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Comparing Estimates of Fuel Economy Improvement Via Fuel-Cell Powertrains

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ABSTRACT

Several studies, conducted from 1997 to 2001, have employed vehicle and powertrain simulation models to estimate fuel economy gains for a variety of fuel-cell powertrains. Many of those studies have attempted to control for the comparability of performance between conventional and fuel-cell vehicles (FCVs), but different sets of performance goals and simulation models have been used. This paper reviews the estimates of fuel economy gain (in mpg) vs. varying measures of performance change for a set of those studies. We examine some of the potential causes for the variability of these estimates — fuel used, powertrain hybridization, vehicle raw energy requirements (load), and variations in analysts' assumptions/estimates — when substituting several types of fuel-cell powertrains.

Our study includes development of a database and detailed examination of the relationships among powertrain and vehicle characteristics and fuel economy gain estimates for the selected studies. We developed simple equations by powertrain type to systematically examine the causes of variation in mpg gain among those conventional/FCV pairs controlled to have the same peak kW per kg of vehicle test weight (a surrogate for acceleration capability).

INTRODUCTION

Two widely publicized recent studies — by Weiss et al. of the Massachusetts Institute of Technology (MIT) (1) and by General Motors Corporation (2) — have drawn attention to the use of full fuel-cycle modeling of advanced vehicle technologies. While both of these studies employ Argonne National Laboratory's (ANL's) Greenhouse gas, Regulated Emissions, and Energy use in Transportation (GREET) model for the "well-to-tank" estimates of energy use and greenhouse gas (GHG) emissions (1,2,3), each uses its own vehicle simulation model for the "tank-to-wheel" portion of the analysis. Both studies introduce and formalize the idea of uncertainty in their estimates. In preparation for the analyses reported in this paper, we set up pairwise comparisons of conventional and advanced technology vehicles from these two studies and examined the estimates of percentage change in fuel economy predicted by switching from a baseline conventional vehicle (CV) to a fuel-cell vehicle (FCV) powertrain. This exercise revealed that — for the gasoline FCV in particular — the most probable change predicted by one study was considered an extremely low-probability possibility in the other. Significant differences also existed for the methanol FCVs.

Pursuant to updating the default, or baseline, tank-to-wheel estimates of fuel economy for various powertrains in the GREET model, Wang surveyed most of the studies that will be examined here and compiled estimates of the ratio of fuel economy of the advanced vs. the conventional vehicles (3). The method used, consistent with past estimates in GREET, was to review various studies to assess their credibility, construct estimates of the ratio of fuel economy for the advanced vs. the conventional vehicles, and select a representative value. Simple averaging was not used. Rather, some professional judgment of the relative quality of the estimates was made and, on this basis, a value was adopted. In light of the emphasis of Weiss et al. (1) and General Motors (2) on the existence of an uncertainty range, the latest approach for the well-to-tank information in the GREET model is to provide readers with the range of estimates developed from studies that have been cited (3). According to Wang's initial estimates, the Weiss et al. (MIT) estimates of fuel economy gained through adoption of fuel-cell powertrains in place of conventional powertrains are pessimistic. However, after adjustments made in this study, it appears that Weiss et al.'s study was more consistently optimistic than other studies.

In a companion paper to this one, Santini et al. (4) argue, in effect, that if analysts are to understand the real degree of uncertainty among vehicle simulation studies used in full fuel-cycle models such as GREET, the vehicle simulation studies will have to be rigorously compared. In fact, a set of rules and requirements for information needs to be developed if studies are to be properly compared to one another. The companion paper assesses only one advanced powertrain type, gasoline-fueled hybrid electric vehicles (HEVs), although a few of the many hybrid powertrain technology types are examined. This paper examines several fuel-cell powertrain/fuel types rather than just one, although each is examined in considerably less detail and with fewer data points than was possible in the companion paper on gasoline-fueled hybrids. Such conventionally powered gasoline hybrids are already on the market. Fuel economy and performance test results are available for these vehicles, and public-domain vehicle simulation models have been "populated" with information on tested components that are used in these vehicles.

FCVs are in the prototype stage, and far less public-domain information on operating components for these vehicles exists. Components are still under development, and present versions are not at the stage where developers intend them to be. We recognize that the FCV powertrain components will require considerable refinement and improvement before they are ready for commercialization and/or wide-scale field-testing. Thus, for FCVs, there is room for considerable differences in the projections of ultimate fuel economy gains of the technology when technical limits to component performance are approached. Analysts can and do have different opinions concerning the likely success of ongoing research and development efforts for the various component attributes.

One goal for policymakers is simply to understand the consequences and nature of the assumptions of vehicle simulation experts who have made projections of FCV fuel economy. In particular, policymakers need to examine the wide differences in the General Motors and Weiss et al. studies — resulting either from the large differences in the projected efficiency of components or from the differences in their estimates of the ultimate specific power (kW per unit mass) attainable from these technologies. If we assume that the specific power of a fuel-cell powertrain will inevitably be considerably less than that of a conventional powertrain, then an FCV with the same vehicle kW/kg ratio as a competing conventional vehicle will be considerably heavier than the conventional vehicle. Consequently the FCV will suffer a mass-related fuel economy penalty, which would work against the inherent efficiency of conversion of the fuel to energy.

The authors of several of the recently completed studies have developed and followed rules for comparison of simulated conventional and advanced vehicle powertrains (1, 2, 4–10). What these studies have in common is that they specify a performance constraint, or constraints, and insist that both the conventional and advanced vehicle technology match or exceed the specified performance constraints. They also insist on use of the same "glider" — vehicle body — and account for the vehicle mass effects arising from switching the powertrains in that glider. The glider has a set of specified determinants of vehicle load: mass, coefficient of drag (C_d), frontal area (A), and rolling resistance (C_r) that are held constant (or nearly so for mass) in both the conventional and the advanced vehicle. All of the above studies insist on similar 0–60 mph performance capability, or require that a surrogate measure — peak powertrain kW per vehicle test kilogram — be held constant. In most cases, a minimum gradeability requirement(s) is/are also specified. In the General Motors (2) and Graham et al. (5) studies, several performance constraints were specified, including top speed. Top speed proved to be an important constraint in both studies. What values for top speed should be used, and the potential affects of this constraint, are discussed in two Santini et al. publications (4, 9). In this paper, for reasons discussed below, we use peak kW per unit of test mass as the "performance equivalent" constraint against which we insist that vehicles be benchmarked. This statistic was also used by Weiss et al. (1). Possible problems with using this measure instead of an actual acceleration prediction are discussed and illustrated in Santini et al. (4).

We complied data on FCV simulations from seven studies for this paper (see Appendix A). Five of the seven (as discussed below) were funded by the U.S. Department of Energy's (DOE's) Office of Transportation Technologies (OTT). The other sources are the Weiss et al. study and the General Motors study. The former will be referred to hereafter as the MIT 00 study because the authors were affiliated with MIT; the General Motors study will be referred to as GM 01.

