Assessing and Modeling Direct Hydrogen and Gasoline Reforming Fuel Cell Vehicles and Their Cold Start Performance (Submitted to FTT Review)

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ABSTRACT

This paper analyzes fuel economy benefits of direct hydrogen and gasoline reformer based fuel cell vehicles. Comparing several existing influential studies reveals that the most probable estimates from these studies differ greatly on the implied benefits of both types of fuel cell vehicles at the tank-to-wheel level (vehicle-powertrain efficiency and/or specific power), leading to great uncertainties in estimating well-to-wheel fuel energy and/or greenhouse gas (GHG) emission reduction potentials. With one exception, we find that these studies consistently ignore cold start and warm-up issues. This paper focuses on cold start and warm-up issues associated with assessing benefits of advanced technology vehicles. To explore the potential for a better understanding of cold start and warm-up behavior, this paper examines results based on two available U.S. Department of Energy and USCAR funded National Laboratory vehicle simulation models – PSAT and ADVISOR. In particular, this paper examines cold-start modeling of fuel cell vehicles. Cold starts play important roles in determining both energy penalties and start-up time of fuel cell vehicles. Our analysis reveals that the predicted cold-start effects are not only influenced by different modeling approaches, but also assumed choices concerning trade-offs between rapid warm-up vs. efficient conversion of energy during cold-starts, and time to achievement of full power capability. It appears that alternative cold start warm-up strategies and powertrain configurations could result in a wide range of (1) vehicle performance capabilities as a function of time from start-up and (2) associated cold start net energy penalties.

INTRODUCTION

An increasing number of comprehensive comparative assessments of energy use and greenhouse gas emissions (GGE) of conventional vehicles (CVs) relative to advanced technology vehicles (ATVs) have been published over the last few years. These studies have created estimates of the potential energy and GHG benefits (or costs) of substituting advanced technology vehicles for either contemporary or advanced CVs. Unfortunately for users of this information, the studies have created considerably different estimates of relative benefits of various advanced technology vehicles. 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 the fifth of a series of papers that focus 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 [1-4].

In this paper, we preliminarily examine cold start issues for conventional vehicles and two types of fuel cell vehicles (FCVs) – gasoline fuel cell vehicles (GFCV) and hydrogen fuel cell vehicles (H2FCVs). We examine results from the following four studies (cited by institutional or corporate affiliation of the authors) [5-8]:

> 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.
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> 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.

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

This paper is basically divided into two parts: 1) to compare the results of the above four studies; and 2) use two U.S. DOE/USCAR sponsored vehicle simulation models to develop insights concerning impacts and trade-offs between cold start energy and warm-up time, using MIT vehicles as examples. The vehicle simulation models used are the Partnership for a New Generation of Vehicles (PNGV) Systems Analysis Toolkit (PSAT) developed by Southwest Research Institute (SRI) and Argonne National Laboratory (ANL) [9], and the Advanced Vehicle Simulator (ADVISOR) developed by the National Renewable Energy Laboratory (NREL) [10].

Before conducting detailed analysis, we first present some important issues associated with assessing benefits of advanced technology vehicles.

KEY ISSUES IDENTIFIED

This section provides a background on results of different studies assessing advanced technology vehicles, as well as issues identified to influence the outcome of the analysis. We focus on relative benefits of hydrogen and gasoline fuel cell vehicles vs. conventional vehicles. We discuss Well-to-Wheel (WTW, or life-cycle) vs. Tank-to-Wheel (TTW, or vehicle level) energy use. However, our focus is on vehicle level analysis. We discuss the real world implications of driving cycle and cold start. During warm-up, we consider available power vs. time after cold start. For the gasoline FCV, we add the reformer power effect to the fuel cell power effect. We also discuss the question of establishment of a proper conventional baseline vehicle for comparison to the FCV. Other general methodological issues are also considered.

WELL-TO-WHEEL (WTW, OR LIFE-CYCLE) VS. TANK-TO-WHEEL (TTW, OR VEHICLE LEVEL) ANALYSIS

Even though 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. The WTW sequence includes both well-to-tank (WTT, or upstream) and tank-to-wheel (TTW or vehicle) steps. Among the four studies being considered here, all include vehicle operation, or TTW process, and all but the DTI study include the upstream, WTT step as well. MIT's analysis is the only one to include energy consumption associated with manufacturing vehicles.

Table 1 presents the energy split between WTT and TTW steps for three types of vehicles analyzed in the MIT and GM studies. These three vehicles are baseline spark-ignition (SI) internal-combustion-engine (ICE) gasoline conventional vehicles (CV), hybrid hydrogen (H2) FCVs, and hybrid gasoline reformer FCVs. The table shows that for the gasoline fuel-based vehicles, vehicle operation, or TTW energy use dominates the overall energy use with a 74-83% share. For the hydrogen-based vehicles, the energy split between WTT and TTW is roughly evenly split, so WTT energy use plays a considerably larger role in the H2 FCV totals.

Table 1 – Energy Splits between Well-to-Tank (WTT) and Tank-to-Wheel (TTW) Steps in MIT and GM Studies

Energy Use Share	MIT		GM	
Technology	WTT	TTW	WTT	TTW
Baseline, Gasoline SI-ICE	17%	83%	23%	77%
Gasoline Hybrid FCV	18%	82%	26%	74%
Hydrogen Hybrid FCV[1]	43%	57%	61%	39%

While it's convenient to divide the WTW process into Well-to-Tank (WTT) and Tank-to-Wheel (TTW) processes, one needs to remember that WTT energy use and emissions depend considerably on TTW energy consumption. Thus the split in contribution between WTT and TTW processes is deceptive in many cases, since up-stream emissions and energy use are driven by down-stream (or vehicle level) energy demand and efficiencies. Generally, as the TTW efficiency goes up, the TTW share of WTW energy use goes down, and vise versa. In this sense, the uncertainties and disagreements from the assessment of TTW, or net vehicle powertrain efficiencies, are directly carried over to WTW results.

