2003-01-0412

Assessing Tank-to-Wheel Efficiencies of Advanced Technology Vehicles

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ABSTRACT

This paper analyzes four recent major studies carried out by MIT, a GM-led team, Directed Technologies, Inc., and A. D. Little, Inc. to assess advanced technology vehicles. These analyses appear to differ greatly concerning their perception of the energy benefits of advanced technology vehicles, leading to great uncertainties in estimating full-fuel-cycle (or "well-to-wheel") greenhouse gas (GHG) emission reduction potentials and/or fuel feedstock requirements per mile of service. Advanced vehicles include, but are not limited to, advanced gasoline and diesel internal combustion engine (ICE) vehicles, hybrid electric vehicles (HEVs) with gasoline, diesel, and compressed natural gas (CNG) ICEs, and various kinds of fuel-cell based vehicles (FCVs), such as direct hydrogen FCVs and gasoline or methanol fuel-based FCVs. We focus on variations in estimates of vehicle gasoline-equivalent fuel energy use, glider and powertrain masses, and introduce powertrain effectiveness as a new surrogate measure for tank-to-wheel vehicle efficiency. We conclude that, while the degree of uncertainty across studies is considerable, it is not as great as a summary investigation and direct comparison implies. Our investigation suggests that there are logical and systematic reasons for variations among the studies. Further studies are required to improve both assessment and understanding of technical potentials of these advanced technologies, and to narrow the range of uncertainty currently present.

INTRODUCTION

In recent years, many studies have assessed the impacts of advanced technology vehicles (ATVs) on gallons of gasoline equivalent (gge) energy use, and some of them also include full-fuel-cycle (or well-to-wheel [WTW]) energy use estimates and greenhouse gas (GHG) potentials [1-9]. Recognizing the importance of this emerging area of research, and the quality of work presented to it, SAE awarded the 1999 full-fuel-cycle energy analysis paper by Stodolsky et al (7) an Arch T. Colwell award as one of the top papers of the year. Stodolsky et al provided a high and low estimate for each fuel/vehicle pathway examined. Studies since have either expanded in comprehensiveness or added depth of detail. In general, these analyses demonstrate very different results for many ATVs and show a wide range of uncertainties. Similar to Stodolsky et al, both Weiss et al (1) and GM (2) recognize the importance of acknowledging uncertainty and include their own estimates of uncertainty ranges. Although uncertainty ranges can be sometimes quite wide, an evaluation of differences among technologies based on percentage change from the base vehicle's reference value reveals that the most probable values of one study are sometimes outside the uncertainty range of the other. Because the stakes are increasing for both industry and the federal government in choosing developmental paths, providing and allocating capital and technological investment, consistent and improving projections of future advanced technology vehicles are crucial for decision-makers at all levels. Advanced vehicles include, but are not limited to, advanced gasoline and diesel internal combustion engine (ICE) vehicles, hybrid electric vehicles (HEVs) with gasoline, diesel and CNG ICEs, and various kinds of fuel-cell based vehicles (FCVs) such as direct hydrogen (H2) FCVs and gasoline or methanol reforming FCVs. Like gasoline, diesel, and CNG ICE technology, FCVs may also be hybridized. Some studies include FCVs with and without hybridization.

In this paper, we examine results from four studies (cited by institutional or corporate affiliation of the authors) as follows [1-6]:

> 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.

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.*

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.

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

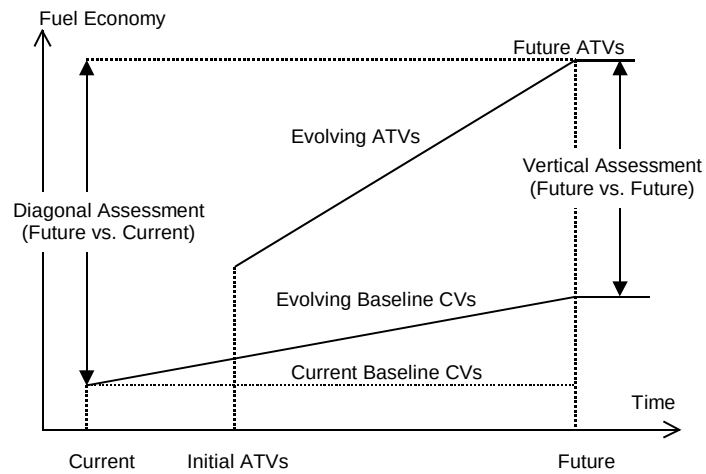
This paper focuses on the so-called "tank-to-wheel" (TTW) portion of the WTW process and introduces a new concept – powertrain effectiveness – to compare relative benefits of ATVs in these studies. The authors of this paper, on behalf of the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, have been attempting to determine the primary causes for differences among these studies, and provide such information to the scientific and technical community. This is one of a series of papers that focuses on a subset of technologies and/or studies, and attempts to provide insights on the many potential intermediate causes for the different final estimates by authors of the various comprehensive studies [10-13]. Before starting our analysis, we would like first to address several critical issues associated with ATV analysis.

TECHNOLOGY TIMELINE ISSUE - "VERTICAL" VS. "DIAGONAL" ASSESSMENT

A careful examination reveals that these studies have assumed very different timelines for baseline conventional vehicles (CVs) and ATVs, creating confusion about which timeframe and baseline should be used for assessing the relative benefits of ATVs. For example, all of MIT's ATV analyses are based on a projected MY 2020 advanced conventional gasoline spark-ignition (SI) vehicle, instead of a current SI-ICE vehicle. However, GM has chosen a current Silverado pickup as a baseline vehicle, even though the study states that GM is "focusing on technologies that are expected to be implemented in 2005 and beyond" and "emissions targets for all vehicles were based on Federal Tier 2 standards, … for the 2010 timeframe"[2]. This creates a dilemma that can be illustrated by Figure 1, where the concepts of "vertical" vs. "diagonal" assessment are introduced. The vertical assessment can be defined as comparisons based on same timeframe, e.g., future ATVs vs. future CVs. The diagonal comparisons can be defined as comparisons based on different timeframes, e.g., future ATVs vs. current CVs.

While the diagonal comparisons are often used in assessing future potentials of the same types of vehicle technologies, as in studies recently conducted by the NRC and others [14-17], it can be argued here that the vertical approach may better suit cross-comparisons of advanced powertrain technologies, because of the following reasons: 1) baseline CVs, as well as ATVs, are evolving, thus all of them are moving targets (not just ATVs); 2) we are most interested in cross-comparing relative benefits of various ATVs under the same timeframe; and 3) vertical assessment gives a more consistent and easier approach to cross-compare different studies.

Figure 1 – Vertical vs. Diagonal Assessment



Nevertheless, the advantage of a diagonal assessment is obvious: it gives a clear picture of absolute benefits over current baselines. Of course, the diagonal approach merges with the vertical approach if the baseline CV is assumed not to be evolving, or in other words, the evolving baseline equals the current baseline. This appears to be the case for GM analysis, where no future evolving base vehicle is analyzed. The diagonal comparison scheme is explored further in the Appendix.

The variation in timelines and baseline vehicle attributes turns out to be a source of much confusion in comparing ATV benefits, which we will further discuss in the following sections. Another issue is how to compare vertical assessments under different future timeframes, e.g., GM under 2005-10 and MIT under 2020. This issue is unsolvable within the scope of this study and we will have to leave it for future analysis.

WELL-TO-WHEEL (WTW) VS. TANK-TO-WHEEL (TTW) ANALYSIS

Although this paper focuses on tank-to-wheel, or vehicle-level analysis, we believe that complete comparisons of advanced technology vehicles should be conducted on a life-cycle, or well-to-wheel (WTW) basis. WTW process includes both well-to-tank (WTT, or upstream) and tank-to-wheel (TTW or vehicle) steps. Both GM and MIT analyses include these steps and are subjects of this section.

These two studies are based on very different baseline vehicles – MIT is based on a midsize conventional car, and GM is based on a light-duty truck (Chevrolet Silverado). Each also includes somewhat different fuel and technology choices, but they share many common powertrain types within a very comprehensive analysis, and thus provide the basis for numerous comparisons. Table 1 lists the most probable WTW GHG emissions (in g/mi) of baseline and advanced technology vehicles, as well as GHG reductions associated with various ATVs. *Note that this paper focuses on the most probable values from each of these two studies, and does not discuss the uncertainty ranges within those studies.*

For vertical assessment purposes, we are interested only in GM assessments of ATVs and the baseline vehicle under the same 2005-2010 timeframe. Since GM provides only a current pickup truck as the base vehicle, we can assume that GM is allowing for no changes in the baseline vehicle in the 2005-2010 timeframe. Using this interpretation, we label the GM case "GM 2005-10." This implies that the GM and MIT (based on 2020) assessments are literately more than 10 years apart. Table 1 shows that these two studies demonstrate significant differences in almost all ATVs in terms of GHG emissions, rankings, and reductions.

Since the MIT baseline vehicle is much lighter and smaller than GM's, the GHG rates of both studies cannot be compared directly. Instead, we compare ranks and percentage of GHG reductions associated with each ATV. Note also that the MIT study provides two nominal 2020 evolving baselines. However, all ATVs are "spun off" the advanced 2020 baseline, so we use it as *the* 2020 baseline in Table 1.

Table 1 – Well-to-Wheel GHG Emissions of Advanced Vehicles in MIT and GM Studies

	MIT 2020			GM 2005-10			MIT-GM
Technology	g/mi	Rank	Reduc-tion	g/mi	Rank	Reduc-tion	Diffs
Current SI-ICE	424*			**554**			
2020 Base SI-ICE	278*	7					
2020 Adv. SI-ICE	**247**	6					
Advanced CI-ICE	218	4	12%	472	6	15%	-3%
Hybrid SI-ICE	176	2	29%	454	5	18%	11%
Hybrid CI-ICE	156	1	37%	384	4	31%	6%
Hybrid H2 FC[1]	201	3	19%	296	1	47%	-28%
Hybrid Gaso. FC	289	8	-17%	366	3	34%	-51%
Hybrid MeOH FC	222	5	10%	324	2	42%	-31%

* These MIT vehicles have different "gliders" (bodies) than remaining MIT cases, which all use the same low mass, low aero drag, low rolling resistance glider.

