one with a contemporary load, and another with a low load. By load, we mean road loads resisting movement of the vehicle. The low-load case had reductions in coefficient of drag (Cd), coefficient of tire rolling resistance (Cr), and mass. The estimated cost of the hybrids analyzed was less in the low-load case than the base case, while the costs of the conventional vehicles were estimated to be identical. Increased costs of low-load gliders were just offset by reduced costs for the conventional powertrain, and more than offset for the hybrids. Further, the estimated gain in fuel efficiency via hybridization for the full hybrid mid-size passenger car in the Graham et al. study was 45% in the base case, but jumped to 80% in the low-load hybrid case. Despite starting from a lower fuel consumption base in the conventional vehicle, the actual fuel saved was slightly higher in the low-load case, while the incremental costs of hybridization were considerably less.

This one example does imply that the interactive effects of placement in order of a sequence of technological steps do not necessarily have to be negative. It is desirable, however, that this finding be repeated and reexamined to confirm its validity.

2.5. Effects of Fuel Switching

In this paper, we present results in terms of liters of gasoline equivalents. In other words, our comparisons are based on the amount of energy in the fuel going into the vehicle tank, using a liter of gasoline as the standard of measure. Cost effectiveness breaks down when units of energy, which may cost different amounts, are used as a standard of comparison, and this is the case here. So, the reader is cautioned that the e-liter comparisons are not valid when another fuel is compared to gasoline. In the U.S., diesel fuel is consistently cheaper than gasoline on a per-unit-of-energy basis,

though it has lately been similar on a per gallon (3.785 liters) basis. Hydrogen is projected to be considerably more costly than gasoline.

3. Results

3.1. Series vs. Parallel Hybrids

Three of the groups of analysts authoring studies examined in this paper have evaluated both series and parallel hybrids. Parallel hybrids differ from series hybrids by providing a mix of mechanical and motor drive to the wheels, while the series relies only on motor drive. These groups (Thomas et al., 1998a [7], 1999 [8]; Plotkin et al., 2001 [9], General Motors Corporation et al., 2001 [10]) found the series hybrid to be inferior to the parallel hybrid in terms of fuel efficiency. The former two also published estimates that the series hybrid was inferior with respect to cost. The GM study did not discuss cost. The NRC study noted that only parallel hybrids are planned for production (NRC, p. 40). Note that the FCV is different from the ICE HEV in that it has a series powertrain, with no conventional mechanical drive whatsoever.

3.2. Studies Examined: Summary of Technologies Evaluated, and Approaches

All further discussion of gasoline or diesel ICE HEVs refers to parallel HEVs. Table 3 provides a summary of characteristics of nine of the studies examined for this report. While these studies are identified by institutional affiliation of the authors, there is no intention to attribute responsibility for analytical results to the institution rather than the authors. In order of appearance, the studies are:

ADL = Arthur D. Little, Inc., 2002, *Guidance for Transportation Technologies: Fuel Choice for Fuel Cell Vehicles*, Final Report [11].

ANL1 = Plotkin, S., et al., 2001, *Hybrid Vehicle Technology Assessment: Methodology, Analytical Issues, and Interim Results,* Argonne National Laboratory Report ANL/ESD/02-2, Argonne, Ill.

EPRI = Graham, R., et al., 2001, *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options,* Final Report, July 2000, Electric Power Research Institute, Palo Alto, Calif.

MIT = Weiss et al., 2000, *On the Road in 2020: A Life-Cycle Analysis of New Automobile Technologies,* MIT Energy Laboratory Report No. MIT EL 00-003, Energy Laboratory, Massachusetts Institute of Technology, Cambridge, Mass., Oct.

DTI = Thomas, C.E., B.D. James, F.D. Lomax, and I.F. Kuhn, 1998, "Societal Impacts of Fuel Options for Fuel Cell Vehicles," SAE paper 982496, Society of Automotive Engineers, Warrendale, Penn. [12]. (This portion of the table relies on multiple studies by Thomas et al., then of Directed Technologies, Inc. The cited SAE paper presents selected results from some of the other references used.)

EF = Energy Foundation = An, F., J. DeCicco, and M. Ross, 2001, "Assessing the Fuel Economy Potential of Light Duty Vehicles," SAE paper 2001-01FTT-31, Society of Automotive Engineers, Warrendale, Penn. (This SAE paper reports on work done for the Energy Foundation [EF].)

J & H = Jeong, K.S., and B. S. Hoo 2002, "Fuel Economy and Life Cycle Cost Analysis of a Fuel Cell Hybrid Vehicle," Journal of Power Sources 105 (2002) pp. 58-65 [13]. (This is the only paper cited that was done by an institution outside the U.S. It did evaluate vehicles as if driven on a U.S. driving cycle.)