Though we do not discuss this point again in the paper, it is worth noting that a given level of percentage uncertainty in H2FCV fuel economy is more problematic than for gasoline FCVs, because the WTT share of energy use for H2FCVs is around 50%. As the TTW share of WTW energy approaches 50%, from either direction, a given percentage error in the TTW energy use estimate increases the total WTW error by a greater amount.

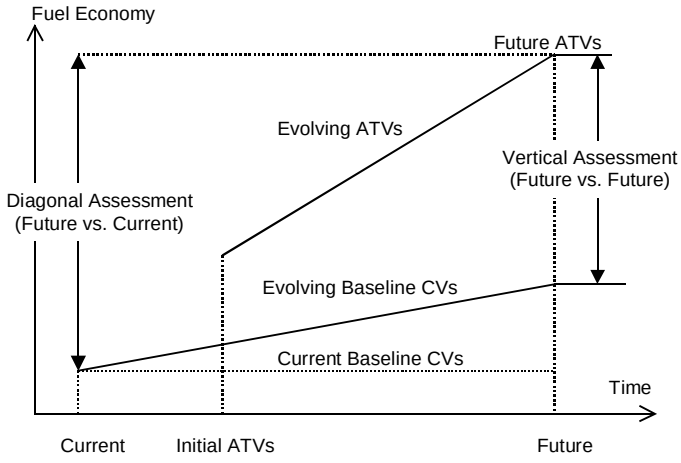
[1] H2 production based on decentralized NG station. The numbers in the table imply 40/60 and 60/40 split for the MIT and GM studies respectively, a big difference! A detailed discussion in this regard is beyond the scope of this paper.

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

As being discussed in the companion paper [1], 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]. ADL analysis has assumed a timeframe of 2010 as well. Among all studies analyzed, 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.

The above situation 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 the 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.

Figure 1 – Vertical vs. Diagonal Assessment



While the diagonal comparisons are often used in assessing future potentials of the same types of vehicle technologies, we'd like to argue 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.

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.

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.

DRIVING CYCLE, COLD START, AND REAL DRIVING ISSUES

Important areas we believe deserving far better care are the selection of driving cycle, cold start, and real driving issues. We refer here to results for two classes of official U.S. driving and test cycles and the weighted combination of those two. The "combined cycle" is determined according to the formula used in computing vehicle-model-specific fuel economy for Corporate Average Fuel Economy [CAFE] purposes. While official testing for vehicle emissions has become more complex, and now involves more than two driving cycles, U.S. testing for fuel economy (and energy consumption) remains unaltered, relying only on the original two driving cycles developed for the purpose.

When discounted for on-road driving conditions, consumers know these two driving cycles as the "city" and "highway" cycle. The more formal appellation for the city cycle for conventional vehicles is the Federal Test Procedure (FTP). The FTP actually decomposes and reassembles, via weighted averages of component parts, a cycle known as the Federal Urban Driving Schedule (FUDS). The decomposition involves the conducting of two separate tests of the first 505 seconds of the FUDS, with the remainder of the FUDS in between these two tests. The parts of the test are known as "bag1, bag2, and bag3". The 505-second speed vs. time traces of bag1 and bag3 are identical, but bag1 is "cold started", with the engine and vehicle at room temperature. Bag3 is "hot started" ten minutes after bag2 is completed. Bag2 is conducted immediately after bag1, with the engine running

continuously, with the "bags" used to collect the tailpipe emissions changed at the 505 second point. The speed vs. time trace of consecutively run bag1 and bag2 is identical to the FUDS. Fuel economy is measured by converting tailpipe carbon dioxide emissions into equivalent fuel consumption. In this paper we present decomposed bag1 vs. bag3 results in order to estimate the effect of the cold start of bag1 on conventional vehicle fuel consumption, as estimated in the FTP. Equation (1) shows the formula to determine FTP fuel economy (MPG_{FTP}) based on fuel economies of bag1, bag2 and bag3 (MPG_{bag1}, MPG_{bag2} and MPG_{bag3}) [17]:

$$\frac{1}{MPG_{FTP}} = \frac{0.207}{MPG_{bag1}} + \frac{0.518}{MPG_{bag2}} + \frac{0.275}{MPG_{bag3}} \qquad (1)$$

For the advanced technology vehicles, the vehicle simulation models use a test cycle called the SAE test procedure (SAETP). This test procedure has a fourth bag in the test. The speed time trace of SAETP bag4 is identical to FTP bag2. Bag4 is started at the 505-second point in what (combined with bag3) amounts to a second run of the FUDS. It is important to recognize that the SAETP is designed to take into account the effects of change of state-of-charge (SOC) in a hybrid electric vehicle, in such a fashion that the SAETP will provide reliable comparable results to the FTP for a CV. In the SAETP, bag2 and bag4 are weighted to cause the same net effect on fuel economy as bag2 in the FTP. Otherwise, bag1 and bag3 carry the same weight as in the FTP. The reason for the SAETP has to do with the role of batteries (or other energy storage devices) on the complexity of accurate measurement of fuel economy of hybrid vehicles. It is beyond the scope of this paper to provide additional details. However, the reader should be aware that, for the purposes of this paper, the FTP and SAETP are measuring the fuel economy of CVs and advanced hybrid vehicles respectively according to the speed time pattern of the FUDS, so that the FTP and SAETP will provide comparable results for the appropriate vehicle powertrain type.