Bearing all the differences in mind, the GHG reductions for MIT ATVs range from -17% for gasoline FCVs to 37% for the diesel hybrid-electric vehicles (Hybrid CI-ICE). The GM study estimates that the benefits of ATVs range from 15% for the conventional diesel vehicles (CI-ICE) to 47% for the direct hydrogen (H2) FCVs. The last column of Table 1 shows the differences between MIT and GM results. While MIT's results show higher benefits for hybrid ICE vehicles (Hybrid SI-ICE and Hybrid CI-ICE), and slightly lower benefits for the CI-ICE, the trend for fuel-cell based fuel cell vehicles (FCVs) is striking: MIT results indicate much lower benefits for all FCVs. One extreme result is the hybrid gasoline reformer FCVs. While MIT shows a negative GHG impact (comparing with the 2020 baseline case with a 17% increase), GM shows a strong positive impact (a 34% reduction over its baseline vehicle).

Please note that this conclusion is consistent with each team's publicized position on technology choice: MIT is generally more enthusiastic about the potential of conventional technologies and skeptical of fuel cell technologies. GM has made no secret that they prefer focusing research on fuel cell technologies, rather than attempt to dramatically improve fuel economy of conventional technology vehicles. GM's study is quite different from the Weiss et al study in that it does not include a case with improved conventional powertrains, even though research and development of such powertrains is being conducted. Another difference between the GM study and Weiss et al (as well as Graham et al (8)) is that the conventional hybrid powertrains do not include a higher efficiency engine than that found in the reference vehicle. Weiss et al assume that a gasoline direct injection engine will be successful in the U.S. in the future and will be used in both conventional and hybrid powertrains. Graham et al assume that the Toyota Atkinson cycle engine technology (not suitable for conventional powertrains) will be used in future hybrids.

There are also many other contradictory implications. Some examples are as follows:

- MIT projects that the hybrid gasoline reformer FC would have the highest GHG emissions rate among all of its 2020 vehicles (ranks 8th of nine in Table 1), including baseline evolving SI-ICE. However, GM projects that the hybrid gasoline reformer FC (ranks 3rd of seven in Table 1) has a lower GHG emissions rate than all of its ICE-based conventional or hybrid vehicles.

- MIT estimates that hybrid hydrogen (H2) FCV (ranks 3rd) compares unfavorably to two ICE-based hybrid vehicles (ranks 1st & 2nd) in terms of GHG emissions. GM estimates otherwise.

- MIT estimates that diesel hybrid vehicles have the lowest GHG rate and largest GHG reduction among all vehicles (ranks 1st). In the GM case, it is the hybrid direct hydrogen FCV.

[1] H2 from decentralized reforming NG stations

Figures 2 and 3 demonstrate the significantly different results of these two studies. These contradictory results lead us to ask hard questions regarding the root of the uncertainties. While it is convenient to divide the WTW process into Well-to-Tank (WTT) and Tank-to-Wheel (TTW) processes, one needs to remember that upstream WTT energy use and emissions are largely driven by TTW energy demands, thus the uncertainties and disagreements often come directly from the assessment of TTW, or net vehicle powertrain efficiencies. More specifically, for vehicles using petroleum fuels or fuels from other feedstock, WTT process would inherit and even expand the uncertainties from TTW process.

Figure 2 – GHG Reductions from Base Vehicles in MIT and GM Studies

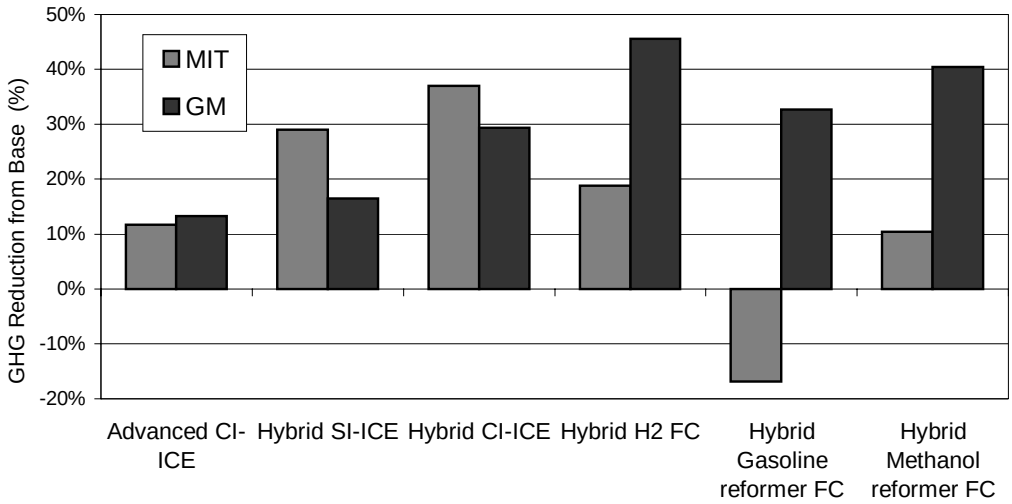
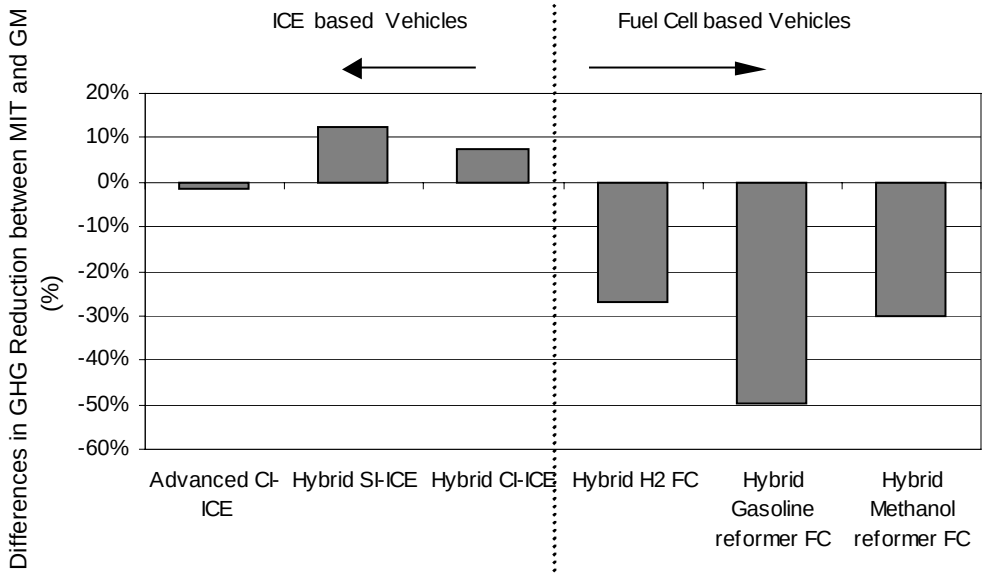


Figure 3 – Differences in GHG Reductions Between MIT 2020 and GM 2010 Scenarios



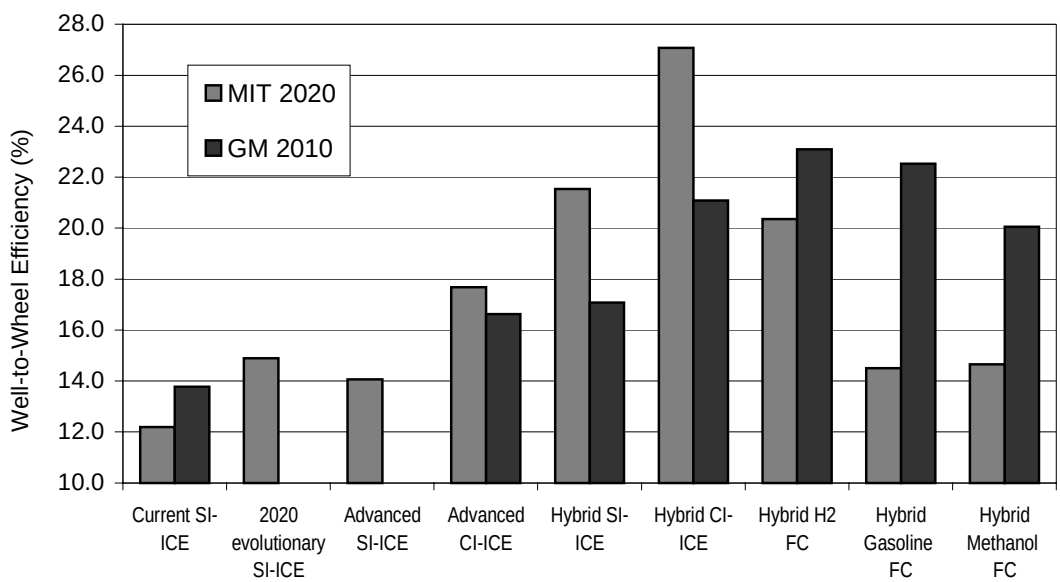
However, for our purposes, we are more interested in causes of variation among studies than within studies. Since the MIT and GM studies both relied significantly (MIT), or totally (GM), on different versions of the same upstream model (Argonne National Laboratory's Greenhouse Gas, Regulated Emissions, and Energy Use in Transportation [GREET] model), the upstream (WTT) variation across the two studies is not as large as the downstream (TTW) variation. Table 2 shows the Well-to-Tank (WTT), Tank-to-Wheel (TTW), and Well-to-Wheel (WTW) energy efficiencies of all ATVs in the MIT and GM studies. Figure 4 compares the WTW efficiencies of ATVs in both studies. Table 2 shows that the upstream WTT efficiencies are quite consistent among these two studies – about 83% for gasoline fuel, 86-88% for diesel fuel, 65% for methanol fuel based on NG pathway, and 56-57% for H2 fuel based on H2 production from decentralized NG stations. However, the vehicle TTW efficiencies differ greatly, as demonstrated by the "MIT-GM" columns. The last three columns of Table 2 under the "WTW Gains" show that the overall WTW efficiency gains of ATVs over the baseline vehicles, and the differences between MIT and GM studies. It shows that the efficiency differences are even greater than the differences for GHG reductions.