GM = General Motors Corp. et al., 2001, *Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems — North American Analysis, Executive Summary Report.*

ANL2 = Santini, Danilo J., A.D. Vyas, J. L. Anderson, and F. An, 2001. "Estimating Trade-Offs Along the Path to the PNGV 3X Goal." In Preprint CD-ROM, 80th Annual Meeting of the Transportation Research Board, Washington, D.C.

Table 3: Elements included in various studies.

	ADL	ANL 1	EPRI	MIT	DTI	EF	J&H	GM	ANL 2
Contemporary Vehicle Loads			Yes	Yes		Yes		Yes	
Vehicle(s) With Lowered Loads	Yes	Yes	Yes	Yes	Yes	Yes			Yes
Load Reduction (mass, Cd, Cr)			Yes	Yes	Yes	Yes			Yes
Gasoline CV Engine Upgrades			#	Yes		Yes			
Transmission Switches		Yes	Yes	Yes	Yes	Yes		Yes	Yes
Gasoline CV Hybridization	Yes	Yes	Yes	Yes	Yes	Yes		Yes	Yes
Varying Battery/Motor Sizes	Yes	Yes	Yes			Yes	Yes		
Gasoline Hybrid ZEV Capability		Yes	Yes					Yes	
CV Dieselization	Yes			Yes				Yes	Yes
Diesel CV Hybridization	Yes			Yes	Yes			Yes	Yes
H2 FCV w/o Hybridization	Yes				Yes		Yes	Yes	
H2 FCV with Hybridization	Yes			Yes	Yes		Yes	Yes	
Detailed Vehicle Specifications		Yes	Yes	Yes	Yes	Yes			Yes
State Performance Requirements		Yes	Yes					Yes	Yes
EV Performance Requirements	n/a	Yes	Yes	n/a	n/a	n/a		No	n/a
Performance Goals Variation		Yes							
Retail Price Estimates	Factory	Yes	Yes	Yes	Yes	Yes	Yes		
Component Details		Yes	Yes	Yes	Yes	Yes	Yes		
Data Modified for This Paper						Yes	Yes		
Models other than Mid-Size Car	Yes				Yes	Yes	Compact only	Pickup only	
Base Driving Cycle(s)		U.S. CAFE	U.S. CAFE	U.S. CAFE	U.S. CAFE	U.S. CAFE	U.S. FUDS	U.S. CAFE	Five
Aggressive Driving Cycles		Yes			Yes				

In this study only, the gasoline engine technology is switched in the hybrid technology. Other studies keep the same gasoline engine technology.

Seven of the nine studies include price estimates for the powertrain switch. Six of the seven provide retail price estimates, and the seventh (ADL) provides a multiplier that can be used to scale up the factory costs for the powertrain to retail prices. All studies include estimates of fuel economy for technologies and/or technology "packages" examined. Thus, for seven of the studies it is possible to calculate e-liter values.

The table is divided into two parts. These are (1) technological steps to improve fuel economy, and (2) methodological assumptions, input information, and output information. The sequence of technological steps in part 1 moves from:

- Improvement of conventional gasoline fueled passenger cars to
- Degrees of hybridization maintaining use of a gasoline-fueled engine, to
- Hybridization including switching to a diesel engine, and finally,
- Adoption of direct hydrogen FC vehicles with varying degrees of hybridization.

Part 2 focuses on the information needed to reproduce the results presented by the analysts. In many cases, the information is not adequate to reproduce results. It can be seen that only three studies provide both detailed vehicle specifications and clearly stated vehicle performance requirements, and only one of these three provides retail price estimates. Only three provide estimates for more than one

vehicle model, including both a truck and passenger car model. Only two provide estimates for "aggressive" driving cycles. Aside from the GM study, all discussion in this paper refers to mid-size passenger car results. To translate the dollar cost and percent gain in fuel economy estimates from the NRC study and from the 1995 OTA study (as cited in Greene and DeCicco), we assume the same reference vehicle fuel economy as used by MIT, 11.8 km/L (27.8 mpg).

The aggressive driving cycles are actually intended to represent real world driving, since the official test cycles consistently used in these studies are actually passive relative to real world driving. Official estimates of fuel economy use the test cycles used in the cited studies and used here, but window sticker fuel economy values presented to consumers to approximate the fuel economy they should expect are discounted from the values used in this report. This is not an inconsequential point, since the Directed Technologies, Inc. (DTI) studies estimated that the fuel economy gain for an FC powertrain is less if evaluated on an aggressive driving cycle than on the official test cycles. However, the ANL1 study also simulated aggressive driving cycles and found that full hybrids were actually estimated to save more fuel on the aggressive cycles than on the official cycles (ANL1, Figure 4-2b). This is not an intuitive finding, because the percent gain in fuel economy was actually *less* on the aggressive cycles than on the official cycles (ANL1, Figure 4-2a). The ANL1 study (Plotkin et al., 2001, p. 92) estimated far higher degradation of CV fuel economy in the aggressive driving cycles that it examined than did the DTI study (Thomas et al., 1998a, p. 37). This is the leading candidate explanation for the differences between the two studies. However, the aggressive driving cycles used in the two studies were not identical, and the vehicle simulation model used by DTI is proprietary, so explanation of these apparently contradictory findings would require more research.