DOE-SPONSORED STUDIES - As a key part of its assessment of FCV attributes, the MIT 00 study makes use of two papers published by C.E. Thomas, B.D. James, F.D. Lomax, and I.F. Kuhn in late 1998. We use an early 1998 contractor report prepared for the National Renewable Energy Laboratory (NREL) by the same four authors, who were employees of Directed Technologies, Inc. (DTI) (11). We also use a subsequent 1999 report by Thomas (12), also completed as an NREL contract with DTI. Funding for these two studies was provided by DOE. Hereafter, we refer to these two studies as DTI 98 and DTI 99. Like the MIT 00 and GM 01 studies. the DTI studies examined hydrogen (H_2), methanol (MeOH), and gasoline as fuels for FCVs. The remaining studies that we examined involved only one fuel.

A third DOE study of FCVs, published in December 2000, was conducted by the Ford Motor Company Research Laboratory (13). This study, which examined hydrogen FCVs, is referred to as Ford 00. The fourth DOE-sponsored study examined here was published in

November 2000 by R. Kumar et al. of ANL's Chemical Technology Division (14). This study, which examined gasoline FCVs without hybridization, will be referred to as ANL 00. A fifth study, conducted by Wipke, Markel, and Nelson of NREL and published in October 2001 (15), examined a switch to a hydrogen hybrid fuel-cell powertrain in a sport utility vehicle (SUV) glider. This study will be referred to as NRL 01.

Of the studies examined, only the GM 01 and NRL 01 studies used contemporary truck bodies as gliders. All other studies examined lightweight passenger cars, generally also with improvement in C_d, A, and C_r. Only one of these studies — ANL 00 — actually varied the performance level of an FCV in order to assess the effect of kW/kg on FCV efficiency. All of the studies other than ANL 00 and NRL 01 provided data on a baseline conventional vehicle with a body (glider) identical to that of the simulated FCVs (except for small chassis mass changes to cope with heavier fuel-cell powertrain mass). Upon request, the NRL 01 authors provided the data on the baseline SUV used in their study (16). In the analysis for this paper, we developed comparable conventional vehicle information to go with the ANL 00 study.

METHOD

ACRONYMS AND ABBREVIATIONS - This survey paper makes reference to several studies and to several powertrain technologies. For consistency, we used to acronyms and abbreviations listed below:

A = frontal area of vehicle body
Aero = aerodynamic
AIV = aluminum- intensive vehicle (a mid-size Mercury Sable car with aluminum body)
ANL 00 = Argonne National Laboratory study published in 2000
C_d = coefficient of drag
city mpg = unadjusted fuel economy according to the federal test procedure (FTP) cycle
COMP mpg = composite city/highway (55/45) average fuel economy rating
C_r = coefficient of rolling resistance
Curb mass = weight of the vehicle without any passengers or luggage
CV = conventional vehicle
DOE = U.S. Department of Energy
DTI 98 and DTI 99 = Directed Technology Inc. studies published in 1998 and 1999
FCV = fuel-cell vehicle
Ford 00 = Ford Research Laboratory study published in 2000
FUDS = Federal Urban Driving Schedule
GHG = greenhouse gas
GM 01 = General Motors study published in 2001
gpm = gallons per mile
GREET = Greenhouse gas, Regulated Emissions, and Energy use in Transportation
H_2 = gaseous or compressed hydrogen
HEV = hybrid electric vehicle
highway mpg = unadjusted fuel economy according to the U.S. Environmental Protection Agency (EPA) highway test cycle
ICE = internal combustion engine
kW/kg = peak powertrain kW per unit of vehicle curb mass
light = lightweight
MeOH = methanol
MIT 00 = Massachusetts Institute of Technology study published in 2000
mpg = miles per gallon
mph = miles per hour
NSp = net specific power
NRL 01 = National Renewable Energy Laboratory study published in 2001
OTT = Office of Transportation Technologies
petrol = gasoline refined from petroleum
pickup = full-size pickup truck
Pm = mass increase of the vehicle above the CV glider mass, caused by the powertrain
PNGV = Partnership for a New Generation of Vehicles; i.e., vehicle body with low load attributes (i.e., low C_d, A, and/or C_r)
rpm = rotations per minute
s = seconds
Test mass = vehicle curb weight in kg plus 136 kg (except for MIT 00, which used 110 kg)

With the exception of the GM 01 study, which did not provide any data on vehicle mass or powertrain power, the data included in the studies examined did allow estimation of the peak kW per test mass of the vehicle, as shown in Appendix A. MIT 00 designed the vehicles it compared so that the kW/kg was a constant 0.075. Aside from the GM 01 study, the use of the kW/kg benchmark and the MIT 00 approach was feasible as a means of standardizing comparisons. A review of the DOE-sponsored studies indicates that they each failed to follow the comparable performance rules used in MIT 00, allowing the FCVs to have a lower kW/kg ratio (implying a longer 0–60 mph acceleration time) than the CV.

Commenting on this paper, Dr. C.E. Thomas indicated that DTI work did include predictions of comparative performance of conventional and fuel cell vehicles, attempting to make the vehicles comparable. The extreme difference in relative CV/FCV kW/kg values assumed by MIT and DTI suggests that predictions of acceleration performance and its effect on powertrain size should be made explicit in future studies.

Examination of the GM study indicated that the performance rules adopted in that study also resulted in the FCVs having a slower 0–60 mph acceleration time than the CV, thus making the base GM 01 estimates comparable to those in the DOE-sponsored studies. GM 01 did follow strict rules for comparable performance, and provided city, highway, and composite mpg (based on 55/45 city/highway fuel consumption) values, along with acceleration time estimates. No studies other than GM 01 and NRL 01 included city and highway mpg *and*

0–60 mph acceleration times. We checked to determine the extent to which the kW/kg values in the remaining studies differed from one another (see Appendix A).

We found that the ANL 00 study did not include estimates of fuel economy for a comparable conventional vehicle and did not attempt to estimate separate powertrain component mass values. MIT, DTI 98, DTI 99, and Ford 00 did so and reported results for most of the vehicle powertrain types analyzed. We found that DTI 98, DTI 99, and Ford 00 each compared advanced technologies to essentially the same baseline AIV, although small differences in the reported AIVs did exist. Within the context of this study, and the level of certainty involved, we decided that one set of starting values for a baseline AIV could be used fairly for all three of these studies. However, the kW/kg value for the AIV was consistently much higher than that for the advanced vehicles. In other words, the studies "cheated" in the sense that they compared advanced vehicles with slow 0–60 mph acceleration times to CVs with considerably faster times.

APPROACHES TO RESIZING POWERTRAINS FOR PERFORMANCE EQUIVALENCE - Two different approaches to developing strict performance comparability have been implemented for this paper. The first involves adjustment of the CV vehicle performance metric (kW/kg) downward to match that of the FCV. The second involves adjustment of the FCV kW/kg value upward to match that of the CV. The former method can be implemented by simulating CVs in a vehicle simulation model. The latter can be implemented by simulating an FCV in a vehicle simulation model. The authors of this paper, however, did not have access to the vehicle simulation models used in most of the studies cited, so inevitably, uncertainty concerning any effects of vehicle simulation models remains. In the future, we would like to try to isolate the effects of variation in results caused by different vehicle simulation approaches. In this initial assessment, however, we used simple approximations derived from information in past modeling efforts to develop methods of adjusting the fuel economy of FCVs and CVs. These methods are certainly subject to reexamination at a later date. To some extent, they set up testable hypotheses for future vehicle simulation studies.