While most vehicle-related studies focus on vehicle fuel economy (miles per gallon, or MPG), other measures such as fuel consumption (in MJ/km or L/km) and TTW efficiency (or vehicle powertrain efficiency) can also be used to analyze and compare ATVs. Vehicle TTW efficiency is defined as a ratio of vehicle useful work to fuel consumption. While the fuel economy and fuel consumption are most commonly used to measure vehicle energy consumption, they are greatly influenced by vehicle weight, aerodynamic characteristics of vehicle body design, and tire resistance, all of which are not exclusively related to specific powertrain technologies. Therefore, our investigation pays special attention to the relative advancement of different powertrain technology platforms. While TTW efficiencies are ideal measures to cross-compare these studies, only two of the four studies examined (MIT and GM) provided TTW efficiency figures. To overcome this, we introduced a new concept

Table 2 - Well-to-Tank (WTT), Tank-to-Wheel (TTW), and Well-to-Wheel (WTW) Efficiencies of ATVs in MIT and GM Studies

Energy Efficiency		MIT 2020			GM 2005-10			MIT-GM			WTW Gains		
Vehicle Type	Fuel	WTT	**TTW**	WTW	WTT	**TTW**	WTW	WTT	**TTW**	WTW	MIT 2020	GM 2010	MIT-GM
Current SI-ICE	Gasoline	82.6	**14.8**	12.2	82.5	**16.7**	13.8	0.1	**-1.9**	-1.6			
2020 evolv. SI-ICE	Gasoline	82.6	**18.0**	14.9									
2020 Adv. SI-ICE	Gasoline	82.6	**17.0**	14.1									
Advanced CI-ICE	Diesel	87.7	**20.2**	17.7	85.7	**19.4**	16.6	2.0	**0.8**	1.1	26%	21%	5%
Hybrid SI-ICE	Gasoline	82.6	**26.1**	21.5	82.5	**20.7**	17.1	0.1	**5.4**	4.5	53%	24%	29%
Hybrid CI-ICE	Diesel	87.7	**30.9**	27.1	85.7	**24.6**	21.1	2.0	**6.3**	6.0	92%	53%	39%
Hybrid H2 FC	H2 (CNG Station)	56.5	**36.0**	20.3	55.8	**41.4**	23.1	0.7	**-5.4**	-2.8	45%	68%	-23%
Hybrid gasoline FC	Gasoline	82.6	**17.6**	14.5	82.5	**27.3**	22.5	0.1	**-9.7**	-8.0	3%	63%	-60%
Hybrid Methanol FC	MeOH	64.9	**22.6**	14.7	64.5	**31.1**	20.1	0.4	**-8.5**	-5.4	4%	46%	-41%

Figure 4 – Well-to-Wheel Efficiencies in MIT and GM Studies



labeled "powertrain effectiveness" as a surrogate measure for the TTW efficiency. The powertrain effectiveness measure is unaffected by the failure of TTW efficiency to deal properly with influences of powertrain mass differences on fuel consumption. This approach would minimize problems in conducting cross-comparison among studies when different weight-class vehicles, including pickup trucks, midsize cars, and PNGV-type vehicles, are used.

GENERAL METHODOLOGICAL ISSUES

It is becoming increasingly clear that, in assessing technical potentials of various ATVs, a set of rules should be adopted to assure the assessment is fair and consistent. Santini et al. showed how violations of different sets of rules could influence the outcome of the technological prediction [10-13]. However, in many studies, standardized rules for comparisons are either not defined or not followed, intentionally or unintentionally. The following are some examples of these rules and related issues:

1. Carefully define and characterize baseline vehicle technologies.

In many studies, the baseline technology is not properly defined and characterized (e.g, NRC CAFE study [14]), resulting in questionable future projections for improvement potentials. It may be noted that in the NRC study, there is no difference in estimated percent fuel economy gain or cost by class of vehicle, despite the fact that separate tables are repeated with the same numbers for passenger cars (NRC Table 3-1), SUVs and Minivans (NRC Table 3-2), or Pickup Trucks (NRC Table 3-3).

2. Establish performance-equivalent criteria, such as 0-60 acceleration time, gradeability, range, interior volume, torque, and safety requirement.

Vehicle fuel efficiency is sensitive to its performance level. The 0-60 acceleration time is a most commonly used criterion. It is important that any comparison and evaluation be based on performance equivalence, and the estimates of performance should be published. However, this rule was violated in varying degrees by many analyses. One illustration of the difference that assumptions about peak powertrain kW per kg of vehicle mass (a surrogate for 0-60 time) can make is found in Santini, Vyas, Kumar, and Anderson [12]

3. Select and use common driving cycles. Comparison and evaluation should be conducted on the basis of the same driving cycles.

Vehicle fuel consumption is very sensitive to drive cycles. Meaningful comparisons can be derived only based on the same test cycles. Various studies worldwide have used FTP, HWY, CAFE, 1.25*CAFE, European and/or Japanese cycles as the basis for evaluation. Comparisons can more easily be made successfully among studies that have used the same cycle(s). If the cycles are not identical, then very detailed information on the vehicles and powertrain components must be provided if evaluators (such as ourselves) are to successfully translate estimates from one driving cycle to another.

4. Base the comparison of vehicle fuel use on fuel economy (such as MPG), fuel consumption (such as MJ/km or L/km), or powertrain efficiency (or tank-to-wheel efficiency, vehicle efficiency). At this time there is no consistent approach agreed upon.

While the fuel economy and fuel consumption benchmarks are most commonly used, the advantage of vehicle and powertrain efficiency benchmarks is not always overlooked. Using TTW efficiency removes the influences of powertrain and vehicle weight and body structures. TTW has often been used to provide cross-comparison among a wide variety of vehicle and engine technologies and analyses, and the MIT and GM studies make use of it. However, we suggest that TTW is imperfect, and we develop and suggest an alternative in the closing section of this paper.

An advantage of using powertrain efficiency is that it gives insight regarding the technology advancement. While there is theoretically no limit to fuel economy potentials (which can in simulation be continuously improved by lowering vehicle weight and load), the limitation of powertrain efficiency is much better defined and understood, e.g., the SI gasoline engine peak thermodynamic efficiency limit is under 40%. Yet, peak efficiency alone is not enough, especially when low load efficiency varies. If idle fuel flow rate information is not available, fuel savings in hybrids by eliminating idling cannot be assessed.

5. When making comparisons, clearly define and synchronize technology scenarios.

The comparison of conventional and advanced technology vehicles should be conducted under well-defined technology aggressiveness or success scenarios. Technology potentials usually have a range defined by upper and lower boundaries. Adoption of upper boundary, middle point or lower-boundary values represents different scenarios often associated with names such as optimistic, moderate, or conservative. It is a mistake and creates confusion when scenarios are mixed but not clearly defined during comparisons. A detailed illustration is in Appendix A.

In many studies, technologies are too often compared on the basis of different scenarios, e.g., conventional vehicle technology in the aggressive upper-boundary scenarios against advanced technology vehicles under conservative lower-boundary scenarios, or vice versa. Distorted results and conclusions could occur under these circumstances.

In our view, a well-defined technology scenario cannot be replaced by simply assigning uncertainty ranges to individual technologies. Investigation of a preliminary draft of the NRC study [14] demonstrated that the multiplicative accumulation of savings at high ends of uncertainty ranges associated with multiple technologies could lead to clearly incorrect results. (For example, accumulation of upper-boundary potentials of all valve train technologies can lead to violation of thermodynamic laws). The problem is that the probability of one technology is often not independent of another technology, and there are very few technologies that are truly independent from others.

6. Conduct the comparison under clearly defined time periods. Confusion is created when projected benefits of distant future ATVs are compared with near-term benefits of different ATVs.

Since we all understand today's technologies better than that of the future, and conventional technologies better than emerging advanced ones, it is important to choose properly defined and comparable time periods to compare different technologies.

7. Advanced technologies are not static, but evolving, just like conventional technologies. For example, hybrid technologies can have many forms that result in different benefits [17-19]. It is not appropriate to designate one form of hybrid technology to be representative. The emergence of so called "minimum" or 42 V- based hybrids starts to blur the distinction between hybrid technology and evolving conventional technologies [15, 19].

8. The cost estimates of future technologies are highly uncertain. Cost considerations may involve ordering of technology sequence, current cost, future mass-production cost, and target cost. A more detailed discussion about technology cost is given by Santini, Vyas, Moore, and An, 2002 [10].

9. Conduct ATV comparisons based on same baseline reference vehicle. *A strongly preferred method for evaluating powertrain effectiveness is to have these ATVs sharing the same vehicle glider,* which includes mostly vehicle body and chassis. If the effects of vehicle aerodynamic drag (Cd), tire rolling resistance (Cr), and body chassis design (glider mass) are to be isolated from powertrain effects, these values have to be held constant in the reference vehicle and the ATVs. Most studies do this, but MIT includes two conventional powertrain vehicle cases that do not.

10. Make the effects of cold start explicit. In addition to the complication that the change in "hot stabilized" idle fuel flow may not change by the same percentage as peak thermal efficiency, there are also problems that energy and time needed to warm the powertrain to operating temperature vary across technologies in ways very different from peak thermal efficiency. Ideally, studies would provide separate estimates of fuel consumption with and without cold start of a given driving cycle. None cited do this.

While we are aware of the complexity of these issues, it is not possible in this paper to address all of them. In the main body of this paper, we compare results of different studies directly, without adjusting them based on the above. So it is important to keep in mind that much of the presented differences come from several of the above sources. However, even with theoretically perfect adjustments according to the rules above, differences of opinion by experts will remain important, and uncertainty will remain. Nevertheless, nothing is more essential than judging the technology itself, isolated from the "noise" created when rules are not followed. Our analysis shows that even after some adjustments to reduce the above problems, there remain fundamental differences among these analyses in estimates of the technology potentials of various ATVs. These differences are the subject of our discussion in the following sections.

SUMMARY RESULTS

In the following sections, we compare results of Weiss et al (MIT), GM, Thomas et al (DTI), and ADL studies on the following three variables: vehicle mass, fuel economy in miles-per-gallon of gasoline equivalence (MPGGE), and powertrain effectiveness.

Largely on the basis of the MIT study, we have chosen vehicles listed in Table 3 as our basis for comparison. Please note that some advanced vehicles are not included in the other studies. Table 3 also lists the timeframe for baseline and ATV analysis under each study. Only DTI didn't explicitly provide a timeframe for their analysis, rather, their analyses are based largely on PNGV and DOE targets. On the basis of this, we interpret their timeframe to be around 2005.