To reiterate, the FUDS is a speed-time trace. The FTP and SAEFTP describe how "bags" of tailpipe emissions are to be collected while the tested vehicle matches portions of the FUDS, and then how the collected bags are to be analyzed and computationally weighted to develop estimates of fuel economy and emissions. Equation (2) shows the formula to determine SAEFTP fuel economy (MPG_{SAE}) based on fuel economies of bag1, bag2, bag3 and bag4 (MPG_{bag1}, MPG_{bag2}, MPG_{bag3} and MPG_{bag4}) [18]:

$$\frac{1}{MPG_{SAE}} = \frac{0.207}{MPG_{bag1}} + \frac{0.223}{MPG_{bag2}} + \frac{0.275}{MPG_{bag3}} + \frac{0.295}{MPG_{bag4}} \qquad (2)$$

Generally, aside from the FTP, most driving cycle tests are started with the engine or other power unit at operating temperature. The FTP and SAETP are the only tests for which the effect of cold start is measured.

In the "real world", households generally cold start their vehicle early in the day for an intended trip, and often leave their vehicle sitting at the trip destination for long enough that when they restart the vehicle it is also a cold start. Cold start conditions in modern CVs account for the vast majority of tailpipe emissions in the FTP. It is seldom recognized that the cold start also has a negative effect on fuel economy. This paper illustrates the effect for recent CVs, and estimates it for H2FCVs and GFCVs. The "highway" cycle is a higher speed cycle than the FUDS/FTP/SAETP, averaging about 48mph (vs. 21mph). The Highway cycle was originally intended to represent suburban driving in an outlying suburb, using two lane roads, therefore having a maximum speed of 55mph. It is conducted as a hot start test, despite the reality that suburbanites also start their vehicle cold, and generally restart it for a return home cold as well.

The FTP and Highway cycles were designed and used as the basis for measuring fuel economy for CAFÉ ratings and also to provide predictive information for consumers on the fuel economy they should expect from their vehicle. After a few years of publishing FTP and Highway results for consumer information, the U.S. EPA found that consumers were unhappy that their vehicles did not obtain the predicted fuel economy obtained in real driving conditions. Since the FTP and Highway cycles formed the constituent parts of the official combined average fuel economy rating for CAFÉ regulatory purposes, and there was no desire to change these tests, the solution for consumers adopted by EPA was to develop adjustment factors to provide a more realistic estimate of real world "city" and "highway" fuel economy to use for consumer information. The adjustment factors are 0.9 to convert the FTP mpg to consumer "city" mpg, and 0.78 to convert the EPA highway mpg to consumer "highway" mpg. While most interpret the discount factor for the Highway test to be due to lower fuel economy on Interstate highways, it is also true that the absence of a cold start in the Highway test plays a role in bringing the consumers' actual highway driving mpg down from the Highway test value. Note that the fact that the highway discount factor is greater than the city discount factor could in part be due to the absence of inclusion of a cold start in the base Highway test. Equation (3) shows the formula to calculate CAFE from City and Highway fuel economy (MPG_{CITY} and MPG_{HWY}):

$$\frac{1}{MPG_{CAFE}} = \frac{0.55}{MPG_{CITY}} + \frac{0.45}{MPG_{HWY}} \qquad (3)$$

Real world driving also involves faster rates of acceleration and deceleration than in the FTP/SAETP/FUDS and Highway cycles. The dynamometers originally developed to test vehicles were not capable of accepting the high rates of acceleration and deceleration since shown to be common in real world driving. Dynamometers and emissions test cycles have been adapted to address higher rates of acceleration, deceleration, and speed in the real world. However, fuel economy tests have not been revised.

Thus, despite a concern by manufacturers and most engineering analysts that good fuel economy be obtained in advanced vehicles when tested on the SAETP and Highway cycles, obtaining such a result will not be enough to assure that consumers will be satisfied with their on-road experience with these vehicles. In particular, if an advanced vehicle pays a more significant cold start fuel economy penalty than a CV, then there is a distinct possibility that consumers' on-road experience in highway and low density suburban driving will have a greater discount than the 0.78 currently predicted by EPA for CVs. If over-predictions of percentage gains in fuel economy are made for advanced technology vehicles because the published values incorrectly rely on discount factors developed for CVs, there could be delayed negative consequences for manufacturers of such vehicles. Conversely, if advanced technology vehicles have less of a cold start penalty than CVs, then the use of discount factors obtained for CVs could under-predict the actual fuel economy gain possible with advanced technology vehicles.

Obviously, a key question to address is whether the negative fuel economy effects of cold start for the advanced technology vehicles examined in this paper should indeed be expected to be significantly better or worst than for CVs.

POWER VS. TIME AFTER COLD START

Another issue that deserves special consideration for fuel cell vehicles is the (lack of) availability of power during cold-start, which is not a big issue for conventional vehicles. There are two elements to this issue – time until adequate power is available to begin driving the vehicle, and time until the percent of rated power available increases to 100%. Diesels have a known difficulty of starting in cold weather. The solution adopted has been the glow plug, but the driver has to wait in a cold car until the cylinders are warm enough for the engine to start reliably. This has in the past been one factor deterring the purchase of diesel vs. conventional spark ignited (SI) internal combustion engines (ICEs) in northern climates.

As discussed in Appendix B, the ADVISOR model used in this study adopts two alternative strategies toward warming up a FCV. One is to heat the FC up to operating temperature before allowing the consumer to depart the parking space. This has the advantage of providing 100% of rated power when the vehicle first begins moving, but the disadvantage of delaying the time until it can be put into service after the decision to start it. As ADVISOR results show later, it also has a disadvantage of requiring more energy, and penalizing fuel economy, relative to the strategy of allowing the vehicle to drive away with less than 100% of rated power, and using waste heat to heat the FC and - in the case of GFCVs - reformer.