Note that the two approaches are *not* expected to produce identical results. In the first approach, in which the CV is "slowed down" to match the FCV's acceleration capability, the pair of vehicles will have a predicted acceleration time in the 10-second range. In the second approach, in which we speed up the FCV to match the CV's acceleration capability, the pair of vehicles will have a predicted acceleration time in the 8-second range. A key point of the Santini et al. paper (4) is that the percent fuel economy gain of pairs of gasoline hybrid vs. conventional vehicles should not be expected to be the same. According to the analysis, the 8-second pair had a higher gain than the 10-second pair. The properties for comparison of FCVs and CVs are discussed and estimated below.

LENGTHENING THE CV 0–60 MPH ACCELERATION TIME TO MATCH THE FVC - There are three major properties that affect the fuel economy of the simulated vehicles:

- Vehicle mass
- Powertrain efficiency
- Vehicle load (C_d, A, C_r)

The studies examined vary all three of these factors relative to one another. For this draft paper, we have not isolated the vehicle load effects from the other two factors. These should be resolved in a later draft, by means of multiple ADVISOR runs for the CV, accounting for the effects of variation of vehicle loads across studies. Mass changes are reasonably well predicted, so the residual — attributable to powertrain efficiency and vehicle load combined — can be separated out.

For a conventional lightweight vehicle with low load and with a contemporary conventional powertrain, we have made predictions of the mass changes and the fuel economy changes arising from improvements in 0–60 mph acceleration time — from 12 to 10 to 8 seconds. The glider design, vehicle load, and powertrain technology are held constant (5-speed manual, single overhead camshaft, 2 valves per cylinder, fuel injection). Vehicle loads are: C_d = 0.26, A = 2.06, Cr = 0.0075.

Table 1 reveals a few relevant points. First, although the same body type (glider) is used in all three cases, the vehicle mass rises as 0–60 mph acceleration time decreases because, at a given powertrain-specific power value, more vehicle power means more vehicle mass. Second, note that the peak kW per kg of vehicle test weight is about 0.061 for a 10-second 0–60 mph acceleration time, and about 0.077 for an 8-second time. The former value is representative of the FCVs in most studies examined, while the latter represents the baseline CVs. Finally, note that the fuel consumption per kg of vehicle mass rises as the vehicle acceleration time decreases. The engine and transmission technologies are not changed. The engine map, however, is scaled — meaning that the powertrain, nominally with an engine having one fixed peak efficiency, actually operates less efficiently as the power-to-weight ratio and weight of the vehicle rise. The "in-use" efficiency of the powertrain on the composite cycle drops by 18% as the size of the powertrain type increases to improve 0–60 mph acceleration capability from 12 to 8 seconds. An alternative way of looking at this is that downsizing the engine by 43% improves in-use efficiency by 22%.

Table 1 Attributes of Simulated Lightweight Mid-Size Conventional Car with Contemporary Engine for Various 0–60 mph Acceleration Capabilities (6)

0–60 mph (s)	Curb Weight (kg)	kW	City gpm (mpg)	COMP gpm (mpg)	Hwy gpm (mpg)	kW/ (kg +136)	1000 COMP gpm/ (kg +136)
12	1175	66	.0311 (32.2)	.0267 (37.5)	.0212 (47.1)	0.0503	0.0203
10	1248	85	.0361 (27.7)	.0307 (32.6)	.0240 (41.6)	0.0614	0.0222
8	1366	116	.0442 (22.6)	.0372 (26.9)	.0286 (35)	0.0772	0.0248

On the basis of the information in Table 1, the following equations were developed by curve fitting (linear regression).

0–60 mph acceleration time

$$s = 19.28 - 147.24 \times kW/(kg + 136) \quad [1]$$

Vehicle mass

$$kg = 813.94 + 7128 \times kW/(kg + 136) \quad [2]$$

City fuel use

$$gpm = 0.006121 + 0.4923 \times kW/(kg + 136) \quad [3]$$

Composite (55% city, 45% highway) fuel use

$$gpm = 0.006798 + 0.3922 \times kW/(kg + 136) \quad [4]$$

Highway fuel use

$$gpm = 0.007357 + 0.2739 \times kW/(kg + 136) \quad [5]$$

These equations contain only three observations and are based on a deterministic simulation. Accordingly, they should have high R-squared values. The R-squared values are 0.999 for all but the acceleration equation [1], which is 0.995.

Only one test of the adequacy of the assumption that the FCV would have a similar acceleration capability to the CV for a given kW/(kg +136) ratio was possible. Only the Ford 00 study provided data on acceleration times, vehicle mass, and peak power. Two comparisons were possible for this study. For the Ford 00 AIV H_2 FCV, the 0–60 mph acceleration time for the chosen case was 11.3 seconds, for a kW/(kg +136) ratio of 0.0537. Equation [1] predicts 11.4 seconds for this ratio. For the Ford 00 AIV H_2 HEV FCV, the 0–60 mph acceleration time for the chosen case was 10.9 seconds, for a kW/(kg +136) ratio of 0.057. Equation [1] predicts 10.7 seconds for this ratio.

Note that simply changing the axle ratio can change the acceleration time for a vehicle. Ford 00 tested a number of axle ratios before choosing one as the "best," given all performance requirements. The reported range of 0–60 mph acceleration times evaluated in simulations in the Ford 00 study varied from 12.9 to 11.4 seconds for the AIV H_2 FCV, providing "overall drive ratios" ranging from 4.6 to 9.2. However, for the two cases (of five) for which acceleration performance was superior to each of the other three cases (but neither of the two was consistently superior across a range of five acceleration measurements), the time variation was 11.1 to 11.3 seconds. These details were not provided for the AIV H_2 HEV FCV; only the projected 0–60 mph acceleration time of 10.7 seconds was provided. Within the range of uncertainty concerning the 0–60 mph acceleration time that can be associated with specific power values for a vehicle, the evidence here is that the same acceleration can be expected from an FCV and CV at the same kW/(kg + 136) ratio.

In Santini et al. (4), analysts found that this finding would not hold true for parallel hybrid vehicles with large battery packs and motors, and that the kW/(kg + 136) ratio that was needed to achieve a given 0–60 mph acceleration time was less in an HEV with a large motor. There is not enough information in the studies cited to evaluate this question any further than has been done here. However, we do note that the motors in FCVs provide all of the motive power, while in parallel hybrids, the motor only provides a portion of the power. Motors for parallel hybrids can be designed to take advantage of high torque at low rpm, and need not have high power and torque at high rpm. For an FCV, which is a series vehicle, the motor will have to be designed differently because it must provide all power for low- as well as high-speed operation. So, until more investigations are completed, analysts cannot conclude from the available information that there is (or is not) a systematic difference between the 0–60 mph acceleration time arising from a given kW/(kg +136) ratio in an FCV vs. a CV. We reiterate that the evidence here is consistent with the MIT 00 assumption that the same acceleration can be expected from an FCV and a CV at the same kW/(kg + 136) ratio.

On the basis of this assumption, we used equations [2] through [5] to estimate the percent change in mass and mpg of a CV when moving from a study's reported kW/(kg + 136) ratio for its CV to the value for its FCV. We used the percent change estimate to change the values for the study's baseline CVs. The kW/(kg + 136) values for FCVs varied, so the adjustments of the CV were tailored to each FCV.