Table 3 – ATVs Considered in the Four Studies

Vehicle Type	MIT	GM	DTI	ADL
Current SI-ICE	X	X		
Timeframe	2020	2005-2010	2005	2010
Evolutionary SI-ICE	X			
Advanced SI-ICE	X		X	X
Advanced CI-ICE	X	X		X
Hybrid SI-ICE	X	X		X
Hybrid CI-ICE	X	X	X	X
Hybrid CNG SI-ICE	X		X	
Hybrid H2 FC	X	X	X	X
Hybrid Gasoline FC	X	X	X	X
Hybrid MeOH FC	X	X	X	X

While all four studies provide MPG figures for various ATVs, only the MIT study provides complete figures of both vehicle mass and TTW efficiency. The GM study does not provide vehicle mass, and DTI and ADL studies do not provide TTW efficiencies. We estimate mass for the GM case, and develop a powertrain effectiveness measure for comparison among all studies that eliminates the need for TTW efficiency for the ADL and DTI studies.

FUEL ECONOMY BASED COMPARISION

The fuel economy in our analysis is defined as gasoline-equivalent miles per gallon: MPGGE or simply MPG. The baseline GM vehicle is a pickup truck and weighs about 1,900 kg; the baseline MIT and ADL vehicles are midsize cars and weigh about 1,300 kg; and the baseline ADL vehicle weighs about 1,170 kg. While it's not appropriate to compare the GM study directly with the other three for fuel economy values, it is more reasonable to compare directly MIT, DTI, and ADL results. As discussed earlier, we choose a vertical assessment approach, where the comparisons between baselines and ATVs are based on same timeframe for each study. Figure 5 shows the vertical assessment based on three different timeframes: DTI, GM, and ADL for 2005-10; and MIT for 2020, for hydrogen and gasoline FCVs and corresponding baseline vehicles.

Figure 5 shows that all three H2 FCVs (MIT, DTI, and ADL in solid squares) are grouped near the top of the map, demonstrating clear energy benefits of H2 FCVs on all scenarios. The three gasoline FCVs (in solid triangles) are grouped in the middle of the map, and the baseline vehicles (in solid diamonds) are at or near the bottom (connected by a dark dotted line). Since GM vehicles are all much heavier and should have lower MPGGE, all GM vehicles are in open symbols, so that they will not dominate the illustration. Among the baseline vehicles, the biggest distinction appears to be the obvious upswing of the MIT base vehicle in 2020, overtaking MIT's gasoline reformer FCV. The other studies estimate clear advantages of gasoline FCVs over the corresponding baseline vehicles. However, the figure also illustrates that if GM had an improved 2010 baseline, some of the advantage it estimates would disappear. This map clearly illustrates that MIT is bullish on the future baseline CV technologies.

Table 4 shows MPG gains over respective baseline vehicles for these studies, under different timeframes, as also shown in Figure 6. The MIT 2020 results show MPG gains range from -14% for the gasoline reformer FCV, to 92% for the direct H2 FCV. GM 2010 results show a range of 18% for diesel ICE vehicle, to 138% for H2 FCV. DTI 2005 results show up to 173% MPG gain for the direct H2 FCV. ADL 2010 study shows a 39% MPG gain for conventional diesel ICE vehicles. The "Gap"

Figure 5 – "Vertical" Assessments of ATVs and Baseline Vehicles for these Four Studies

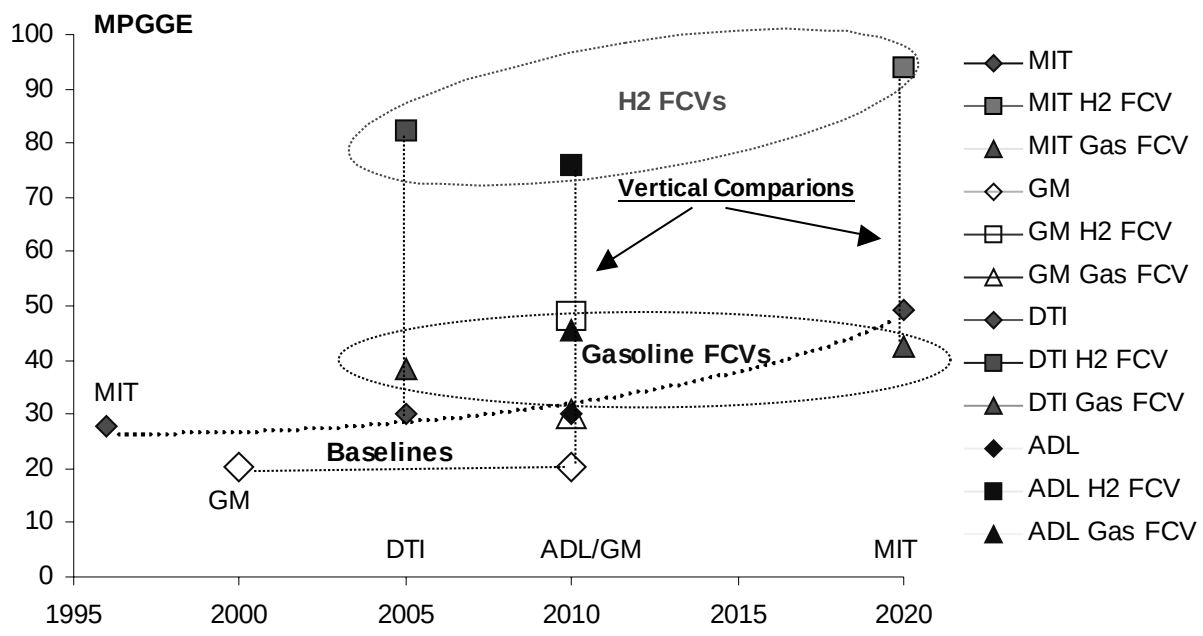


Table 4 – MPGGE and MPGGE Gains Over Baseline Vehicles for the Four Studies

MPG and Gains		MIT 2020		GM 2005-10		DTI 2005		ADL 2010		Gain
Vehicle Type	Fuel Type	MPGGE	Gains	MPGGE	Gains	MPGGE	Gains	MPGGE	Gains	Gap
Current SI-ICE	Gasoline	27.8		20.2		30.1		30.1		
Base evolutionary SI-ICE	Gasoline	43.2								
Advanced SI-ICE	Gasoline	49.1								
CI-ICE	Diesel	56.0	14%	23.8	18%			41.7	39%	25%
Hybrid SI-ICE	Gasoline	70.8	44%	24.4	21%			38.0	26%	23%
Hybrid CI-ICE	Diesel	82.3	68%	29.4	46%	58.0	93%	44.0	46%	47%
Hybrid CNG SI-ICE	CNG	73.4	49%			50.9	69%			20%
Hybrid H2 FC	Hydrogen	94.1	92%	48.1	138%	82.3	173%	76.0	152%	82%
Hybrid gasoline FC	Gasoline	42.3	-14%	30.2	50%	38.4	28%	45.6	51%	65%
Hybrid Methanol FC	Methanol	56.9	16%	34.5	71%	54.6	81%	48.5	61%	65%

Figure 6 – Fuel Economy Gains of Advanced Vehicles over Baseline Vehicles in the Four Studies

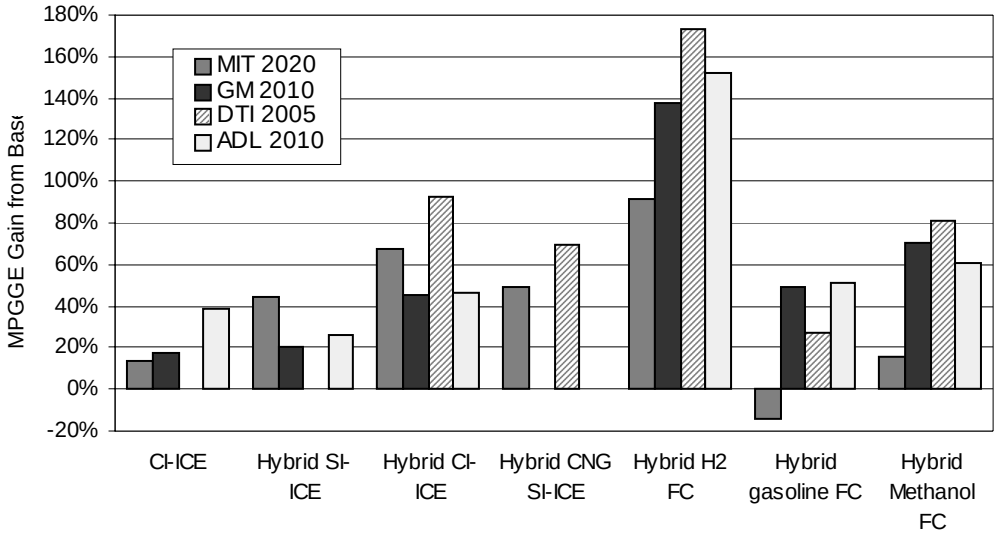
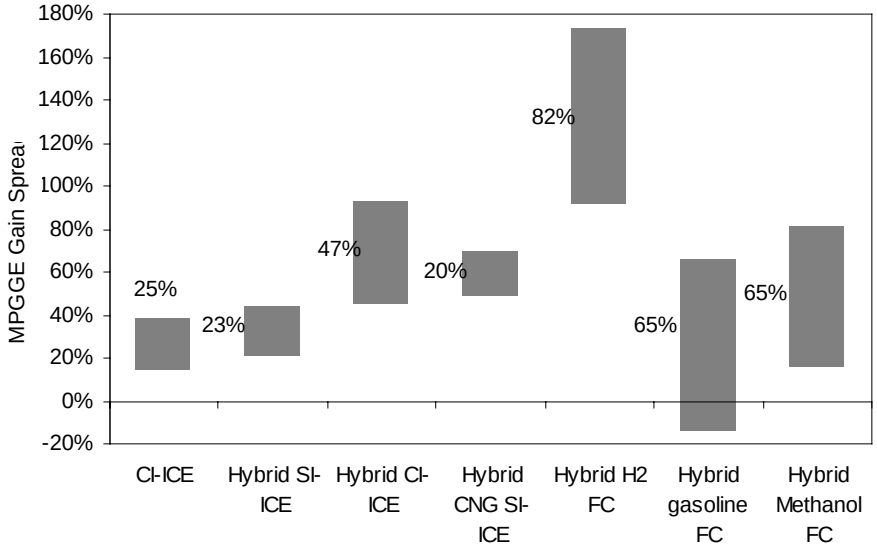


Figure 7 – Fuel Economy Gains and Gaps in the Four Studies



column in Table 4 represents the spread of the results over a different timeframe, or the largest differences of MPG gains among these studies, as shown in Figure 6. These figures clearly show that the gaps in MPG gain vary greatly among these studies, ranging from 23% to 82%. Not too surprisingly, the average gap rises from two-study comparisons to four-study comparisons. Figure 7 also shows that (by the measure printed in the figure), the largest uncertainty gaps among these three studies are associated with FC-based ATVs.