Modifications were made for two studies. Jeong and Hoo did not include the base fuel economy of a comparable reference vehicle. We used a ratio of fuel cell vehicle (FCV) gasoline-equivalent fuel economy to a comparable conventional vehicle consistent with that developed by Santini et al. (2002) [14] to construct estimates of the fuel economy gains via direct hydrogen FCVs. This paper is referenced primarily for the relative effects of degrees of hybridization. The Energy Foundation analysts (An, DeCicco and Ross) folded an integrated starter generator (ISG) and aggressive idle-off strategies as one of the first technologies to be implemented. They did not describe this as a stage in hybridization. However, in this paper, this is regarded as the first step in hybridization, involving an increase in battery "pack" size and in voltage (up to 42 volts from 14). An, DeCicco and Ross did provide the most detailed technology-by-technology analyses of the incremental fuel economy gains from one selected sequence of 10 different technological steps to improve the fuel economy of a mid-size passenger car. Included are two separate improvements from an ISG — more electric auxiliary equipment and idle-off. A cost value for the ISG was also included in the paper. This allowed us to "back out" the effect of the ISG and treat it as the first step in a sequence of three steps involving an increasing degree of hybridization — from minimal to mild to full hybridization.

Only one of the studies examined within-study variation in required level of performance (ANL1). This study varied the 0-97 km/h (0-60 mph) acceleration requirements for pairs of baseline and hybrid vehicles from 12 to 10 to 8 seconds. It was estimated that the higher the level of acceleration performance of the vehicle hybridized, the more cost effective hybridization would be.

Two of the three studies for which evaluated hybrid vehicles had all-electric operation capability specified their performance requirements for the vehicle were it to be driven all-electrically. The EPRI study required that the vehicle be able to successfully match the speed vs. time trace required by the aggressive US06 driving cycle for two repetitions of the cycle, starting from about 20% battery state-of-charge (SOC). The ANL1 study examined requirements for the vehicle to accelerate from 0-97 km/h (0-60 mph) in 12, 14, or 16 seconds, starting from 20% SOC. Due to the component attributes and other performance requirements, those vehicles in the ANL1 study that could operate all-electrically had a charge-sustaining (normal hybrid mode operation) 0-97 km/h (0-60 mph) acceleration capability from 8 to 9 seconds. The EPRI hybrids also had charge-sustaining 0-97 km/h (0-60 mph) acceleration capability of 9 seconds, considerably faster than that required by the US06

cycle. Thus, both studies that simulated all-electric operations capability allowed the vehicle to have "deteriorated" performance capabilities when operating all-electrically. Nevertheless, the electric operations capabilities should easily satisfy all but the most demanding of drivers.

The all-electric ranges examined varied from a minimum of 12 km (7.5 miles) (GM) to about 32-48 km (20-30 miles) (ANL1) to 32 km (20 miles) and 97 km (60 miles) (EPRI). GM did not specify vehicle performance when it is operating all-electrically.

EPRI and GM each specified a relatively large set of differing performance minima (11 and 8, respectively), while ANL1 and ANL2 specified only 0-97 km/h (0-60 mph) acceleration and ability to climb a 6.5% grade at 89 km/h (55 mph) or more for at least 20 minutes. Five of the eight performance criteria specified by GM involved acceleration, compared to three of eleven by EPRI. Among the three base case (contemporary vehicle body) hybrids examined by EPRI, those two capable of all-electric operation were estimated to be capable of top speeds of 156 and 158 km/h (97 and 98 mph). The full hybrid (without any all-electric operations capability) was estimated to be capable of 193 km/h (120 mph) top speed. The minimum top speed required by GM was 177 km/h (110 mph), and by EPRI, 145 km/h (90 mph). EPRI also required capability to maintain 80 km/h (50 mph) for 15 minutes on a 7.2% grade, compared to GM's 89 km/h (55-mph) speed requirement for 20 minutes on a 6% grade. GM examined a pickup truck, not a passenger car.

Among the studies reviewed, the base vehicle that is hybridized is an advanced, lightweight, low Cd, low Cr vehicle in the ANL1, MIT, EF, and ANL2 studies. The base vehicle is contemporary in the EPRI and GM studies. The base vehicle in the ADL study had moderate load reduction. The DTI study used a low mass aluminum vehicle with contemporary Cd and Cr values. There was no base vehicle in the Jeong and Hoo (J & H) study.

Among the nine studies, it appears that a total of seven different vehicle simulation models have been used to estimate fuel economy gains.