SHORTENING THE FCV 0–60 MPH ACCELERATION TIME TO MATCH THE CV - In the case of CVs, we were able to rely on a prior study, in which the authors had conducted simulations of CVs that had 0–60 mph acceleration times ranging from 8 to 12 seconds. In the studies examined in this paper, there was only one case in which a particular type of FCV was "designed" with varying 0–60 mph performance capabilities for a given FCV powertrain: the ANL 00 study, which examined gasoline FCVs. Its authors conducted experiments with an 80-kW and a 40-kW fuel cell in a vehicle with the same simulated mass and the same vehicle loads (C_d = 0.163, A = 2.18, C_r = 0.0064). While the study might be criticized for failing to account for the fact that the 40-kW powertrain would weigh less than the 80-kW powertrain, the evaluation nevertheless gives us an observation of the predicted gpm/kg variation with a change of kW/(kg +136) ratio for an FCV. Fortunately, the ratio for the 80-kW case, based on the test mass of 1043 kg, is 0.0767 — exactly 8.0 seconds according to equation [1]. For the 40-kW case, the predicted acceleration time is 13.6 seconds. Thus, the values chosen in the ANL 00 study span the 0–60 mph acceleration time values listed in Table 1. Interestingly, in this FCV simulation, the "gasoline-equivalent" composite fuel economy dropped from 92 to 89 mpg as the size of the fuel cell dropped from 80 to 40 kW. Note that this is opposite of the direction of change for a CV as the peak kW of the powertrain changes. These ANL 00 results imply that, as the acceleration capability of an FCV varies from 8 to 10 seconds, there will be about a 1% change in vehicle efficiency. So, we assume here that, as a fuel-cell powertrain is enlarged — changing an FCV with approximately a 10-second 0–60 mph acceleration time to one with an 8-second 0–60 mph acceleration time (to match the baseline CV) — there will be no change in FCV powertrain efficiency (i.e., no change in gpm/[kg+136]). This finding implies that any changes in FCV mpg (for given C_d, A, and C_r values) will be caused only by mass effects.

One attribute of FCV powertrains in the surveyed studies is that their specific power is always less than that of a conventional gasoline vehicle powertrain. When the study included an estimate of the glider mass and the vehicle curb mass, we were able to deduct the glider mass to obtain an estimate of the vehicle's powertrain mass. In this study, we include the fuel tank mass as an inherent attribute of the powertrain and define the powertrain mass to include fuel tank mass. Fuel tank mass is an important issue for the H_2-fueled vehicles. In most of the studies examined, the reported glider mass increased slightly as the vehicle mass increased. In other words, the studies considered the fact that materials would have to be added to the glider to provide more structural strength to carry a heavier powertain and fuel tanks and to provide larger tires and springs in the chassis. We computed the net addition to vehicle mass arising from a powertrain switch — the net of so-called mass compounding. Thus, to compute powertrain mass for a CV/FCV pair, we always subtracted the CV glider mass. We developed an equation to predict the increase in mass caused by an increase of powertrain mass, which itself was caused by a desire to decrease 0–60 mph acceleration time (increase kW/[kg+136] ratio).

First, we estimate the "net" specific power of the powertrain, incorporating the vehicle mass compounding effects of that powertrain.

$$NSp = kW/(FCV\ kg - CV\ glider\ kg) \qquad [6]$$

Then, to determine the powertrain mass associated with any desired ratio of kW/(kg+136), we use the equation

$$Pm = (\{[kW/(kg+136)]/NSp\} \times (CV\ glider\ kg+136))/(1-[kW/(kg+136)]/NSp) \qquad [7]$$

In the case of the MIT 00 study, 110 kg was added to the vehicle curb mass instead of 136 kg to set test mass, so for the MIT 00 cases, 110 would have been substituted for 136. However, in the MIT 00 study, no adjustments were needed. The NSp values varied from a worst of 0.1575 for the Ford 00 study's H_2 FCV AIV Sable to an estimated 0.3175 for our generic CV powertrain for the DTI 98, DTI 99, and Ford 00 studies. The effect of this variation, in a vehicle designed to have a kW/(kg + 136) value of 0.0775, is to cause a tripling of the powertrain mass in the H_2 FCV version, for an 840-kg glider. In the case of the H_2 FCV, the predicted powertrain mass exceeds the glider mass. Only the Ford 00 study is this pessimistic with respect to H_2 FCV NSp.

To estimate the adjusted FCV gpm, we used equation [7] to predict the change in mass caused by increasing the value of kW/(kg + 136), and we multiplied by the gpm/kg value for the study's initially projected FCV. We estimated mpg by inverting gpm.

GLIDER MASS ISSUES - The DTI 98, DTI 99, and Ford 00 studies all used an AIV of about the same mass and kW. The level of detail for this vehicle was greatest in the DTI 98 study. DTI 99 and Ford 00 did not report a glider mass. Unfortunately, multiple glider mass values were reported in various tables in DTI 98. Thus, we had to make a guess at the glider mass of the AIV for these studies. The MIT 00 study did report (only one) glider mass for all vehicles simulated, so its NSp values provide a cross check for a CV powertrain. We estimated a glider mass of 840 kg for the CV AIV. We used the executive summary table's glider mass values for the FCVs from DTI 98, under the assumption that these were the intended values. No value was given for the CV, but our assumed 840-kg mass compares to 865 kg for the H_2 FCV in the DTI 98 study, the lightest of the FCVs in that study.

A word about the Ford 00 study: the baseline AIV curb mass is reported in Table 2.1 of that study. At 1168 kg, it is consistent with mass values in the DTI 98 and DTI 99 studies, and if 840-kg glider mass is appropriate for those studies, it should be appropriate for this one. However, if one takes the FCV curb mass values from

Table 2.7 (1348 kg) of the Ford 00 study and subtracts the mass of fuel cell, electric motor, and tanks, the remaining mass is 956 kg — over 100 kg more than the estimated glider mass. Note that MIT 00 estimates the glider mass for a contemporary mid-size vehicle at 930 kg. If one used a value in the neighborhood of 950 kg as glider mass for the AIV CV, the resulting NSp value would be far higher than the MIT or the DTI 98 values. So, there may be a mistake in the Ford study that causes our estimated mass increases for their FCV powertrains to be too high and causes their estimated vehicle mass values for the H_2 FCVs to be too high. This apparent discrepancy requires resolution.

CONVENTIONAL VEHICLE ISSUES - A part of study method is related to study philosophy. An issue made apparent by our examination of these studies is the "compared to what?" issue. The baseline vehicle in the set of vehicles with constant loads and the same glider is inherently different in the MIT 00 study than in all other reviewed studies that include a baseline CV. The key difference is that, in the MIT 00 study, the gasoline CV that uses the same glider as the FCVs is an advanced CV. It has an engine with peak indicated efficiency of 41%, vs. an estimated 38% for MIT's current 1996 gasoline vehicle. An intermediate gasoline CV with a heavier glider and higher load than the advanced gasoline CV is also characterized in MIT 00. This CV has the same powertrain as the lighter, lower-load advanced vehicle. Thus, the MIT 00 study essentially characterizes three gasoline CVs.