In the next two sections, we look separately at weight and a newly defined powertrain effectiveness measure. Both influence fuel efficiency. After first examining mass alone, we construct a powertrain effectiveness measure that combines effects of TTW efficiency and powertrain mass on fuel consumption required to move the glider and its passengers.

DECOMPOSITION PART A - MASS ANALYSIS

As we discussed earlier, vehicle fuel economy is significantly influenced by vehicle weight. While weight of conventional vehicles is well established, the assumptions associated with future technology vehicle weight are less certain. This uncertainty will spill over into uncertainty in vehicle fuel economy. In the following analysis, we will compare weight assumptions associated with these four studies.

Vehicle weight of each ATV is presented explicitly by the MIT, DTI, and ADL studies. GM did not present vehicle weight in its study. However, since the baseline vehicle is an MY 2000 Silverado pickup truck, and given information for both city/HWY MPGs, 0-60 time, and vehicle powertrain efficiencies, we are able to select the likely base Silverado model and estimate vehicle weight at each stage of advanced technology development.

Table 5 presents curb weight of baseline and advanced technology vehicles in these studies. Vehicle weight for the GM study is from our own estimates (in *italics*). The reference vehicle weight in each study is in **bold**. Table 5 also presents vehicle weight gains over baseline vehicles (in percentage). Again, these analyses show large differences, as demonstrated by Figures 8 and 9. It also appears that these differences do not show a consistent pattern that can be easily explained by timeframe differences. We can also separate the whole vehicle weight into “glider” and “powertrain” portions, and examine the weight increases of the powertrain portion only. More detailed discussion on this matter can be found in the Appendix. We consider the vehicle weight increment to be mostly from powertrain weight gain, and compare vehicle percentage weight gains as a first-order approximation analysis.

Table 5 shows that the weight-gain gaps among these studies range from 7% to 34%. The GM study estimates considerably higher weight gains associated with ICE-based hybrid vehicles. One of the large gaps is from diesel hybrid vehicles, where the DTI study shows a 5% decrease, MIT shows a 5% increase, and GM shows a 15% increase in mass. Both GM and MIT estimate much higher weight increases for FC-based vehicles. ADL assumes weight decreases for all ATVs with the exception of methanol FCVs. The largest gap is from hybrid gasoline FCVs, with MIT showing 32% mass increase and ADL a -2% increase.

In comparing MIT and GM studies, MIT assumes aggressive powertrain and vehicle weight reduction for ICE hybrid vehicles, while GM’s estimates appear to be based on current technology. However, this appears not to be the case for fuel cell based advanced technology vehicles. The FC vehicle weight impacts are relatively close. Both MIT and GM comparisons indicate 15-17%

Table 5 – Curb Weight of Advanced Vehicles in the Four Studies

	MIT 2020		GM 2005-10		DTI 2005		ADL 2010		Wt.
Technology	Mass curb wt. (kg)	Increase over base	Mass curb wt. (kg)	Increase over base	Mass curb wt.	Increase over base	Mass curb wt.	Increase over base	Gain Gap
Current Reference, SI-ICE	1,322	31.3%	***2,134***		**1,168**		**1,304**		
Base evolutionary SI-ICE	1,108	10.0%							
Advanced SI-ICE	**1,007**								
CI-ICE	1,062	5.5%	*2,135*	0.5%			1,284	-1.5%	7%
Hybrid SI-ICE	1,023	1.6%	*2,430*	13.9%			1,289	-1.2%	15%
Hybrid CI-ICE	1,060	5.3%	*2,454*	15.0%	1,109	-5.1%	1,282	-1.7%	20%
Hybrid CNG SI-ICE	1,039	3.2%			1,083	-7.3%			10%
Hybrid H2 FC	1,179	17.1%	*2,457*	15.2%	1,155	-1.1%	1,219	-6.5%	24%
Hybrid gasoline FC	1,330	32.1%	*2,695*	26.3%	1,339	14.6%	1,284	-1.5%	34%
Hybrid Methanol FC	1,253	24.4%	*2,731*	28.0%	1,277	9.3%	1,314	0.8%	27%

Figure 8 – Mass Gains of Advanced Vehicles over Baseline Vehicles in the Four Studies

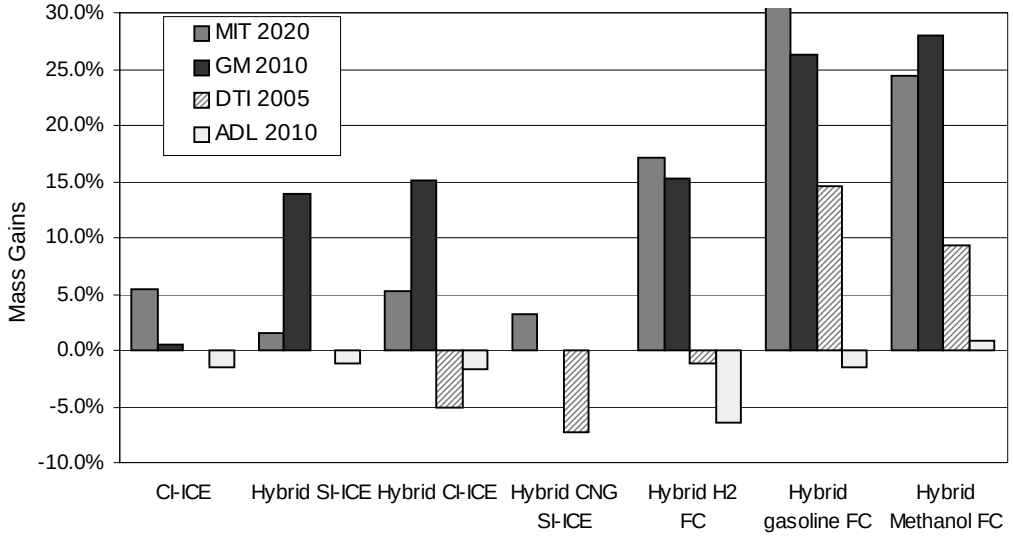
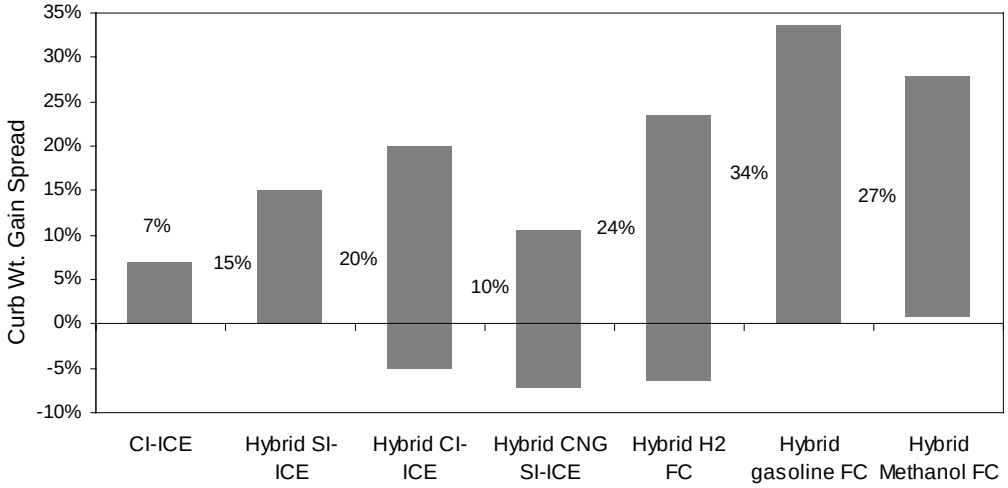


Figure 9 – Advanced Vehicle Weight Gains and Gaps in the Four Studies



weight increase in direct hydrogen fuel cell vehicles. MIT assumes a 32% increase in mass for gasoline FCVs and 24% for methanol FCVs; GM assumes a 26% increase for gasoline FCVs and 28% in methanol FCVs.

Among all these studies, the ADL and DTI analyses demonstrate consistently optimistic estimation of weight impacts for all advanced technology vehicles. This is a result of ADL and DTI's more optimistic assumption for both specific power of powertrains and application of lightweight materials for all advanced vehicles, while it appears that GM assumes current technology-based materials. In other words, much of ADL and DTI's MPG gains are the results of more aggressive mass reduction projections. In the Appendix, we illustrate the important effect of vehicle glider (body/chassis) mass in altering estimated changes in total vehicle mass when specific power of the powertrain is held constant.

DECOMPOSITION PART B – POWERTRAIN EFFECTIVENESS

While MIT and GM provide TTW efficiency estimates, DTI and ADL do not. TTW estimates should themselves be created by use of the specific vehicle simulation model that was used in the study. An external attempt to recover the TTW values with another vehicle simulation model would introduce another potential source of error in the estimate of what study authors intended. In order to compare the estimates of powertrain effectiveness across all four studies, we would like to have a relatively easy metric to construct that would allow us to circumvent the problem of missing TTW efficiency estimates.

TTW efficiency itself does not tell the entire story, since mass does matter, though some simple calculations

imply that this is a secondary effect. For the most efficient conventional vs. FCV comparisons – the hybrid diesel vs. the hydrogen-fueled hybrid FCV – the MIT estimate of TTW efficiency gain shown in Table 2 is 16.5% (36% vs. 30.9%), and for GM it is 68% (41.4% vs. 24.6%). The gasoline equivalent fuel economy gains indicated in Table 4 are less, at 14.3% (94.1 vs. 82.3 mpgge) for MIT and 64% (48.1 vs. 29.4 mpgge), due to the fact that the hydrogen-fueled hybrid FCV powertrain is heavier than the diesel hybrid powertrain. So, although TTW is a good measure, and probably will capture most of the cause for difference in fuel economy gain, it does have the flaw that it does not completely address the net effects of both TTW efficiency and powertrain mass.