While ADVISOR has only one, the PSAT model used in the study includes two "maps" of efficiency vs. power (Appendix B). One of these maps is for cold start (room temperature, not low temperature), and another is for operating temperature. The two maps imply a difference of maximum power on the order of 25% when the fuel cell system is cold. Thus, if an FCV were not hybridized, then if the FCV were allowed to depart the parking space when at room temperature, then the vehicle would have only about 75% of rated power. In the event of subfreezing temperatures, the penalty would be even greater.

For the cases examined here, simulated warm-up times with the cold start strategies adopted by ADVISOR and PSAT vary from 250 to 2500 seconds for an H2FCV, and from 128 seconds to 1000 seconds for a GFCV (see detailed discussion in Appendix B and the later summary session). Note that a GFCV powertrain system is less efficient than a H2FCV, because the reforming step is done on board the vehicle. While lower GFCV rated efficiency (at operating temperature) is clearly a disadvantage, it is an advantage with respect to cold start, since a higher fraction of energy is "wasted" as heat. In the case of cold start, this "waste" is partly offset by providing more heat for warming the powertrain from cold conditions to operating conditions.

Note that the simulated warm-up times with PSAT and ADVISOR appear unacceptable. Goals for FC warm-up are 30 seconds. CVs are operational for drive-away in well under 30 seconds, but we do not have information on the percent of rated power available as a function of time since start for CVs. The PSAT simulation for the GFCV does estimate 30 seconds for the reformer, primarily based on assumptions about what is needed to get the reformer to operating temperature in 30 seconds. However, the FC stack itself is estimated to take 128 seconds or more to warm up. Compared to the H2FCV simulations, it appears that a GFCV has an advantage with respect to warm-up, presumably because of the extra waste heat generated by the

reformer. The minimum time of 600 seconds for the H2FCV is ten minutes, which is undoubtedly a significant portion of most trips.

One way to compensate for slow warm-up is to provide a battery pack to provide immediate power. According to GM simulations, which included advanced electric drive FCVs with and without battery packs (with and without hybridization), the addition of a battery pack to a FCV improves fuel economy. ADL simulated FCVs with two separate battery pack sizes, small and large. Fuel economy was estimated to be higher with the larger battery pack. Further, with the larger battery pack, ADL "downsized" the fuel cell stack and system from 60kW to 38kW. According to ADL estimates provided in this paper, this reduced the FC warm-up energy requirement as a fraction of fuel used on the test cycle. Time to warm-up to operating temperature was not evaluated by ADL. However, note that if the battery is able to provide full power in just a few seconds (not guaranteed in all battery types or temperatures), then the percent of rated powertrain power as a function of time from start from a hybrid electric FCV (HEV FCV) with a larger battery pack will be greater than one with a small pack or no pack at all. The provision of a significant fraction of peak power via a battery pack can provide (A) "instantaneous" power for departure from a parking spot; (B) assure a higher percentage of rated powertrain power is available during warm-up; and (C) reduce the mass of the FC being warmed up, thereby reducing energy needed for cold start. However, it is shown in the EVS-19 paper by Santini et al (4) that too large a fraction of power via a battery pack can actually reduce fuel economy. An appropriately sized battery might also be used to provide heat energy that could lead to more rapid warm-up, but the analysis in this paper does not provide any insight into the energy vs. power trade-offs involved with such a strategy. Further, while reducing the size of the FC can reduce warm-up energy use, it would also reduce the vehicle's continuous top speed and the peak speed at which it could climb long grades.

Provision of a battery pack provides the option to adopt the warm-up strategy used in the PSAT model without dumping energy. In particular, the PSAT strategy is "intermediate" between the two strategies in ADVISOR. While the PSAT strategy assumes the vehicle is driven away immediately, it also assumes that the FC is run at a power level in excess of needs to move the vehicle, with extra energy generated used to heat the FC. In its drive away warm-up option, ADVISOR assumes that only enough energy is generated by the FC to move the vehicle, and no more. Inclusion of a battery pack allows the extra electrical energy produced with the PSAT strategy to be stored in the battery for later retrieval, less losses. Without a battery pack, this energy would be lost. The estimates presented later show that the PSAT warm-up strategy is intermediate between the two ADVISOR strategies, both in terms of time to achievement of operating temperature and power and in terms of energy losses incurred. The cases run are for a FCV with a battery pack providing about 30% of peak powertrain power.

POWERTRAIN MASS EFFECTS

Among the four studies examined, the ADL study is the only one to estimate cold start effects on energy consumption. It does not address time to achieve operating temperature and rated power. According to ADL's estimates, the energy needed to warm up a fuel cell stack is directly related to mass, which is directly related to power. The ratios of peak kW, "active mass", and start-up energy all happen to be 0.63 when the 38kW case is compared to the 60 kW case. ADL's estimates of the percent fuel economy penalty for a GFCV are somewhat less than generated by ADVISOR (fast start, no drive away until 100% power case) or PSAT. However, ADL assumes a lower ratio of FCV peak power to vehicle mass than does MIT, for which the ADVISOR and PSAT cases are run. Since ADL estimates that cold start energy consumption is directly proportional to mass, then increase of the kW of the ADL FCV in order to match the kW/kg ratio of the MIT FCV would increase the ADL cold start energy consumption estimate, perhaps making it nearly identical to the results obtained for the "MIT case" by ADVISOR and PSAT. More detailed discussion of this issue can be found in a later section.