In light of the fact that these studies vary so widely in performance rules, level of mass, Cd, and Cr reduction, vehicle simulation models, component characteristics and prices, caveat emptor.

3.3. Degree of Hybridization

The parallel hybrid analyst essentially starts the analysis with a conventional vehicle (CV) and modifies it by adding various degrees of motor and battery power. One can think of vehicles powered by either an ICE or FC PPU, with a range of possible supplemental power levels to be provided by electric power stored in a battery. The degree of hybridization of the vehicles ranges from none for both ICE and FC PPUs to 60-66% for ICE HEVs (Plotkin et al., 2001, Graham et al., 2001) and to 73% for FC HEVs (Jeong and Oh, 2002). The higher percentages of hybridization of ICE HEVs *are* associated with HEVs designed to be capable of all-electric operation with more than 32 km (20 miles) and up to 97 km (60 miles) of all-electric range. The FC case simply involves a coarse sensitivity analysis of the effects on fuel economy arising from various degrees of hybridization.

Degrees of hybridization are recognized in the terminology used by analysts of hybrid drive. One convention used has been "mild" vs. "full" hybridization. There is no strict definition of what this means. However, it is used in these studies to refer in both cases to hybrids not designed to operate all-electrically. Plotkin et al. refer to these hybrids as "grid independent." For practical purposes, all that can be said is that the full and mild terminology as used here refers to hybrids not capable of all-electric operation. The one with the larger motor and battery pack is called a "full" hybrid, and the one with lesser power from the motor and battery pack is called a "mild" hybrid. In both cases, the electrical systems probably operate at hundreds of volts rather than dozens. To identify hybrids that have all-electric range in this paper, we use the convention adopted by Graham et al., and attach the estimated all-electric range to the HEV acronym. To illustrate, an HEV with 97 km (60 miles) of all-

electric range is an HEV60, one with 32 km (20 miles) is an HEV20. The HEV0 in the Graham et al. study is a "full" hybrid by this paper's definition.

At the other end of the hybridization scale, the minimum level of hybridization is examined in only one of the studies cited here (An, DeCicco, and Ross, 2001). In fact, we call it hybridization while An, DeCicco and Ross do not identify it as such. We might call this "minimal" hybridization. It is associated with an increase of voltage from 14 to 42 volts or slightly more. One minimal hybrid technology, called the integrated starter generator (ISG), involves a system that can allow the engine to be turned off at idle and during decelerations. Some of these systems can also provide a bit of regenerative braking.

In a recent presentation (March 8, 2002), T. Ikeya noted that Japan produces a range of degrees of electric drive [15]. For HEVs, this includes the Toyota Crown, which has only idle off; the Honda Civic, which includes idle off and regenerative braking; and the Toyota Prius, which includes idle off, regenerative braking, and motor assist (electric launch). There are presently no Japanese production HEVs that include idle stop, regenerative braking, electric launch, and all-electric operation capability (grid connectability). At the end of the drivetrain electrification continuum is the all-electric vehicle (EV), several of which have been produced in Japan.

For our purposes, we consider any modification of a contemporary vehicle that includes a higher than standard voltage, and idle off, to be the first step in a continuum of hybridization. By our definition, the hybrid options are:

Minimal hybrid = idle off, perhaps some degree of regenerative braking (ISG)
Full hybrid = idle off, considerable regenerative braking, electric launch
Mild hybrid = between minimal (or nothing) and full, in any given study
HEV## = a grid connected hybrid with ## miles of electric range

The logical ordering in an evaluation is from minimal to mild to full to grid connected (HEV##). Table 4 provides our estimates of e-liter for gasoline SI ICE hybrids examined in four studies, and includes an e-liter estimate for an ISG, derived from the NRC study. After the NRC study case, for which no performance level is specified, the cases are ordered from fastest 0-97 km/h (0-60 mph) time for the pair of compared vehicles to slowest. There are two groups of e-liter figures. The first group is the e-liter figure for the given hybrid relative to the conventional vehicle. The second group is the e-liter figure for the incremental step from one hybrid to the next hybrid characterized by the study, going from the least to most "hybridized." In five of the eight cases, it is possible to compare the e-liter figures as the share of power provided by a battery pack rises. In four of the five cases, it is estimated that the incremental e-liter cost effectiveness declines as the relative size of the battery pack increases. There is some evidence, going from left to right, that the e-liter effectiveness of hybridization rises as the performance level of the pair of vehicles rises. Most of this is based on results from one study. While all vehicles in this table are nominally mid-size passenger cars, the scatter in vehicle mass, aerodynamic drag, and rolling resistance is large. The two high e-liter estimates (MIT and EPRI low) are for cars with very low vehicle loads (i.e., mass, aerodynamic drag, and rolling resistance).