After deliberation, we suggest and compile a candidate standard measure of powertrain fuel consumption improvement effectiveness. First, although we elsewhere in this paper present fuel economy numbers that are consistent with the studies examined, we have recently argued that evaluations of advanced technology should be based on comparisons of fuel consumption, not fuel economy (10). Thus, the measure we suggest is based on fuel consumption (liters per km) rather than fuel economy (km per liter). We also convert here to metric units, though the papers cited consistently presented results in terms of miles per gallon of gasoline equivalent.

We ask the rhetorical question, what are the respective purposes of a vehicle and its powertrain? Think of the horse and buggy. The buggy is the object designed to carry passengers, and its motive power may be readily switched, and is clearly a separate part. In a modern automobile, the flexibility to switch motive power is far more limited. Nevertheless for the problem at hand, it is actually the glider (like the buggy) that is the object to be moved. Effectiveness of alternative powertrains in moving the glider and its passengers is the topic of interest. Ignoring economic issues here, we compare these technologies only on the basis of units of energy required to move a glider and passengers after a given powertrain has been incorporated into it. Since the question at hand is whether powertrain switches in a base glider should be made, we use the mass of the base (reference vehicle) glider and passenger load as the denominator in estimating energy use (liters of gasoline equivalent) per kg to estimate powertrain effectiveness. This corrects for the fact that TTW efficiency gives “credit” for moving the mass in a heavier powertrain, when no such credit is logically justifiable. This removes the vast majority of effects of different sizes of vehicle on the comparisons of powertrain effectiveness across studies.

Appendix A illustrates how much difference glider mass can make when constructing MPG change comparisons that do not standardize for glider characteristics.

The measure we present is “liters of gasoline equivalent consumed per 1000km of travel per 1000kg of glider plus passenger load.” This metric provides two-digit values shown in Table 6. Glider mass used in the cases in Table 6 are as follows: MIT Current reference = 930 kg; MIT evolutionary 2020 = 845 kg; all other MIT 2020 = 756 kg; GM = 1451 kg; DTI = 852 kg; ADL = 900 kg. The GM glider mass is an educated guess. Glider mass share for the MIT 1996 reference passenger car was 29%. For DTI, the current reference car glider mass share was 27%, and for the ADL case, it was 31%. We assumed that the mass of the body of a pickup relative to its powertrain is less than that for a passenger car, and assumed 32% for the GM case.

Note that there is contradictory information in the DTI studies. Table 1 of Ref. 5 indicates glider mass is 852 kg. However, Table 4 of Ref. 4 indicates that the gliders of the Hybrid CI-ICE and Hybrid CNG SI-ICE are 694 and 723 kg respectively, with the same total vehicle mass as that we show in Table 5. However, according to our system of comparison, it is the mass of the base case glider that is to be used for the powertrain effectiveness measure. If the powertrain is heavier and causes modification of the glider that adds weight, this is a penalty assigned to the powertrain. Similarly, if the powertrain is lighter, allowing the glider mass to be less, then this provides a fuel saving properly credited to the lighter powertrain. Nevertheless, this degree of difference in reported glider mass calls into question the assumption that the same glider has been used in the DTI cases. MIT did have changes in glider mass consistent with the direction of change of powertrain mass, but these changes were *far* less relative to the base vehicle than reported by DTI.

Please note that since the powertrain effectiveness measure does rely on the underlying vehicle glider mass, the rule of selecting baseline vehicles still applies. The powertrain effectiveness measure has corrected for several comparison problems. These are: (1) the huge mass difference in the GM pickup truck and the remaining passenger cars; (2) the tendency of MPG values to “explode” for relatively small changes in actual fuel consumption; (3) the fact that the common glider in the MIT study was a 2020 glider, much lighter than the 1996 reference car characterized.

According to the estimated powertrain effectiveness measure, the net powertrain effectiveness of baseline vehicles for the 1996-2010 time frame are very similar to one another (ranging from 73 to 79 in Table 6), with the exception of the MIT 2020 baseline advanced SI-ICE (54 in Table 6). All studies are very similar in hydrogen H2 FCVs and methanol FCVs as well. Significant differences exist for diesel ICEs, hybrid ICE vehicles, and gasoline reformer FC vehicles among these studies. In the 2005-2010 timeframe, DTI is considerably more optimistic about the Hybrid CI-ICE powertrain than GM and ADL, and considerably more pessimistic about the hybrid gasoline FCV. To the extent that the hybrid ICE results of DTI are representative of optimism for relatively conventional powertrains, this optimism appears to be reflected in the MIT study as well, only to a greater

Table 6 - Liters of gasoline equivalent per 1000km per 1000kg of glider plus passenger load for four studies

	MIT 2020		GM 2005-10		DTI 2005		ADL 2010		L/kg Range
Technology	Liters/glider kg measure	Drop vs. current ref.	Liters/glider kg measure	Drop vs. current ref.	Liters/glider kg measure	Drop vs. current ref.	Liters/glider kg measure	Drop vs. current ref.	divided by Mean
Current Ref., SI-ICE	79		***73***		79		75		8%
Evolutionary SI-ICE	55								
Advanced SI-ICE	54								
CI-ICE	***47***	-13%	62	-15%			54	-28%	28%
Hybrid SI-ICE	***37***	-31%	61	-17%			60	-21%	45%
Hybrid CI-ICE	***32***	-41%	50	-31%	41	-48%	52	-32%	45%
Hybrid CNG SI-ICE	***36***	-33%			47	-41%			26%
Hybrid H2 FC	***28***	-48%	31	-58%	29	-63%	30	-60%	9%
Hybrid gasoline FC	62	15%	***49***	-33%	62	-22%	50	-34%	24%
Hybrid Methanol FC	46	-15%	***43***	-41%	44	-45%	47	-38%	9%

degree in the 2010 timeframe. The DTI studies were completed before the MIT studies (two 1998 DTI publications are cited by MIT) and both were completed before the GM and ADL studies. The DTI pessimism about the hybrid gasoline FCV is also reflected in the MIT results.

Generally, with the exception of gasoline and methanol FCVs, MIT characterizations of 2020 powertrain effectiveness indicate lower inherent fuel consumption than for the same technologies in the 2005-2010 time frame from the other three studies. The gasoline and methanol FCVs are exceptions. However, careful inspection reveals a pattern of greater incremental optimism for the variants of conventional drivetrains than for FCVs as a class of powertrains.

Thus, relative to the three studies characterizing 2005-2010 technology, MIT results imply greater gains from 2010 to 2020 for conventional drivetrain technology than for FCVs. In effect, MIT results imply that powertrain technology that has been in the market for over a century (ICEs and electric drive – though admittedly, electric drive has been in, out, and back in) will continue to improve from 2010-2020, while FCVs will not. However, another paper presented in this meeting suggests that there is potential for hydrogen FCVs to be even more efficient than characterized in these four studies (20).

Surprisingly, among the four studies, there is apparently considerable agreement based on this powertrain effectiveness measure. It should be stressed that this agreement masks considerable underlying differences. Study of Table 5 vs. Table 6 illustrates that some of the similarities are likely the result of differences in estimates of changes in powertrain mass and TTW efficiency that offset one another. For general purposes, it is comforting to see a degree of similarity in estimates of what advanced powertrains can achieve. However, if opinions differ considerably concerning the degree to which it is TTW gain or achievement of good specific power that contributes most to the powertrain's improved effectiveness, then the efficient allocation of research dollars will be more difficult. Thus, we stress that those who prepare such studies in the future should present estimates of powertrain mass, kw, and TTW efficiency for each glider/powertrain pair. MIT's study is the model for documentation of assumptions and estimates.

While it is beyond the scope of this paper to delve into many of the more important details in these studies, we note that details can alter results considerably. Degree of hybridization is one example where differences can result (10, 11, 13, 17). For example, using numbers for the 10-second 0-60 time cases from Ref. 17, we compute powertrain effectiveness values of 43 for a "full" SI-ICE hybrid, and 47 for a "mild" hybrid (Table 7). The full hybrid provided 48% of peak power with a motor, while the mild hybrid provided 25%. The MIT case in Table 6 provides 33%, while the ADL cases that we cite in this study are for their "small battery" case, for which 9% of power is provided by a motor in the hybrid SI-ICE. GM's degree of hybridization is unknown, but we speculate that it would be between 9% and 25%. As discussed in Ref. 13, in the GM case, the hybridization also provides faster acceleration, a choice that works against fuel efficiency. So, while it warrants a separate study in itself, the degree of and approach toward hybridization can result in a wide range of fuel efficiency changes when a vehicle is hybridized. Some of the ADL and GM vs. MIT differences for hybrid ICEs are undoubtedly explainable by differences in degree of hybridization and performance requirements/changes.

Among the references cited, the only one to conduct sensitivity analysis with respect to effects of performance requirements was Plotkin et al [17]. This study only examined SI-ICE HEVs. Like ADL and DTI, this study failed to include TTW efficiency. However, taking advantage of the powertrain effectiveness measure, Table 7 illustrates that study's indication that acceleration performance requirements make a large difference in the effectiveness measure, especially for conventional vehicles. It can be seen that the performance effectiveness measure for a conventional vehicle from

Table 7 - L/1000km/1000kg-glider/pass [17]

0-98 km/h >	12 sec.	10 sec.	8 sec.
Conventional	57	65	79
Mild HEV	46	47	51
Full HEV	42	43	46

that study is consistent with the estimates in Table 6, since the acceleration capabilities of the conventional vehicles are in the 8-9 second range for 0-98 km/h (0-60 mph) time. Table 6 also illustrates how comparison of conventional vehicles with 8-9 second 0-98 km/h capability to those with 10-12 second capability can exaggerate estimated fuel consumption reduction estimates.

Another probable cause of differences in ICE results among the studies is the assumption of direct injection technology by MIT for the ICE engines. GM and ADL do not specify the ICE technology used, nor the peak efficiency of the ICE engines simulated. If they do use less inherently efficient ICE technology, then this contributes to some of the variation in powertrain effectiveness shown in Table 6.

Considering differences in hybridization approach, engine technology assumptions, and time frame, a good bit of the differences between the MIT study's projections of the potential for advanced ICE powertrains and those of the other three studies could be explained. However, the information given in the studies is not enough to readily develop an estimate of how much.