REFORMER POWER EFFECT

ADL presents estimates that cold start energy consumption could be reduced by 75%. The argument made is that the reformer could be divided into four separate reforming units, and only one used during the warm-up to drive away phase. We are skeptical of this approach, since if only 25% of the reformer capacity is at operating temperature, then the reformer must produce considerably less hydrogen (perhaps a bit more than 25% if the other three reforming units are beginning to warm up) than needed to run the FC at rated power. Further, if we assume that the waste heat generated by the reformer is used to heat the FC stack, then the already long delay in achievement of operating temperature in the stack would become problematic, also reducing available power and efficiency. So, while this approach might reduce energy requirements for cold start, it might be the worst of the approaches examined in this paper with respect to percent of rated power achieved as a function of time after start.

OTHER 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 el at showed how violations of different sets of rules could influence the outcome of the technological prediction [2-4]. However, in many studies, standardized rules for comparisons are either not defined or not followed, intentionally or unintentionally. A detailed discussion of these rules is given by our companion paper [1]. The following is a short summary of these rules as applied to powertrain evaluations:

- Carefully define and characterize baseline vehicle technologies
- Establish performance-equivalence criteria, such as 0-60 acceleration time, gradeability, range, interior volume, torque, and safety requirements
- Select and use common driving cycles.
- Technology scenarios should be clearly defined and synchronized with respect to degree of optimism/pessimism.
- The comparison should be conducted under the same timeline for conventional vehicles and ATVs.
- The ATV comparisons should be conducted based on the same vehicle glider; only the powertrain portion should be varied.
- Effects of cold start should be made explicit.

It is not possible in any single paper to develop adjusted comparisons addressing all of the above issues as they relate to previously published studies. In fact, we have been unable to do such a full adjustment at this point in time, due to the complexities involved, and uncertainties about assumptions and methods used in various studies. The best we can do is provide this list as a warning concerning the limited scope of any individual paper on the broad subject. In this paper, we directly compare results of different studies, without adjusting them based on the above rules as attempted in other studies [2-4]. So it's 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 the rules above are not followed. Our analysis shows that even after some adjustments to reduce the above problems, there remain fundamental differences in estimates of the technology potentials of various ATVs among these analyses.

PART I - REVIEW AND COMPARE OF EXISTING TTW STUDIES

This part of the paper reviews and compares unadjusted vehicle analysis conducted by MIT, GM, DTI and ADL. As discussed earlier, we use the vertical assessment approach to compare future ATVs to future CVs. 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. Both GM[2] and ADL analysis is based on for 2010 timeframe, and MIT analysis based on 2020 timeframe.

Among all these analyses, only ADL discussed cold-start impacts of fuel cell vehicles. However, all ADL simulation results are based on hot-start. The cold start discussion provides estimated adjustments that could be applied to hot start results. ADL has presented FCVs with two hybrid cases: a small battery case and a large battery case. The large battery case involves battery power about same as the fuel cell power, which is basically a so-called "dual-mode" hybridization scheme. At the present time, this scheme that has fallen out of fashion as an option for hybrid powertrains for conventional vehicles. The MIT hybrids involve battery power only about half the power of the primary power unit, and we deduce that the GM case involves a relatively small battery, though there is not enough information provided to create a precise estimate. Due to our judgment that the large battery case in the ADL study is not comparable to the MIT and GM studies, here we only consider the small battery case. However, we note that ADL is to be commended for providing two clearly distinct mixes of battery and primary power unit power levels, something that other studies did not do.

GM uses a pickup truck (Silverado) as the baseline. All other studies that have also evaluated FCVs use a midsize sedan as a baseline vehicle. Table 2 lists curb weights of baseline and FCVs by these four studies. As discussed previously, these two vehicles, as well as the two FCV cases, would share the same vehicle "glider", and only differ by powertrain mass. 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.

[2] GM didn't explicitly project future baseline conventional vehicle. We assume its future baseline vehicle would be the same as the MY 2000 Silverado.

Table 2 – Curb Weights of Baseline and Gasoline Fuel Cell Vehicles by These Four Studies

Curb wt. (kg)	Baseline	H2 FCV	Gain	Gas FCV	Gain
MIT 2020	1,019	1,179	16%	1,330	31%
GM 2010	1,929	2,253	17%	2,497	29%
DTI 2005	1,168	1,155	-1%	1,339	15%
ADL 2010	1,304	1,219	-7%	1,284	-2%

In Table 2, only GM mass figures are the authors' own estimates. The baseline GM vehicle (a pickup truck) weighs about 1,929 kg, baseline MIT vehicle weighs about 1,019 kg, baseline DTI vehicle (a PNGV-type car) weighs about 1,168 kg, and ADL baseline vehicle (a midsize car) weights about 1,304 kg. Table 2 also presents the weight changes associated with each fuel cell vehicle. It shows that MIT 2020 and GM 2010 cases have similar projections on the increases of vehicle masses associated with FCVs. However, both DTI and ADL's assessment on impacts of vehicle masses for FCVs are very different. ADL even projects weight decreases for all FCVs. Table 2 also shows that the curb weights of hydrogen and gasoline fuel cell vehicles in DTI, ADL and MIT cases are very similar - about 1,200 kg for the former and 1,300 kg for the latter.

FUEL ECONOMY COMPARISION

The fuel economy in our analysis is defined as gasoline-equivalent miles per gallon: MPGGE or simply MPG. 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. Table 3 lists fuel economies of baseline and fuel cell vehicles of all these cases, as well as corresponding mpg gains of fuel cell vehicles over their respective baseline vehicles. Generally speaking, the MIT 2020 case would make the fuel cell vehicle much less attractive, especially for gasoline FCVs - its MPG rating would lose 14% relative to the baseline 2020 vehicle. For the gasoline reforming FCVs, GM and ADL show the most optimistic projection of fuel economy gains of about 50%.