When compared to dieselization (discussed below), the first step of hybridization, the ISG system, appears to be more cost effective. Based on share of power provided by the motor, the Honda Civic hybrid is somewhere between the minimal HEV case and mild HEV cases in this paper. The estimated cost effectiveness of minimal to full hybridization in these recent studies is well in excess of what is obtained using numbers from the Office of Technology Assessment's 1995 study. The e-liter estimate derived from the lead acid battery-equipped hybrid hypothesized in that study (see Greene and DeCicco, 2000, table 11) is 25.9 L of gasoline saved per 10,000 km of operation (11 gallons of gasoline per 10,000 miles of operation) per $1000 of incremental vehicle cost, far below recent estimates. Our estimate of e-liter for the 9kW battery pack (small battery) case from the Arthur D. Little study is 105, and for the large battery case, it is 73, comparable to values in the table.

Table 4: Fuel saved per incremental dollar cost for degrees of hybridization of SI HEVs.

	NRC	ANL 1	ANL 1	EF revised	MIT	EPRI base	EPRI low	ANL 1
Reference 0-97 km/h time (s)	-	12	10	10	≈10	9	9	8
Fuel Economy (km/L)								
Future CV	11.2	15.9	13.9	15.4	20.9	12.3	14.8	11.4
Minimal HEV	11.6-12.0			17.3				
HEV Mild		19.8	19.1	22.4	30.1			17.7
HEV Full		21.6	21.0	25.2		17.8	26.7	19.8
HEV20			20.2			18.5		19.2
HEV60						19.3	25.8	
Estimated Cost ($)								
Future CV		$21,200	$22,500	$19,827	$19,400	$18,984	$18,984	$25,100
Minimal HEV	$210-350*			$20,327				
HEV Mild		$24,150	$25,710	$23,057	$21,100			$28,200
HEV Full		$24,610	$26,520	$24,624		$23,042	$21,268	$29,770
HEV20			$29,740			$24,966		$33,070
HEV60						$29,523	$25,881	
Liters saved per 10,000 kmper $1000 when switching from-to:								
CV-Minimal HEV	171-172			147				
CV-Mild HEV		42	62	63	86			100
CV-Full HEV		48	61	53		62	132	79
CV-HEV20			31			46		44
CV-HEV60						28	42	
Minimal-Mild				47				
Mild-Full		93	57	32				39
Full-HEV20			-6			11		-5
HEV20-HEV60						5		
Full-HEV60						7	-3	

* Represents incremental cost. All other values represent retail vehicle price.

The A.D. Little study's fractions of power provided by the battery are 0.09 for the small battery case, and 0.45 for the large battery case. A.D. Little HEV acceleration design values were 11.5 seconds. The U.S. Prius provides about the same fraction of battery power (≈ 0.39) as the ANL1 12-second full HEV case, and also has a 0-97 km/h acceleration capability of a bit over 12 seconds. In contrast, the Honda Civic hybrid has a fraction of battery power of 0.13, compared to A.D. Little's "small battery" case fraction of 0.09. Based on this alone, the Civic HEV should be considerably more cost effective than the Prius, although the specifics of the analyses in the studies in Table 4 are certainly not identical to either the Civic HEV or Toyota Prius. For example, the ANL1 study did not alter engine technology in the HEV, while Toyota switched to a more efficient, yet cheaper Atkinson cycle engine.

3.4. Mass Reduction and Hybridization of a Gasoline ICE

With regard to improvement of the conventional vehicle prior to hybridization, the EF, MIT, and ANL2 studies have the greatest number of steps, but only the former two studies include vehicle and powertrain price estimates. The EPRI study allows extraction of one step, from baseline to low-load vehicle. The EPRI study provides a retail price estimate for both the high-and low-load vehicle.

Table 5 illustrates the mass reductions from the conventional vehicle that were adopted in five studies before switching to a hybrid powertrain. These studies also included other changes in the vehicle as mass was reduced. Other load reductions included lowered aerodynamic drag, and/or tire rolling resistance. Both MIT and EF incorporated a gasoline direct injection engine before hybridization. The ANL2 study incorporated a moderately more efficient engine. The ANL1 and EPRI studies did not incorporate a more efficient engine in their conventional vehicle prior to hybridization. Among these five studies, the EPRI study was the only one to incorporate a more efficient Atkinson cycle gasoline engine (as in the Toyota Prius) after the hybridization step.

The mass reduction cost estimates are sparse and inconsistent. MIT's first step of 14% mass reduction was costless. In fact, if the MIT $240 credit for engine downsizing is considered, mass reduction was actually accomplished with cost reduction. This contrasts sharply with the NRC estimate that a 5% mass reduction would cost $210-350. EPRI estimated that 16% mass reduction would also be free. The cost of the lighter glider was estimated to rise by $552, or 4.4%. This was completely offset by a $552 reduction in powertrain cost, amounting to 8.6%. EF also estimated that its first mass reduction step of 9% would be free, and did not list a credit for engine downsizing. In principle every study of the effects of mass reduction should include separate costs for the glider mass change and powertrain mass change, as MIT and EPRI did. The second 9% of mass reduction in the EF study was estimated to cost $166, again with no credit listed for engine downsizing. Clearly, EF, MIT, and EPRI are far more optimistic regarding the costs of an initial step of mass reduction than is the NRC.