With respect to the vehicle that qualifies as a baseline vehicle by this paper's rules, the advanced vehicle of the MIT 00 study is at one end of the spectrum, being the most advanced, lightest-weight (aside from the vehicle used in the ANL 00 study), and lowest-load (again aside from ANL 00) vehicle. The baseline vehicles in the GM 01 and NRL 01 studies — contemporary trucks with heaviest bodies and highest loads — are at the other end of the spectrum. The DTI 98, DTI 99, and Ford 00 studies characterize lightweight AIV vehicle bodies, but otherwise the powertrain and loads are contemporary. (For the sake of simplicity and consistency with the intentions of the authors of the respective studies, our "contemporary" case will be contemporary with respect to powertrain efficiency and vehicle load, but not vehicle mass.) However, the DTI 99 study does examine a "PNGV" case — an even lighter-mass vehicle than the AIV, with lower loads as well. Nevertheless, the CV version of this PNGV vehicle uses the contemporary powertrain, with a gpm/kg value only slightly less than the AIV CV, consistent with the lower load on the PNGV CV and no engine efficiency improvement.

In fact, it is stated for the DTI 99 study that the peak efficiency for both the AIV CV and PNGV CV engines is 30%. Note that "indicated efficiency" (used in the MIT 00 study) is higher than thermal efficiency, which is likely the type of efficiency measure used for the 30% engine efficiency estimate reported in the DTI 99 study. This assumption is supported by the fact that the gpm/kg values for the MIT 1996 CV and the DTI AIV CV are very similar: 0.0000249 and 0.0000258, respectively.

The MIT 00 advanced CV has a gpm/kg value of 0.0000179, arising from a more efficient engine and transmission and a lower vehicle load. We think that the MIT 00 perspective — comparing advanced conventional vehicles to advanced FCVs — is appropriate, as is the comparison to contemporary vehicles as a benchmark. To be consistent with the philosophy of comparisons that we have set up, we stick with the same glider, C_d, A, and C_r throughout our comparisons based on a given study. However, we compare FCVs both to a contemporary powertrain *and* to an advanced powertrain with the gpm/kg capability of the MIT 00 advanced gasoline CV.

We make this comparison only for the cases where we "speed up" the FCVs to match the CV in acceleration capability. Because the gpm/(kg +110) values for the MIT 00 study are at a kW/(kg + 110) value of 0.075 — very close to that for the AIV Sable — we are comfortable with the suitability of the advanced powertrain gpm/(kW +110) values in conjunction with the baseline AIV CV. However, we have not simulated an advanced engine (of the type used in the MIT 00 study for kW/(kg + 110) ratios) that would result in 10- and 12-second 0–60 mph acceleration times. We have seen in the prior section that, for a conventional engine, this will change the "in-use" efficiency of the engine. However, without having a simulation for the particular advanced engine type used in the MIT study, it would not be appropriate to make an assumption concerning the change in advanced gasoline CV gpm/(kg + 110) that would result from a switch at a kW/(kg +110) level of about 0.061.

DRIVING-CYCLE ISSUES - Comparisons presented in this paper are based on composite mpg values computed from the inverse of a composite average fuel consumption value with city fuel consumption at 55% and highway at 45% of the total. However, some of the studies (MIT 00, GM 01, DTI 98, ANL 00, and NRL 01) separately estimated city and highway mpg. We assumed that the city and highway values took precedence over the composite value, and we checked the published composite value in every case by re-computing it. As discussed earlier, this led to a slight reduction in the AIV CV composite mpg value that was used in the DTI 98, DTI 99, and Ford 00 studies. In addition, the Ford 00 study reported "FUDS" (Federal Urban Driving Schedule) mpg values for the FCVs, not composite values, and not highway values. FUDS is an identical speed time trace to the "city" values we present, although differences relating to vehicle warm-up exist. We neglect these. Inspection of the results indicated that the gains in mpg when switching from a CV to FCV are larger on the city cycle than on the composite city and highway cycle. Thus, it would not have been accurate to compare city-cycle mpg gains from the Ford 00 study to composite mpg gains elsewhere. Ratios of composite to city mpg values for

the H_2 FCV and H_2 HEV FCV developed from other studies were used to scale up the city mpg values from the Ford 00 study to a composite value. As reported, we used the AIV CV from the DTI 98 study as the reference vehicle for the Ford 00 FCV cases. Despite citing the AIV as the baseline mid-size vehicle, Ford 00 did not report estimates of the AIV CV mpg, instead reporting estimates for the contemporary steel-bodied production Mercury Sable. Both of these decisions — use of FUDS and use of the steel-bodied contemporary Sable for baseline mpg — compensate for the possible error in computing too high a value of the FCV mass, thereby implying a similar gain in mpg to other studies, but for the wrong reasons.

Note that this paper only examined the standard certification driving cycles. The work of DTI included examinations of more aggressive, higher speed cycles, by multiplying the speed of the standard cycles by 1.25. DTI estimated that an FCV suffered a considerably larger loss in fuel economy than an ICE powered vehicle. Unfortunately, none of the other studies cited here examined such a driving cycle. Confirmation and crosschecking of the relative effects of aggressive driving (more real-world) on FCV vs. ICE fuel economy is clearly desirable in light of the work of DTI.

RESULTS

Ratios of FCV to CV mpg are presented in Table 2. Six types of FCVs are evaluated. Fuels examined are H_2, MeOH, and gasoline. Each FCV type is either hybridized or non-hybridized. In the second column of Table 2, we present initial comparisons of FCVs and CVs developed for use in the GREET model by M. Wang (3). In three of the remaining four columns, we present adjusted standardized comparisons of vehicles with the same 0–60 mph acceleration capability. The third and fourth columns of the table provide comparisons of vehicles with a 0–60 mph acceleration capability of about 8 seconds. The third column uses a contemporary CV as the baseline, while the fourth column uses an advanced CV with the powertrain efficiency characteristics of the MIT 00 2020 Advanced internal combustion engine (ICE) CV. The fifth column generally presents the initial, unadjusted comparison as published in the study, although some "cleaning up" of the mpg estimates has been done, as described earlier. The sixth column provides comparisons of vehicles with a 0–60 mph acceleration capability of about 10 seconds, with a contemporary CV as the baseline. All comparisons in this study are based on pairs of vehicles with the same glider. "Noise" in the estimates, caused by variation in C_d, A, and C_r values, has not been eliminated.

Table 2 Ratios of FCV to CV mpg Standardized by 0–60 mph Acceleration Capability

	Kind of Comparison				
H_2 FCVs	Simple Initial (Wang[a])	Both ≈ 8 s 0–60 FCV vs. Current CV	Both ≈ 8 s 0–60 FCV vs. Advanced CV	Current CV ≈ 8 s, FCV ≈ 10 s	Both ≈ 10 s FCV vs. Current CV
GM 01	2.1	2.1	ii[b]	ii	ii
DTI 98 AIV	ne[c]	2.5	1.7	2.7	2.1
DTI 99 AIV	2.5-2.7	2.5	1.7	2.7	2.3
DTI 99 PNGV	ne	2.5	1.7	2.8	2.2
Ford 00	ne	1.7	1.2	2.2	1.6
Mean	2.3	2.3	1.6	2.6	2.0
High-Low	0.4	0.8	0.5	0.6	0.7
H-L/Mean	0.17	0.35	0.31	0.23	0.35

H_2 HEV FCVs	Simple Initial (Wang[a])	Both ≈ 8 s 0–60 FCV vs. Current CV	Both ≈ 8 s 0–60 FCV vs. Advanced CV	Current CV ≈ 8 s, FCV ≈ 10 s	Both ≈ 10 s FCV vs. Current CV
GM 01	2.4	ii	ii	2.4	ii
MIT 00	2.2	2.8	1.9	na[d]	na
DTI 98 AIV	2.5-2.7	2.5	1.7	2.7	2.2
DTI 99 AIV	2.5-2.7	2.5	1.7	2.8	2.2
DTI 99 PNGV	2.6-2.7	2.5	1.8	2.8	2.3
NRL 01	ne	2.2	1.4	2.4	2.1
Ford 00	ne	1.8	1.3	2.2	1.8
Mean	2.4	2.4	1.6	2.55	2.1
High-Low	0.4	1.0	0.6	0.6	0.5
H-L/Mean	0.17	0.42	0.38	0.24	0.24

Table 2 Ratios of FCV to CV mpg Standardized by 0–60 mph Acceleration Capability (Cont.)