Table 3 – Fuel Economies of Baseline and Gasoline Fuel Cell Vehicles by These Four Studies

MPGGE	Baseline	H2 FCV	Gain	Gasoline FCV	Gain
MIT 2020	49.1	94.1	92%	42.3	-14%
GM 2010	20.2	48.1	138%	30.2	50%
DTI 2005	30.1	82.3	173%	38.4	28%
ADL 2010	30.1	76.0	152%	45.6	51%

Closely examining Table 3 reveals that, what makes the MIT 2020 case stand out is not its projection of H2 and gasoline FCVs, but its optimistic projection for the 2020 baseline CV. Keep in mind that all of these analyses don't include cold-start effects for the FCVs, but do include such effects for current conventional powertrains. As will be discussed in a later section, cold-start effects estimated by ADL and by us with PSAT and ADVISOR have big impacts on FCVs, thus reducing their energy benefits.

Figure 2 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 2 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.

TANK-TO-WHEEL (TTW) EFFICIENCY COMPARISION

Vehicle tank-to-wheel (TTW) efficiency often can be referred to as vehicle powertrain combined efficiency, which is defined as energy output to drive a vehicle at the wheels as a percentage of total fuel energy consumption. Strictly speaking, TTW energy efficiency is also somewhat influenced by vehicle weight, e.g., heavier, more slowly accelerating vehicles tend to be more efficient in terms of energy use than lighter and faster accelerating counterparts (see ref. 1). However, the weight dependence of TTW efficiency is much less than is vehicle fuel consumption or fuel economy, where energy use is directly linked to how much work is needed to overcome total vehicle load, including primarily mass effects and secondarily drags from air and tires.

Figure 2 – "Vertical" Assessments of ATVs and Baseline Vehicles for these Four Studies

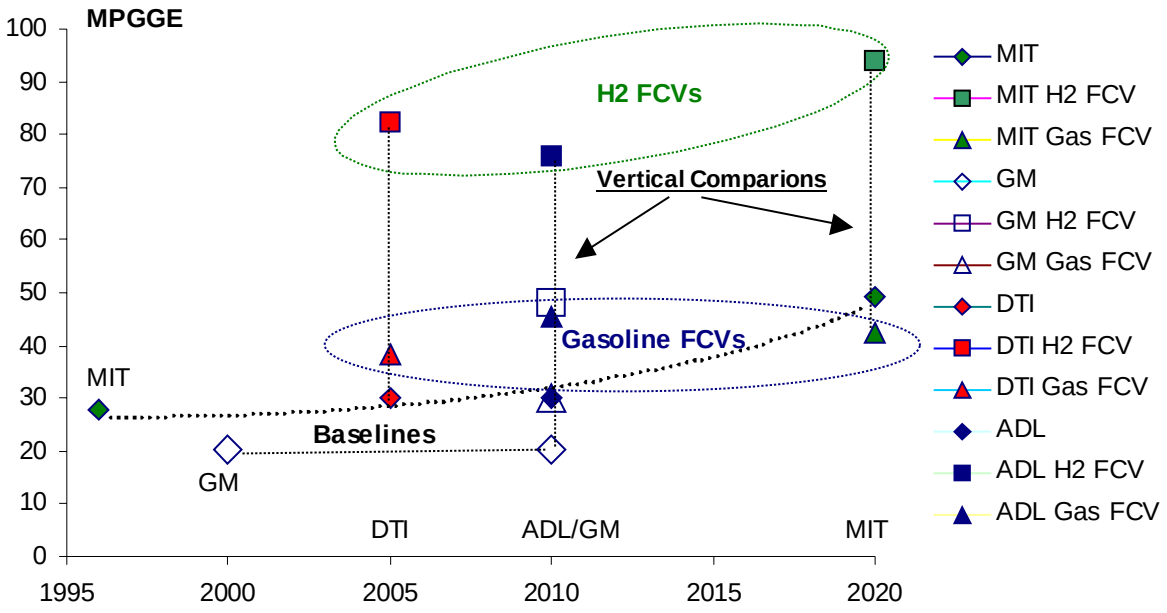


Table 4 lists Tank-to-Well (TTW) efficiencies of baseline and gasoline fuel cell vehicles by these four studies, as well as corresponding TTW efficiency gains of these fuel cell vehicles over their respective baselines. Only MIT and GM provided tank-to-wheel efficiency figures. Both DTI and ADL's TTW figures are the authors' estimates.

Table 4 shows that all baseline conventional vehicles have similar tank-to-wheel efficiency, ranging from about 15.6-17%, for a variability of estimates of about 15%. The TTW efficiencies of H2FCVs have a similar variability of estimates, ranging about 18% (from 36 to 42.5%). However, the range of estimated TTW for GFCVs is far larger, at about 50% (from 17.6% to 27.3%) While MIT consistently has the low TTW efficiency estimate, the high value for H2FCVs is from DTI, and the high value for GFCVs is from GM.

Table 4 – TTW Efficiencies of Baseline and Gasoline Fuel Cell Vehicles by These Four Studies

T-t-W Eff.	Base-line	H2 FCVs		Gasoline FCVs	
	Eff (%)	Eff (%)	Gain	Eff (%)	Gain
MIT 2020	17.0	36.0	112%	17.6	3%
GM 2010	16.7	41.4	148%	27.3	63%
DTI 2005	16.8	42.5	153%	22.5	34%
ADL 2010	15.6	37.1	138%	23.0	47%

The efficiency gains for H2 FCVs range from a low of 112% from the MIT study to 153% from the DTI study. Far larger differences are found in the assessments of gasoline reformer FCVs. The corresponding TTW efficiency gains range from 3% from MIT 2020 to 63 % from GM 2010.