The large hybrid gasoline FCV differences also require explanation and evaluation. We hope to contribute to an explanation in a separate future paper.

CONCLUSIONS

This paper presented a comparative assessment of ATV energy consumption improvement potential from the "most probable" cases of four recent major studies carried out by MIT, GM, DTI, and ADL. Detailed analysis reveals that some of the "most probable case" estimates from these studies differ greatly on the implied MPGGE benefits of advanced technology vehicles at the tank-to-wheel level, leading to a superficial appearance of considerable uncertainties in estimating well-to-wheel greenhouse gas (GHG) emission reduction potentials.

Specifically, this paper compared these analyses on the basis of previously compiled fuel economy (MPGGE), mass and/or tank-to-wheel efficiency measures. Finally, we developed and discussed a suggested measure of powertrain efficiency that is meaningful across studies with widely varying light duty vehicle types. While the MPGGE and mass analyses provide results commonly used, the superior (a) TTW efficiency and (b) liters of fuel consumed to move glider and passengers measures provide most of the intrinsic insight regarding the differences of powertrain effectiveness estimated among these studies.

This investigation indicated that while the degree of uncertainty across studies is considerable, it is not as great as a summary investigation and comparison implies. Our investigation suggests that there are logical and systematic reasons for variations among the studies. We note where more thorough documentation of results and input assumptions could help us to explain even more of the differences. Among the four studies discussed in detail here, the Weiss et al (MIT) group of analysts provided the most technical information and implicitly set up the best overall set of comparison rules. We have tried to build on that transparency. In addition to our assertion that differences can be understood with better documentation, we have also evaluated the methods used in the studies we have examined, and have suggested rules and tools for comparison that we hope could contribute to improvements in future studies.

ACKNOWLEDGMENTS

We gratefully acknowledge the support of Drs. Robert S. Kirk, Steven G. Chalk, Patrick Davis, and Peter R. Devlin of the Department of Energy Office of Energy Efficiency and Renewable Energy in supporting this and other cited efforts to evaluate studies comparing advanced technology vehicles. We also gratefully acknowledge the support of Dr. Larry Johnson, Director of the Argonne National Laboratory Transportation Technology Research and Development Center. We would like to thank John DeCicco and John German for comments provided. Errors are, of course, the responsibility of the authors, not the supporting institutions or reviewers. The manuscript was authored by a contractor of the U.S. Government under contract no. W-31-109-ENG-38. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

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APPENDIX - ISSUES OF TECHNOLOGY TIMELINE AND SCENARIOS

In the section on Methodological Issues, we mentioned that ATV comparisons should use the same baseline glider (related to Issues 1 and 9) and be based on the same timeline (Issue 6) and technology scenarios (Issue 5). We have also discussed the differences between "vertical" and "diagonal" assessment (Figure 1). This section addresses for the first time in our own work how the effort to standardize the technology baseline, timeline, and scenario can affect the outcome.

We note that this effort is hardly the only way, as noted in our ten points made earlier. Another dramatic effect involves performance equivalence assumptions (Issue 2), particularly for the power of the powertrain chosen for each ATV in a set of comparisons. How this can affect results is illustrated in Santini, Vyas, Kumar and Anderson (12).

On the performance-equivalence issue, within these four studies, the DTI and ADL studies appear to deviate considerably from the GM and MIT studies. For ATVs, DTI and ADL allow much lower peak power per unit of vehicle mass than in the reference vehicle. The MIT study holds this constant. While the DTI study does not provide any explanation of the performance capabilities of the vehicles, ADL concludes from examination of prior examples that 11.5 seconds or less is acceptable 0-60 performance for ATVs, but compares such vehicles to a base conventional vehicle capable of considerably faster acceleration (≈ 0.076 kW/kg for base vehicle – about 9-10 seconds capability – see Ref. 17). The potential for use of unequal 0-60 time capability to significantly affect results for compared pairs is shown in Ref. 12, although the question of the "right" performance metric is not.

We note that the MIT and GM studies adopted constraints related to acceleration performance that should result in reasonably good comparability, so re-estimation to account for that effect should not significantly alter the readjusted MIT vs. GM results we present here. Nevertheless, the reader should keep in mind that many of the papers cited discuss different attempts to develop standard comparisons. A comprehensive analysis according to the ten points presented here (a challenge) has not yet been developed.

Previous MIT advanced vehicle technology analyses are based on the 2020 advanced SI-ICE because it shares the same vehicle glider with sequential ATVs. Now we would like to ask the following question: How can we assess MIT's ATV projection over current baseline vehicles (diagonal assessment)? What would happen if MIT's ATVs were based on a current baseline vehicle glider, as in the GM study? How would this change the outcome? Here we would like to conduct a hypothetical experiment to answer these questions.

There are two fundamental reasons for choosing the MIT case in this Appendix: 1) MIT provides most complete data for detailed analysis; and 2) by establishing three baseline scenarios as current SI-ICE, 2020 evolving ICE, and 2020 advanced ICE, the MIT study provides a platform to conduct this "what if" analysis.

First, Table A1 presents the mass breakdown on all MIT vehicles. The glider mass includes predominantly vehicle chassis and body weight; propulsion system includes predominantly the engine (ICE or FC) and transmission systems; fuel mass is 2/3 of full tank. Load is a standard 136 kg two passenger weight (300 lb.) and is the difference between test weight and curb weight. Table A1 also lists rated power of the IC/FC engine, battery weight and rated power, total rated power of the vehicle. The last column lists power to weight ratio, which MIT held constant to maintain hypothetical "performance equivalence" throughout all ATVs. We note that vehicle simulation results in references 9 and 17 imply that a vehicle with a motor rather than ICE engine as a source of power can achieve the same 0-60 time with approximately 10% lower peak kw/kg requirements. However, the DTI and ADL studies far exceed this decline in kw/kg in their comparisons.

In MIT's assumptions, the glider mass decreases from the current SI-ICE to 2020 base ICE, and further to advanced SI-ICE. However, glider mass remains roughly the same afterwards. The small differences in different ATVs' glider mass are adjustments to support different weights of the propulsion system. Figure A1 shows the 1996-2020 evolution of the conventional powertrain specific power (defined as rated peak power/weight in kW/kg), and the specific power estimates associated with different 2020 ATV powertrain technologies. The higher number, the better. It shows that, with the exception of the big jump in specific power from current base ICE to 2020 evolving ICE, the hybrid and fuel cell based propulsion systems have diminished specific power rates relative to conventional ICE powertrains, thus increasing powertrain mass in the hybrids and FCVs. However, in comparison with the current SI-ICE (Table A1), all the ATVs have much smaller glider mass (using much lighter materials), so the total vehicle test weights of ATVs are lighter than the current SI-ICE, with the exception of the gasoline FCV.

In the following analysis, we assume all advanced ATVs use the same glider as MIT's 1996 SI-ICE with glider mass of 930 kg, as shown in Table A2. In the process, we increase mass of all other components accordingly, as well as rated power to keep the power-to-weight ratio of both the vehicle and propulsion system unchanged. It then becomes possible to project the impacts of ATVs as if they were installed in MIT's current SI-ICE (as GM did).

Table A1 – MIT Vehicle Mass Breakdown (based on Table 3.4 of Reference 1)

	Mass (kg)						Rated Power			
	Glider*	Propulsion System	Battery	Fuel	Load	Total Test Wt.	IC/FC Engine (kW)	Battery (kW)	Total kW	kW/kg
Current SI-ICE	930	340	12	27	136	1445	110		110	0.076
2020 Base SI-ICE	845	226	12	16	136	1235	93		93	0.075
Advanced SI-ICE	756	217	12	15	136	1136	85		85	0.075
Advanced CI-ICE	759	271	12	13	136	1191	89		89	0.075
Advanced SI-HEV	756	216	36	11	136	1155	58	29	87	0.075
Advanced CI-HEV	759	251	37	9	136	1192	60	30	89	0.075
Advanced H2 FCV	763	371	41	2.7	136	1314	66	33	99	0.075
Adv. gasoline FCV	794	465	46	17	136	1457	73	36	109	0.075
Adv. methanol FCV	778	390	43	28	136	1375	69	34	103	0.075

Figure A1 – Specific Power of Propulsion System in MIT Analysis

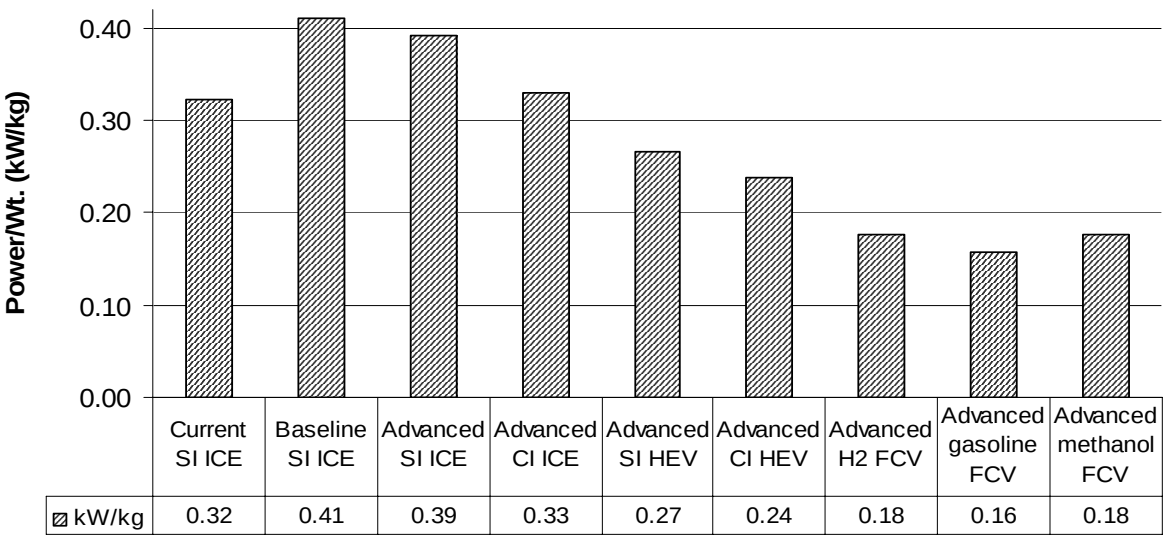

Table A2 – Hypothetical MIT Vehicle Masses based on Current SI-ICE Vehicle Glider

Hypothesis	Mass (kg)						Rated Power			
	Glider*	Propulsion System	Battery	Fuel	Load	Total	IC/FC Engine (kW)	Battery (kW)	Total kW	kW/kg
Advanced SI-ICE	930	259	14	18	136	1357	102		102	0.075
Advanced CI-ICE	930	322	14	17	136	1419	106		106	0.075
Gasoline SI-HEV	930	258	43	13	136	1380	69	34	103	0.075
Diesel CI-HEV	930	298	44	11	136	1420	71	35	106	0.075
H2 FCV	930	439	48	3.3	136	1556	78	39	116	0.075
Gasoline FCV	930	528	52	20	136	1666	83	41	124	0.075
Mmethanol FCV	930	452	50	33	136	1602	80	40	120	0.075

This allows us a fairer comparison of the degree of relative optimism/pessimism for ATV powertrains in the two studies, as if those powertrains had been installed in contemporary vehicle gliders in both cases. The implications do change.