	Kind of Comparison				
MEOH FCVs	Simple Initial (Wang[a])	Both ≈ 8 s 0–60 FCV vs. Current CV	Both ≈ 8 s 0–60 FCV vs. Advanced CV	Current CV ≈ 8 s, FCV ≈ 10 s	Both ≈ 10 s FCV vs. Current CV
GM 01	1.5	ii	ii	1.5	ii
MIT 00	ne	1.7	1.2	na	na
DTI 98 AIV	ne	1.6	1.1	1.8	1.5
Mean	1.5	1.65	1.15	1.65	1.5
High-Low	0	0.1	0.1	0.3	0.5
H-L/Mean	0	0.06	0.09	0.18	0.24

MEOH HEV FCVs	Simple Initial (Wang[a])	Both ≈ 8 s 0–60 FCV vs. Current CV	Both ≈ 8 s 0–60 FCV vs. Advanced CV	Current CV ≈ 8 s, FCV ≈ 10 s	Both ≈ 10 s FCV vs. Current CV
GM 01	1.7	ii	ii	1.7	ii
MIT 00	1.3	1.7	1.2	na	na
DTI 98 AIV	1.8-*2.0*	1.6	1.1	1.8	1.5
DTI 99 AIV	1.7-*2.0*	1.6	1.1	1.8	1.5
DTI 99 PNGV	1.7-*2.0*	1.7	1.2	1.9	1.6
Mean	1.6	1.65	1.15	1.8	1.5
High-Low	0.5	0.1	0.1	0.2	0.1
H-L/Mean	0.31	0.06	0.09	0.11	0.07

Gasoline FCVs	Simple Initial (Wang[a])	Both ≈ 8 s 0–60 FCV vs. Current CV	Both ≈ 8 s 0–60 FCV vs. Advanced CV	Current CV ≈ 8 s, FCV ≈ 10 s	Both ≈ 10 s FCV vs. Current CV
GM 01	1.3	ii	ii	1.3	ii
ANL 00	ne	1.7	na	na	na
Mean	1.3	1.7	na	1.3	na

Gasoline HEV FCVs	Simple Initial (Wang[a])	Both ≈ 8 s 0-60 FCV vs. Current CV	Both ≈ 8 s 0-60 FCV vs. Advanced CV	Current CV ≈ 8 s, FCV ≈ 10 s	Both ≈ 10 s FCV vs. Current CV
GM 01	1.5			1.5	
MIT 00	1.0	1.3	0.9	na	na
DTI 98 AIV	1.3-*1.8*	1.1	0.8	1.3	1.1
DTI 99 AIV	1.2-*1.6*	1.1	0.8	1.3	1.1
DTI 99PNGV	1.2-*1.6*	1.2	0.8	1.3	1.1
Mean	1.2	1.2	0.8	1.35	1.1
High-Low	0.5	0.2	0.1	0.2	0
H-L/Mean	0.41	0.17	0.12	0.15	0

[a] Wang includes best cases from DTI studies. We do not (and cannot, because we had insufficient information to generate an estimate) include a best case. The DTI best-case results are italicized and are not used in the estimate of the mean and high-low difference.
[b] ii = insufficient information to generate an estimate.
[c] ne = not estimated.
[d] na = no assumption to allow an estimate was made.

Note that the DTI studies provide a foundation for the FCV results provided in the MIT 00 study. The Ford 00 study also clearly intended to start with the DTI baseline vehicle in its study. Whether or not the DTI studies are cited, chronologically they precede the other studies. In total, they are more comprehensive and detailed with respect to information provided and cases examined. The DTI study results are found to be very consistent here. Thus, we use the DTI studies as the reference point for discussion. Wang included the "best-case" estimates from the DTI studies in his estimates. We only use the "most-probable" DTI cases. The "best-case"

results compiled by Wang are shown in italics and otherwise ignored.

According to Wang's simple estimates, the MIT 00 and GM 01 studies are consistently more pessimistic relative to the DTI studies with regard to the gains in mpg-equivalent fuel economy that can be obtained by FCVs. The only exception is the GM 01 estimate for MeOH FCVs, which is identical to the low value for two of three DTI comparisons. Further, the MIT 00 study — which only compiled results for HEV FCVs — is consistently pessimistic relative to the GM 01 study.

Adjusted standardized comparisons tell a different story. MIT 00 ratios are consistently more optimistic than the comparable DTI study results. For H_2 and MeOH, GM 01 is pessimistic relative to DTI studies. So, based on deductive logic, if the information were available to compare the MIT 00 and GM 01 studies on a common basis, the MIT 00 study would be the more optimistic of the two for H_2 and MeOH fuels. With respect to gasoline in HEV FCVs, both GM and MIT are more optimistic than DTI, and there is a possibility that MIT 00 and GM 01 are equally optimistic in this regard.

Of the remaining, more limited studies, the Ford 00 study is least optimistic, and the ANL 00 study is most optimistic — but for different fuels. The Ford 00 study examined only H_2 FCVs and has the least optimistic FCV/CV mpg ratios of any of the studies examined. As discussed earlier, we suspect that there are mistakes in this study, at least for the vehicle glider type that we examined for this paper. The NRL 01 study — for an H_2 HEV FCV only — is also pessimistic (or realistic) relative to the DTI studies. For the one kind of comparison in which the NRL 01 study can be compared to the GM 01 study, the results are identical. Note that the NRL 01 study uses a contemporary steel-bodied SUV as a glider, while the GM 01 study uses a contemporary pickup truck. Among the included studies, the gliders for these two are most comparable to one another and not particularly comparable to the gliders used in other studies.

GM 01 is optimistic with respect to gasoline in an HEV FCV, while ANL 00 is optimistic with respect to gasoline in an FCV. Although a direct comparison is not possible, it appears that the ANL 00 study is optimistic with respect to the GM 01 study for a gasoline FCV. Note that both the GM 01 and ANL 00 studies were conducted later than the DTI and MIT studies. MIT, in turn, relied heavily on the DTI studies, which show little change from 1998 to 1999. Thus, all other studies addressing gasoline FCVs may rely on assumptions about technology as of 1998 or earlier. Since that time, a team of Argonne scientists has "developed and patented a compact fuel processor that 'reforms' ordinary gasoline into a hydrogen-rich gas to power fuel cells" (18). Note the word "compact" is used. A compact reformer should reduce the pronounced gasoline FCV powertrain mass increases simulated in the DTI and MIT studies. This article also reports a hydrogen concentration of about 45%, vs. 40% assumed in MIT 00, so this also could contribute to the greater optimism in the ANL estimates. Although there is no specific information regarding GM's gasoline reformer assumptions, we assume that GM is more optimistic than DTI and MIT 00.