In summary, Figure 3 graphically presents Tank-to-Well (TTW) efficiencies of baseline, hydrogen and gasoline fuel cell vehicles of these four studies.

Figure 3 – TTW Efficiency Comparisons of Baseline and Fuel Cell Vehicles by These Four Studies

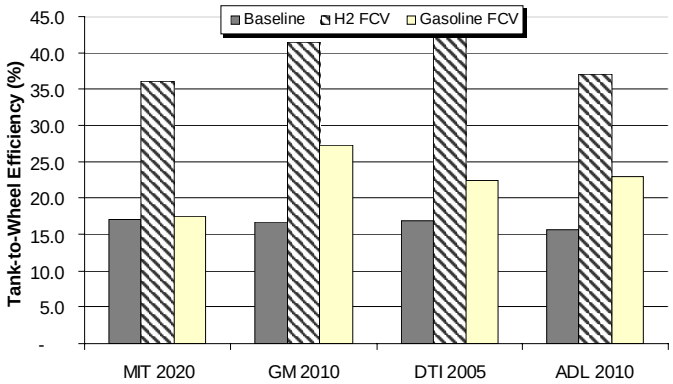
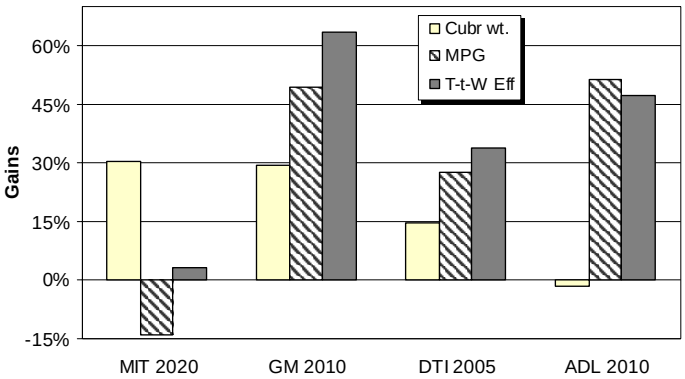


Figure 4 compares percentage gains of curb weight, MPG and TTW efficiency of gasoline fuel cell vehicles (GFCVs) over their corresponding baselines of these four studies. It clearly shows that GM and ADL have more optimistic projections for gasoline fuel cell vehicles than that of MIT and DTI. The MIT case estimates negative or negligible gains of MPG and TTW efficiency.

All other cases show strong positive gains, ranging 25-58% gains for MPG and 34-64% gain for TTW efficiency. ADL's projection on vehicle mass is the most optimistic with net weight reduction from a gasoline FCV. Our estimates indicate that both GM and MIT project nearly 30% weight gains from GFCV powertrains.

Figure 4 –Comparisons of Curb Weight, MPG, and TTW Efficiency Gains of Four Gasoline Fuel Cell Vehicles



Note that the powertrain mass percentage differences are considerable . Ultimately this is important when one gets to the point of estimating cold start effects. The larger the mass of the powertrain – especially the FC and/or reformer – the more energy required for warm-up. Thus, if greater test-stand efficiency of a fuel cell or reformer is obtained by adding components such as compressors or blowers, or additional compartments (ADL reformer), this will increase mass and reduce net efficiency in the vehicle, by increasing cold start and mass-related vehicle load energy requirements. Of course, if such components otherwise improve cold start attributes, the net effects could be positive.

PART II - FUEL CELL VEHICLE MODELING: METHODOLOGIES AND RESULTS

In the second part of paper we will discuss modeling issues associated with hydrogen and gasoline fuel cell vehicles, with emphasis on cold start FCV modeling. We start the discussion with cold start impacts of conventional ICE vehicles.

COLD START IMPACTS OF CONVENTIONAL ICE VEHICLES

Appendix A presents detailed analysis of cold start impacts of conventional ICE vehicles. Table 5 summarizes the testing results conducted at University of California, Riverside, based on averaging 4-, 6- and 8-cylinder conventional gasoline ICE engines. Table 5 shows cold start impacts measured as relative gain of warm-start "Bag 3 MPG" versus cold start "Bag 1 MPG" (MPG_{Bag3}/MPG_{Bag1}-1). The cold-start MPG impacts and energy penalty over the entire City cycle, which is composed of Bag 1, Bag 2 and Bag 3, are also estimated. The City-cycle cold-start impacts are assessed by comparing results of "cold start" City cycle MPG as defined by Equation (1) and "hot start" City cycle MPG. The penalty estimate was constructed by substituting cold-start MPG_{Bag1} with hot-start MPG_{Bag3} in Equation (1) to estimate an equivalent hot start fuel economy. This is a sample of 12 vehicles. In theory, more cylinders would require more cold start energy because more engine mass is involved. However, if this effect exists, it is apparently swamped by other factors in the few cases selected for examination here, since such a pattern does not show up. However, one point of speculation is that the "V" engine configuration retains heat better than an in-line configuration by reducing exposed surface area per unit of mass. If this is true, then the results shown in Table 5 are consistent with the argument that more mass will require more energy to warm the engine to operating temperature. The 4-cylinder engines are in-line engines, while the 6 and 8 cylinder engines are "V" configurations. Among the "V" configurations, the cold start penalty is greater on average with 8 than with 6 cylinder engines.