Table 5: Mass and fuel economy estimates from various studies.

	ANL2	ANL 1	ANL 1	MIT	EF	EPRI base	EPRI	ANL 1
Reference 0-97 km/h time (sec)	12	12	10	≈10	10	9	9	8
Mass (kg)								
CV 2000	1407	n/a	1418	1444	1644	1682	1682	n/a
CV 2020 baseline	1181			1236	1494			
CV 2010 (ANL1) or 2020		1175	1248	1136	1343		1408	1366
HEV 2010 (ANL1) or 2020 (mild)		1246	1321		n/a			1453
HEV 2010 (ANL1) or 2020 (full)	1215	1247	1328	1154	n/a	1603	1392	1466
Mass fraction of CV 2000								
CV 2020 baseline	0.84			0.86	0.91			
CV 2010 (ANL1) or 2020	0.86		0.88	0.79	0.82		0.84	
HEV 2010 (ANL1) or 2020			0.93					
HEV 2010 (ANL1) or 2020	0.86		0.94	0.80	n/a	0.95	0.83	
Fuel Economy (km/L)								
Base CV	13.5	n/a	n/a	11.8	11.1	12.3	12.3	n/a
Future CV	17.3	15.9	13.9	20.9	17.3		14.7	11.4
HEV Mild		19.8	19.1		22.4			17.7
HEV Full	23.2	21.6	21.0	30.1	25.2	17.8	26.7	19.8
Fuel Economy Gain								
CV Improvement	28.0%	n/a	n/a	76.6%	55.3%	n/a	19.7%	n/a
Mild HEV Improvement		24.3%	38.0%		29.2%			54.6%
Full HEV Improvement	33.9%	35.7%	51.5%	44.2%	45.7%	45.0%	81.2%	73.2%
Notes	Moderate efficiency engine in ANL cases			GDI engines prior to HEV step	GDI engines prior to HEV step	Engine switch at HEV step	Engine switch at HEV step	

Using 11.8 km/L as the mid-size passenger car base, it is estimated that mass reduction has an e-liter value of 94 to 118 according to the NRC, well below the estimate of 171 to 172 for the ISG with idle off. Thus, according to the NRC, the correct cost-effectiveness sequence would be minimal

hybridization before any mass reduction. Since EF, MIT, and EPRI report the net cost of their first step of mass reduction as zero or negative, by their estimates mass reduction should clearly be adopted before minimal hybridization.

The EF second mass reduction step is estimated to have an e-liter value of 390, in comparison to an e-liter value of 147 for the ISG with idle off. By this estimate, even the second step of mass reduction, from 10 to 20%, should be adopted before minimal hybridization. In the EF study, this is the ordering mistake that was referred to earlier. Despite these estimated e-liter values, the EF study adopted mass reduction after minimal hybridization. The EF e-liter results have implications opposite to those of the MIT study, concerning the ordering of the second mass reduction step and minimal hybridization.

For its second mass reduction step from 14% to 21%, MIT estimated sharply rising costs of $1600, with an engine downsizing credit of $360. It has been mentioned earlier that MIT made a mistake if one believes that the logical cost effectiveness system should be used for ordering of selection of technical steps. The e-liter figure for MIT's first step was 376. This value is related to a bundle of technologies, not to mass reduction alone. The step incorporated free mass reduction and a $240 engine downsizing credit with a gasoline direct injection [GDI] engine with variable valve control [VVLT] costing a total of $800. However, the second step (with additional mass reduction, engine downsizing, and aerodynamics) has an e-liter value of 47. The next step (hybridization and a switch to a CVT) has an e-liter figure of 86. So, if the cost effectiveness system were used, a preliminary look at these numbers would have indicated that the second mass reduction step was not as cost effective as hybridization, and this step would have been moved to a later position in the sequence of steps. Even if we were to use Stodolsky et al.'s [16] more optimistic estimates of $800 for net costs of 19% mass reduction in aluminum bodied vehicles in 1995 (including powertrain mass reduction benefits), our inflation-adjusted estimated e-liter value for the second step in the MIT study would only rise to about 61.