When we compare FCV/CV ratios for the same studies for 10- and 8-second 0–60 mph acceleration times for the FCV against a contemporary CV, we see that the mpg ratio is higher for the 8-second than for the 10-second case. This effect was also observed and examined by Santini et al. (4) for hybrids, but the magnitude of the effect for FCVs is smaller, if the values in Table 2 are representative. The effect seems to be a little larger for H_2 FCVs (about 15% increase in ratio from 10 to 8 seconds) than in reformer-based systems (about 10%). The added mass of the reformer probably causes the smaller gain for the reformer-based systems.

When consistent comparisons are possible, it appears that hybridizing an FCV increases mpg by only a small amount, if at all. This finding deserves further investigation. GM 01 does generally estimate that the percent mpg gains via hybridization of CVs are greater than those for hybridizing FCVs. Hybridization allows reduction of engine size. The estimates herein and elsewhere (4, 6) indicate that this provides significant improvement of "in-use" efficiency of a typical ICE technology. The ANL 00 study estimated that this effect does not exist for a gasoline FCV. The GM 01 results for hybridization of conventional powertrains vs. fuel-cell powertrains are consistent — in a relative sense — with this finding from the ANL 00 study.

Finally, it has been demonstrated that if one is optimistic about the potential for improvement of the CV powertrain, consistent with the MIT 00 study, the estimated incremental fuel economy benefits of FCVs diminish greatly. Gasoline FCVs in particular are estimated to have no benefit relative to advanced gasoline CVs. Though the GM 01 study is relatively optimistic with respect to gasoline FCVs, even the GM 01 benefits — which are optimistic relative to those found in earlier DOE-sponsored studies —- seem unlikely to make the gasoline FCV technology worth pursuing. This statement, of course, is conditional on the assumption that an advanced gasoline powertrain like that projected in the MIT 00 study can be achieved. Only the ANL 00 projections for its new reformer technology appear to provide a justification for pursuing gasoline FCV technology.

Comparisons of FCVs to gasoline and diesel hybrids have not been made, but the groundwork has been laid here and in Santini et al. (4).

SUMMARY AND CONCLUSION

We recommend a standardized method and rule of comparison for conventional and advanced technology vehicles, based on the lead in several recent studies (1, 2, 5–8, 10). The analysis presented here pursued the

use of a fixed 0–60 mph acceleration capability as the technical "anchor" for comparisons. On the basis of the data available in several recent studies of FCVs (1, 2, 11–16), methods suitable to adjust published vehicle simulations from one 0–60 mph performance level to another to meet the "anchoring" requirement for vehicle pairs have been developed. We observed that nearly all of the cited studies comparing CVs to FCVs compared CVs with an approximate 8-second 0–60 mph acceleration capability to FCVs with an approximate 10-second 0–60 mph acceleration capability. We have made use of estimates of characteristics of conventional vehicles from a prior study (6) to develop equations from which we "slow down" CVs to match the FCV acceleration capability. We have also used key internal information on the (absence of) fuel economy effect of fuel cell downsizing from the cited FCV studies (14) to allow us to develop a different method of "speeding up" the FCVs to match the CV acceleration capability. We apply both adjustment methods, developing comparisons as if the vehicle pairs *both* had either 8- or 10-second
0–60 mph acceleration capability.

Nearly all of the studies cited used a vehicle with a contemporary conventional powertrain as a baseline. The one exception, the MIT 00 study, anchored its comparison of advanced technology FCVs to advanced technology CVs. We used the MIT 00 advanced powertrain gpm/kg and powertrain kW/kg values to estimate the mass and fuel consumption of advanced versions of the baseline vehicles in the cited studies.

Numerous findings and implications of the numbers obtained with the methods of adjustment and performance rules are provided in the Results section of this paper. The one finding that should at this time be a "conclusion" is that the method and rules of comparisons of conventional and advanced vehicle pairs can make a very large difference in the results obtained. If numerous studies are to be compared to one another, and if the science of vehicle technology is to be advanced rapidly, then rules of comparison should be developed and adhered to in setting up simulation experiments and in publishing the results from those experiments. This paper contributes to the refinement of precedents in other studies that suggest a baseline method of comparison. In this paper, we describe our interim method of adjustment of values; the adjustment would have been better accomplished by re-running vehicle simulations conducted in the studies cited and adding considerably to the sets of experiments conducted. This paper uses an approximate method of experimentation — one that should be replaced by a method that makes use of rapidly improving vehicle simulation models to increase the certainty in comparative evaluations of technologies for use by policymakers. As is always the case, policymakers may use interim findings in the absence of anything better. However, in the case of FCVs, at this time it seems more appropriate to conclude that we should continue to refine research and measurement methods than make any conclusions concerning the best technical options. We hope that this paper is a positive step along that path.