Table A3 shows the adjusted weight gain comparisons among MIT-current (based on the hypothetical case of Table A2), MIT 2020 (based on the original mass distribution of Table A1), and the GM case. It shows that compared to MIT-2020, the MIT-current case dramatically reduced percentage weight gains for all ATVs. This implies that, based on this adjusted technology scenario, MIT's assessment of mass impacts for all ATVs is greatly reduced, as clearly demonstrated by Figure A2, which shows that the ATV weight-gain gaps between the MIT and GM cases significantly increase. This is a logical reflection of MIT's assumption that its powertrain technology is based on the year 2020, which appears to be much more optimistic in comparison to GM's assumption.

The reduction in percent weight gains translates into increases in fuel economy gains, as shown in column 1 of Table A4. Here we use the approximation that the tank-to-wheel efficiencies of Table 4 will be unchanged by glider and powertrain masses. Thus the reductions in weight gain translate into decreases of percent gain of workload of the vehicles, resulting in increased percent gains in the revised MIT-current fuel economy gains for all ATVs. Under this assumption, Table A4 lists the adjusted MPG estimates for the MIT current cases, and compares the adjusted fuel economy gains among the MIT current case, MIT 2020 case, and GM case. The MIT current case shows significant jumps in MPGGE for all ATVs, as further demonstrated by Figure A3.

Table A3 – Comparisons of Original and Revised Curb Weight Gains of MIT-current, MIT-2020, and GM ATVs

Curb_Weight Gains	MIT current	MIT 2020	GM	MIT_current less GM
Advanced SI-ICE	-7.6%	0.0%		-8%
Advanced CI-ICE	-3.0%	5.5%	1%	-3%
Gasoline SI-HEV	-5.9%	1.6%	15%	-21%
Diesel CI-HEV	-2.9%	5.3%	17%	-19%
H2 FCV	7.4%	17.1%	17%	-9%
Gasoline FCV	15.7%	32.1%	29%	-13%
Methanol FCV	10.9%	24.4%	31%	-20%

There are two striking trends shown in Figure A3: while the gaps between MIT and GM cases have increased significantly for ICE-based ATVs, the gaps for gasoline and methanol based FCVs have narrowed significantly. The gap for the H2 FCV is about the same, but with the revised MIT result over-predicting, instead of under-predicting, the GM result.

Table A4 – Comparisons of Fuel Economy Gains of "Current Baseline" based ATVs and "2020 Baseline" based ATVs

MPGGE Gains	Adjusted MPG	MIT_ current	MIT_ 2020	GM	MIT_current less GM
Advanced1 SI-ICE	41.4	49%	0.0%		19%
Advanced CI-ICE	47.3	70%	14%	18%	18%
Gasoline SI-HEV	59.5	114%	44%	21%	51%
Diesel CI-HEV	69.3	150%	68%	46%	54%
H2 FCV	79.5	186%	92%	138%	-9%
Gasoline FCV	37.2	34%	-14%	50%	-42%
Methanol FCV	49.4	78%	16%	71%	-29%

Table A4 shows that advanced SI-HEV gains of 114% in MPG over the current SI-ICE baseline vehicles, and advanced CI-HEV gains of about 150% in MPG. Among these gains, the SI-ICE technology itself gains 49% in MPG over the current SI-ICE baseline vehicles, and hybridization itself gains another 44%. For diesel vehicles, advanced CI engine technology gains about 70% in MPG and hybridization gains another 47%. For the GM cases, the gasoline HEV gains 21% in MPG over its baseline ICE vehicle, while the diesel hybrid gains 46% over the baseline, with only 18% gain from diesel engine technology alone. These numbers have two implications: 1) MIT projects very significant potentials for further improvement in gasoline and diesel engine technologies; and 2) MIT also projects higher potential for hybridization than GM does.

In all MIT HEV and FCV cases, the battery power is 33% of peak power, which qualifies as full hybrids similar to Toyota Prius. The 40% plus MPG gain associated with full hybridization is consistent with our previous analysis on the Prius and other full hybrids [18]. Based on GM's estimate of 21% gain associated with hybridization, our prior research [16] implies that if GM is considering a so-called "mild" hybrid, with battery power fraction below 15%, then the estimates of percent gains via hybridization by MIT and GM are perfectly reasonable. So it is fair to say that the MIT result represents an upper bound potential of current hybrid technology, while GM assumes a less aggressive degree of hybridization. This demonstrates the importance of technology scenarios.

Since the MIT and GM hybridization percentage gains appear consistent with the few contemporary hybrids that exist, it appears that MIT is not overly optimistic about improvement in hybrid technology in the next 20 years. Clearly, MIT's very large gains for conventional powertrains imply an opinion that much improvement can be squeezed out of further refinement of today's dominant technology. For the FCV cases, the narrowed gaps are perhaps deceptive, because the narrowed MPG gaps are largely associated with widening weight gaps. In other words, MIT's optimistic assumption associated with mass of FC powertrains results in

narrowed net MPGGE gain gaps vs. GM. The more intrinsic comparisons rely on tank-to-wheel efficiency comparisons as described in the text. Nevertheless, these comparisons demonstrate the importance of baseline, timeline, and scenarios of technological analysis.

Having made adjustments to make the MIT and GM studies more comparable, it appears that the largest difference between the MIT and GM studies is in the estimate of the net potential for improvement and refinement of the conventional powertrain over the next 20 years. In this regard, the GM study provides no competing estimate to the MIT study. In effect, GM did not provide an opinion concerning how great an improvement can be made over 20 years in the conventional powertrain. Notably, both studies imply great potential for the H2 FCV. Given the research that we have conducted on contemporary hybrids and simulated hybrids with contemporary component and engine efficiencies, these two studies also imply that hybrid technology has already reached a plateau.

Figure A2 – Comparisons of Curb Weight Gains of "Current Baseline" based ATVs and "2020 Baseline" based ATVs

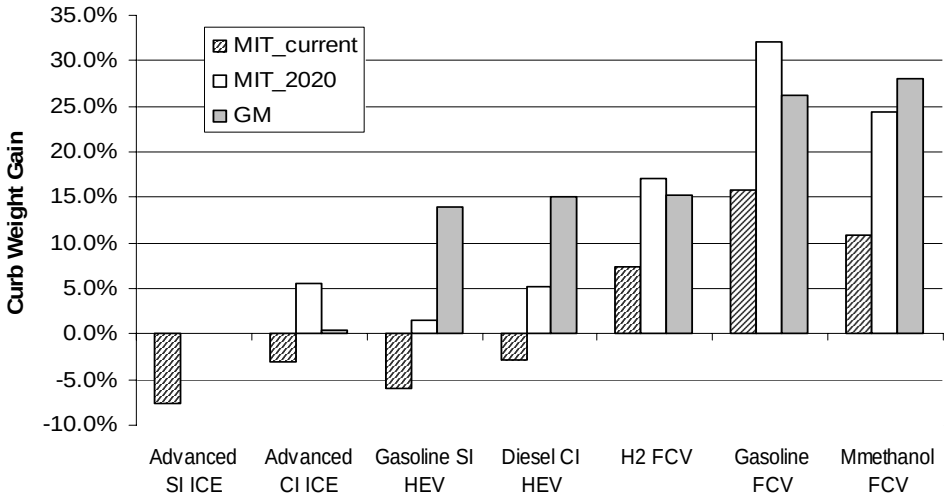
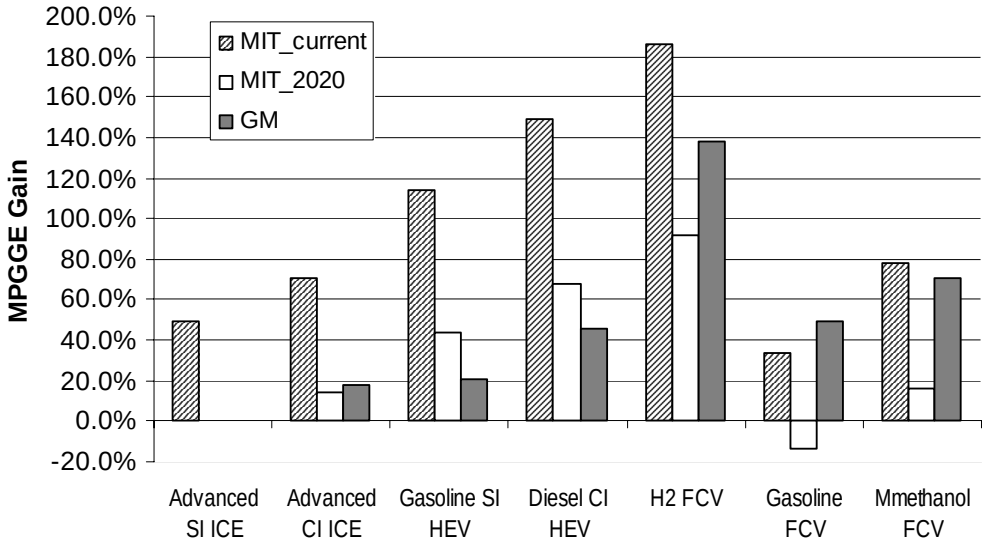
Figure A3 – Comparisons of Fuel Economy Gains of "Current Baseline" based ATVs and "2020 Baseline" based ATVs