Despite the fact that MIT adopted aggressive technology for the conventional vehicle, it was still estimated that the hybridization step would return 44% fuel economy improvement. Of course, as was illustrated in the methodology discussion, the decision to place this step after the second mass reduction step led to a lower e-liter value than would have been obtained had hybridization been placed in the correct sequential order. By its choice of assumptions, the MIT study team was clearly a very aggressive advocate for continuation of improvement of conventional vehicles in conjunction with conventional powertrains. Before hybridization was simulated, coefficients of drag and rolling resistance were reduced by 33% each, well in excess of EF's 10% and 20% values. An error also resulted from this effort to combine the conventional powertain with significant load reduction. The frontal area was reduced from 2 square meters to 1.8 square meters in a nominally mid-size vehicle. This is quite unlikely, considering that the narrow Honda Insight 2-seater vehicle has a 1.9 square meter frontal area. These assumptions combined led to an estimated potential gain for a vehicle with conventional powertrain of 77%, the highest in the group of studies in Table 5.

Of course, if the MIT study team is to be criticized for being overly aggressive in favor of improved conventional powertrains, ANL1 study analysts can be accused fairly of being far too pessimistic. The EPRI study, however, does provide a case with mass and other load reductions almost as aggressive as for MIT (but without powertrain changes), and estimates considerably lower gains in fuel economy (20%) than either MIT (77%) or the EF (55%). This suggests that powertrain changes play a major role in the MIT and EF estimates of the potential to improve conventional vehicles. We note that, although both of these studies switch transmissions as well as engines in their conventional powertrains, neither provides an estimate of the cost or credit for the transmission.

Even though the MIT and the EF studies adopt GDI and variable valve control technologies that capture some of the fuel savings that a hybrid could capture without these two technologies, they nevertheless estimate a considerable gain in fuel economy via hybridization. In general, Table 5

illustrates that mild to full hybridization has the potential to improve fuel economy from 24-81%, a range well in excess of any single technology listed in Tables 3-1 through 3-3 in the NRC study.

Variation in cost estimates of mass reduction in these studies is well in excess of the variation in cost estimates of hybridization for similar levels of hybridization. Thus, to evaluate the cost effectiveness of mass reduction vs. hybridization, the greater need appears to be for study of costs of mass reduction.

Compilation of the studies done in the tables here shows that there are a large number of differences among studies done to date, and many holes in the comparison matrix that could be filled productively.

3.5. Dieselization vs. Hybridization

Five of the studies reviewed in Table 3 include dieselization cases. Of those, two do not include vehicle prices (GM, ANL2). Another (DTI) does not include a gasoline fueled SI engine as a reference case for the conventional vehicle or the hybrid. Thus, there are only two studies that allow us to construct the e-liter value for a conventional powertrain gasoline SI case to a conventional diesel CIDI case, as well as for a hybrid powertrain gasoline SI case to a hybrid diesel CIDI case. These are:

Vehicle pair	e-liter
MIT CV Dieselization vs. GDI	54
MIT HEV Dieselization vs. GDI HEV	46
ADL CV Dieselization	110
ADL Sm. Bat. HEV Dieselization	91

The MIT study converts from a high-efficiency GDI engine, and estimates a lower e-gal value than does the Arthur D. Little study, which converts from a contemporary gasoline engine. The MIT study implies that hybridization is more effective than dieselization. The ADL study obtains an e-liter value of 106 for "small battery" hybridization, which is nearly identical to the value obtained for dieselization. However, recall that diesel prices are consistently less than gasoline prices per unit of energy delivered. In recent years, the retail prices in the U.S. have been similar, so the price-related benefit of switching to diesel would be on the order of 10-20%. Taking this into account, the two studies provide inconclusive results with respect to the incremental cost effectiveness of dieselization vs. hybridization. In most of Europe, diesel prices are far lower than gasoline prices, due to unequal taxation. Thus, these comparisons imply that the diesel would be the more cost-effective technology for the typical European consumer.

The information from these studies indicating that hybridization is competitive with dieselization is a considerable change from a 1995 OTA study cited by Greene and DeCicco (2000). The estimates of cost-effectiveness of the hybrid have risen upward from OTA's value of 26, while the estimates of cost effectiveness of dieselization of a CV have dropped from OTA's 138. The OTA estimates of cost-effectiveness of dieselization after hybridization drop off more sharply than the MIT and ADL estimates. For the high fuel economy end of the possible range, the OTA cost effectiveness is 86, while for the low fuel economy gain end of the range, the cost effectiveness is 38.

The MIT, GM, and ANL2 studies each estimate that the diesel's gasoline equivalent fuel economy improvement would be less than the '95 OTA estimate. For dieselization of the CV, the estimated gains were 14%, 18%, and 15% respectively, vs. 25% by OTA. For dieselization of the hybrid, the estimated gains were 16%, 20%, and 9%, respectively, vs. 3% to 8% by OTA. The contrast in the before and after hybridization results is striking.