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APPENDIX A

Table A1 Characteristics of Conventional and Fuel-Cell Vehicles Analyzed

Study and Date	Vehicle/Body	0–60 (sec)	City mpg	COMP mpg	Highway mpg	Study Glider Mass (kg)	Glider Mass Used (kg)	Curb Mass (kg)	Test Mass (kg)	Net kW	kW/(kg +136)	Estimate of NSp
NRL 01	Typical 2000 SUV — CV	ne[a]	18.1	21.2	26.7	1202	1202	1788	1924	144	.0748	0.246
NRL 01	Typical 2000 SUV — FCV	9.2	51.1	51.2	51.4	1202	1202	1887	2023	127	.0628	0.185
Ford 00	CV AIV[b]	ne	24.1	ne	ne	ne	840	1168	1321	103	.0780	see text
Ford 00	H_2 FCV AIV	11.3	61.3	ne	ne	ne		1348	1491	80	.0537	0.157
Ford 00	H_2 HEV FCV AIV	10.7	65.8	ne	ne	ne		1355	1491	85	.0570	0.165
ANL 00	Petrol FCV Light&Aero80kW	ne	79	92	109	ne		ne	***1043***	80	.0767	ne
ANL 00	Petrol FCV Light&Aero40kW	ne	ne	89	ne	ne		ne	***1043***	40	.0384	ne
This	CV Light&Aero62kW.78 kg[c]	8.0	44.5	54.5	75.2	ne		678	814	62.4	.0767	ne
MIT 00	CV 1996	ne	23.7	27.8	35.2	930	930	1334	1444	110	.0760	0.272
MIT 00	CV 2020	ne	42.4	49.1	60.8	756		1026	1136	85.2	.0750	0.316
MIT 00	H_2 HEV FCV	ne	83.7	94.1	111	763		1204	1314	98.5	.0750	0.220
MIT 00	MeOH HEV FCV	ne	49.9	56.9	68.4	778		1265	1375	103	.0750	0.203
MIT 00	Petrol HEV FCV	ne	37.2	42.3	50.9	794		1348	1458	109	.0750	0.185
DTI 98	CV AIV	ne	25.5	30.1	38.5	821-899	***840***	1168	1304	100	.0775	0.317
DTI 98	H_2 HEV FCV AIV	ne	79.7	82.2	85.4	821-899	865	1155	1291	78.4	.0607	0.249
DTI 98	H_2 FCV AIV	ne	75.0	81.1	90.1	***821-899***	***865***	***1155***	***1291***	***78.4***	.0607	0.249
DTI 98	MeOH HEV FCV AIV	ne	52.4	54.6	57.6	879-905	879	1277	1413	87.6	.0620	0.200
DTI 98	Petrol HEV FCV AIV	ne	36.8	38.4	40.6	882-909	882	1339	1475	91.9	.0623	0.184
DTI 99	CV AIV	ne	ne	31	ne	ne	840	1155	1304	100	.0767	0.305
DTI 99	H_2 HEV FCV AIV	ne	ne	82	ne	ne		ne	1291	78.3	.0607	0.249
DTI 99	H_2 FCV AIV Sable	ne	ne	81	ne	ne		ne	1283	74.1	.0578	0.241
DTI 99	MeOH HEV FCV AIV	ne	ne	54	ne	ne		ne	1414	88.1	.0623	0.201
DTI 99	Petrol HEV FCV AIV	ne	ne	38	ne	ne		ne	1475	91.7	.0622	0.184
DTI 99	CV PNGV	ne	ne	38.5	ne	ne	649	906	1042	80	.0768	0.311
DTI 99	H_2 HEV FCV PNGV	ne	ne	107	ne	649		896	1032	62.6	.0607	0.253
DTI 99	H_2 FCV PNGV	ne	ne	105	ne	ne		ne	1023	59.1	.0578	0.248
DTI 99	MeOH HEV FCV PNGV	ne	ne	72	ne	ne		ne	1119	71.1	.0635	0.213
DTI 99	Petrol HEV FCV PNGV	ne	ne	50.5	ne	ne		ne	1172	74.5	.0636	0.193
GM 01	CV Pickup Truck	7.9	17.4	20.2	25	ne		ne	ne	ne	ne	
GM 01	H_2 HEV FCV Pickup	10.0	51.5	48.1	44.5	ne		ne	ne	ne	ne	
GM 01	H_2 FCV Pickup	8.4	41.6	43.2	45.4	ne		ne	ne	ne	ne	
GM 01	MeOH HEV FCV Pickup	9.8	35.8	34.5	33	ne		ne	ne	ne	ne	
GM 01	MeOH FCV Pickup	9.4	28.8	30.3	32.4	ne		ne	ne	ne	ne	
GM 01	Gasoline HEV FCV PNGV	9.9	31.9	30.2	28.5	ne		ne	ne	ne	ne	
GM 01	Gasoline FCV PNGV	10.0	26.2	27.2	28.6	ne		ne	ne	ne	ne	

Table A1 Characteristics of Conventional and Fuel-Cell Vehicles Analyzed (Cont.)

Study and Date	Vehicle/Body	Engine or Fuel Cell kW	Engine or FC Fuel Cell Efficiency (%)	FCV Refor-mer kW	FCV motor kW	FCV Batt-ery kW	C_d	A	C_r	Grade-ability
NRL 01	Typical 2000 SUV — CV	144	34	na[d]	na	na	0.44	2.66	0.0120	ne
NRL 01	Typical 2000 SUV — FCV	58	58 peak	na	127	100	0.44	2.66	0.0120	6.6
Ford 00	CV AIV[b]	103	na	na	na	na	0.33	2.13	0.0078	ne
Ford 00	H_2 FCV AIV	80	56.9	na	90	na	0.33	2.13	0.0078	17.1
Ford 00	H_2 HEV FCV AIV	40	ne	na	90	45	0.33	2.13	0.0078	15.9
ANL 00	Petrol FCV Light&Aero80kW	80	ne	ne	80	na	0.163	2.18	0.0064	ne
ANL 00	Petrol FCV Light&Aero40kW	80	ne	ne	80	na	0.163	2.18	0.0064	ne
This	CVAero&Light62kW.78 kg	62.4	ne	na	na	na	0.163	2.18	0.0064	ne
MIT 00	CV 1996	109.7	ne	na	na	na	0.33	2.00	0.0090	ne
MIT 00	CV 2020	85.2	ne	na	na	na	0.22	1.80	0.0060	ne
MIT 00	H_2 HEV FCV	65.7	52	na	98.5	32.8	0.22	1.80	0.0060	ne
MIT 00	MeOH HEV FCV	68.7	47	ne	103	34.4	0.22	1.80	0.0060	ne
MIT 00	Petrol HEV FCV	72.9	41	ne	109	36.4	0.22	1.80	0.0060	ne
DTI 98	CV AIV	100	ne	na	na	na	0.33	2.13	0.0092	ne
DTI 98	H_2 HEV FCV AIV	38.1	54	na	82	40.3	0.33	2.13	0.0092	ne
DTI 98	H_2 FCV AIV	***78.4***	57	na	***78.4***	na	***0.33***	***2.13***	***0.0092***	ne
DTI 98	MeOH HEV FCV AIV	44.4	ne	44.4	88.3	43.2	0.33	2.13	0.0092	ne
DTI 98	Petrol HEV FCV AIV	48.8	ne	48.8	88.1	43.1	0.33	2.13	0.0092	ne
DTI 99	CV AIV	100	30	na	na	na	0.33	2.13	0.0092	ne
DTI 99	H_2 HEV FCV AIV	38	ne	na	82.1	40.3	0.33	2.13	0.0092	ne
DTI 99	H_2 FCV AIV Sable	74.1	ne	na	81.5	na	0.33	2.13	0.0092	ne
DTI 99	MeOH HEV FCV AIV	45.1	ne	45.1	88.1	43.2	0.33	2.13	0.0092	ne
DTI 99	Petrol HEV FCV AIV	56.5	ne	56.5	91.7	45	0.33	2.13	0.0092	ne
DTI 99	CV PNGV	80	ne	na	na	na	0.27	2.08	0.0072	ne
DTI 99	H_2 HEV FCV PNGV	29.8	ne	na	65.6	32.8	0.27	2.08	0.0072	ne
DTI 99	H_2 FCV PNGV	59.1	ne	na	65	na	0.27	2.08	0.0072	ne
DTI 99	MeOH HEV FCV PNGV	35.7	ne	35.7	71.1	35.6	0.27	2.08	0.0072	ne
DTI 99	Petrol HEV FCV PNGV	45	ne	45	74.5	37.3	0.27	2.08	0.0072	> 6
GM 01	CV Pickup Truck	ne	ne	ne	ne	ne	ne	ne	ne	> 6
GM 01	H_2 HEV FCV Pickup	ne	ne	ne	ne	ne	ne	ne	ne	> 6
GM 01	H_2 FCV Pickup	ne	ne	ne	ne	ne	ne	ne	ne	> 6
GM 01	MeOH HEV FCV Pickup	ne	ne	ne	ne	ne	ne	ne	ne	> 6
GM 01	MeOH FCV Pickup	ne	ne	ne	ne	ne	ne	ne	ne	> 6
GM 01	Petrol HEV FCV Pickup	ne	ne	ne	ne	ne	ne	ne	ne	> 6
GM 01	Petrol FCV Pickup	ne	ne	ne	ne	ne	ne	ne	ne	> 6

[a] ne = no estimate presented.
[b] Regular Sable mpg (so stated), not AIV Sable.
[c] Based on other petrol FCV simulations, the relative mass of the CV simulated for this paper was set at 78% of the mass of the FCV.
[d] na = not applicable.

Bold and italics imply that the values are inferred from the study and are not direct citations.