3.6. Direct Hydrogen Fuel Cell Vehicles vs. Diesel Hybrids

The most thermodynamically efficient of the technology options under consideration are diesel hybrids and direct hydrogen fuel cell vehicles. Our estimates of the e-liter figures derived from the 1995 OTA study, and the four studies from Table 3 that include dollar values for FCVs, are shown in Table 6. It is apparent that the DTI study of 1999 was quite optimistic relative to other studies, for the cost effectiveness of either the diesel hybrid or the H2 FCV. However, Table 6 also illustrates that even the DTI study estimates a relatively low e-liter figure for the incremental step from a diesel hybrid to a hydrogen fuel cell vehicle. MIT is alone in predicting that the fuel cell hybrid is more e-liter effective than the diesel hybrid. This is because the MIT study estimates that the cost of a fuel cell vehicle is identical to a diesel hybrid, but the FCV is estimated to obtain only 14% better gasoline equivalent fuel economy than the diesel HEV. With respect to estimated fuel economy gains, the MIT study is the most pessimistic of the six studies that include both diesel HEVs and FCVs (GM in addition to studies with price estimates cited in Table 6). Thus, it is desirable to keep in mind that the e-liter estimate is affected by both price and fuel economy gain estimates. Among the six studies, there is a general pattern that the higher the estimate of gain in diesel HEV relative to the CV, the lower is the estimated gain of the FCV relative to the diesel HEV.

In addition to the fact that the incremental e-liter effectiveness of the FCV (relative to the diesel HEV) is consistently estimated to be low, it is also necessary to recall that when fuel switches are involved, the cost of fuel must also be considered. Hydrogen is likely to be a very costly fuel, probably two or more times the cost of gasoline. Diesel, on the other hand, costs less on an energy equivalent basis. Thus, if the e-liter values were adjusted by expected relative fuel prices, the cost-effectiveness of the FCV would drop considerably compared to values illustrated.

Table 6: Liters saved per 10,000 km per $1000 (e-liter) by diesel HEVs & H2 FCVs.

	DTI	MIT	J&H	OTA	ADL small bat.	ADL large bat.	GM
e-liter Estimate							
Diesel HEV vs. CV	344	72	na	85	100	63	12.5†
H2 FC HEV vs. CV	225	85	38	71 (MeOH)	51	55	
H2 FC HEV vs. Diesel HEV	55	infinite	na	52	32	46	20.4†
H2 FC vs. CV	225	na	15	na	na	na	
H2 FC vs. Diesel HEV	48	na	na	na	na	na	
Fuel Economy Gain (%)							
H2 FC HEV vs. Diesel HEV km/L gain	17%	14%		46%	69%	67%	64%
Diesel HEV vs. CV km/L gain	128%	68%		72%	47%	60%	46%

† Represents km/L value.

The incremental energy economy gain of the fuel cell vehicle is considerable, ranging from MIT's estimate of 14%, to ADL's small battery case estimate of 69%. The average among the six studies is 46%, a considerable jump relative to an already efficient diesel HEV technology. The estimates here do not attempt to place a value on the ability of the H2 FCV to use fuels other than oil, to produce almost no tailpipe emissions of criteria pollutants, and/or to make use of methods of hydrogen production with very low greenhouse gas emissions. Such topics are beyond the scope of this paper.

4. Findings

Series hybrids cost more than parallel hybrids, and are less efficient (DTI, ANL1, GM).

Ranking of dieselization vs. hybridization is uncertain (ADL, MIT, DTI, GM, ANL2, NRC).

Optimum ordering of hybridization within multiple steps of load reduction is uncertain (MIT, EF, DTI, EPRI, NRC).

Minimal hybridization is desirable before some other steps commonly evaluated (EF, MIT, NRC).

Hybrids provide an opportunity for a significant discrete jump in fuel economy (all studies).

Hydrogen fuel cell vehicles provide an opportunity for a second discrete jump in energy efficiency, relative to hybridization of CVs with ICEs (ADL, MIT, DTI, GM), but are least cost effective among the technologies examined in this paper.

The cost effectiveness of substituting battery pack power for primary power unit power drops rapidly and even turns negative for very large battery packs (ADL, ANL1, EPRI, EF, J&H).

Effects of aggressive driving on relative fuel economy gains and fuel consumption savings of advanced electric drivetrains are inconclusive, and differ across the only two studies that examined the effect (DTI, ANL1).

The desirable sequential order of multiple mass reduction steps vs. minimal to full hybridization is inconclusive (MIT, EF, NRC, EPRI).

In view of the significant improvement in relative cost effectiveness of hybrid vs. diesel technology from 1995 (OTA) to the present (NRC, ANL, EPRI, MIT), we remind readers that this demonstrates that research and development can alter fairly rapidly the relative merit of the technologies discussed in this paper. Advancements in electric drivetrains have the potential to improve the relative merit of both hybrids and fuel cell vehicles, while research is especially necessary to reduce the cost of fuel cell PPUs.

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