Table 5 - Cold Start Impacts of Conventional ICE Vehicles

Sample ICE Vehicles	Cold Start Impacts (Bag3/Bag1 –1)	City Cycle MPG Penalty	City Cycle Energy Penalty
4 Cylinders	18.7%	8.1%	7.4%
6 Cylinders	14.7%	6.4%	6.0%
8 Cylinders	18.8%	8.3%	8.0%

Table 5 shows that the cold-start impacts of Bag 3 vs. Bag 1 of conventional vehicles range from 15-19%. Over the City cycle, the cold-start MPG and energy impacts range from 6-8%. The energy penalties are mostly results of inefficiency associated with cold IC engines. However, one distinct feature associated with cold-start ICE is that the maximum engine power available during cold start is not largely reduced from its hot-stabilized capacity, which is not likely the case for FC based engines, as will be discussed below.

A. D. LITTLE COLD-START ANALYSIS

ADL has analyzed energy required to warm up gasoline and methanol based fuel cell systems [8]. ADL's energy analysis is nominally based on catalyst volume, heat capacity, system mass and operating temperature. However, start-up energy relationships shown below in Table 6 scale directly with kW and "active" mass, as noted earlier. Start-up energy requirements are dictated by the energy input to warm-up catalyst beds and reformers. Table 6 summarizes ADL's analysis, where "RFG ATR" represents reformulated gasoline autothermal reforming fuel cell system, and "Methanol

SR" represents methanol steam reforming system. Each system has two cases – one for a large 60 kW reforming system (combined with a smaller battery pack for a hybrid FCV), the other a smaller 38 kW reforming system (combined with a larger battery pack for a hybrid FCV). The start-up energy calculation is based on energy required to fully warm-up active material mass. E.g. for a 60 kW RFG ATR system, 2,800 kJ of energy is required to warm up 9.0 kg active mass. During the City drive cycle, ADL estimates the overall energy required at the vehicle wheels is about 17,000 kJ.

Table 6 – ADL's Analysis on Energy Impacts of Cold Start

		Active Mass, kg	Current Start-up Energy, kJ	Future Start-up Energy, kJ	City Drive-cycle, kJ	Hwy Drive-cycle, kJ
RFG ATR	60 kW	9.0	2,800	700	17,700	21,900
	38 kW	5.7	1,770	443	15,600	20,600
Methanol SR	60 kW	8.8	2,260	565	17,700	21,900
	38 kW	5.6	1,430	358	15,600	20,600

These figures imply a 16% energy penalty, or 19% MPG penalty for cold starts in the City drive cycle, as shown in Table 7. Thus based on ADL's analysis, cold-start impacts on gasoline FCVs are two to three times as much as for the conventional vehicles.

ADL has also presented a case where the catalyst bed can be partitioned into 4 independent sub-systems, and only one subsystem (1/4 of the total) needs to be started during cold-start process. By doing this, it is claimed by ADL that the cold start energy requirement can be reduced by three fourths. If a smaller ATR system (the 38 kW one) is used in combination with a larger battery pack, the future theoretical MPG penalty for a gasoline reforming FCV is less than 3%, less than half of that of a conventional ICE engine.

Table 7 – ADL's Analysis on Energy/Fuel Economy Penalties of Cold Start

City Cycle		Current		25% Warm-up	
		Energy Penalty	MPG penalty	Energy Penalty	MPG penalty
RFG ATR	**60 kW**	**15.8%**	***18.8%***	4.0%	*4.1%*
	38 kW	11.3%	*12.8%*	2.8%	*2.9%*
Methanol SR	60 kW	12.8%	*14.6%*	3.2%	*3.3%*
	38 kW	9.2%	*10.1%*	2.3%	*2.3%*

We judge that this is an extremely optimistic view. Partially starting one fourth of the system during cold start means that drivers can only access the maximum power of one fourth of designed capability, which may be unacceptable for average consumers. Nevertheless, ADL's analysis did raise a trade-off question between rapid warm-up and energy conservation. We further explore this issue later.

Another potential drawback of a mass-based cold start energy analysis is a failure to consider the energy inefficiencies of reformer and stack systems during cold start. Energy inefficiencies of these components during cold-start will consume more energy than during hot-start conditions. So even though ADL is to be credited as the only study among those reviewed to address cold start, providing informative reference estimates, we conclude that its analysis is likely to be overly optimistic.

ARGONNE'S RE-ANALYSIS OF MIT-LIKE CASES

In our own analysis, we use two DOE models – ADVISOR and PSAT. At this time, MIT's study is the only one to provide enough tabular, numerical information to allow us to conduct vehicle simulations to compare with and contrast to its' results. The MIT study presents more complete information than the other three studies, thus allowing us to construct MIT-like hydrogen and gasoline fuel cell vehicles based on given information on vehicle mass, FC power and battery power. However, many basic assumptions in terms of engine, transmission and motor efficiencies are embodied in ADVISOR and PSAT, and are not necessarily in agreement with MIT's own assumptions. Also, while the MIT analysis doesn't include cold-start effects, both DOE models have the capabilities to model cold-start effects.

ADVISOR is vehicle simulation software developed by NREL (National Renewable Energy Lab) [10]. PSAT, the PNGV System Analytic Toolkit, is vehicle simulation software developed by SwRI and Argonne [9]. One major difference between ADVISOR and PSAT is that the former is a "backward" model and the latter is a "forward" model. The "backward" model estimates energy and power needed to match a specified driving cycle and specifies the behavior of the powertrain without the action of an accelerator or brake pedal. The "forward" model simulates a driver attempting to match a driving cycle by depressing the accelerator and brake, as required. This approach requires far smaller computational intervals, and takes longer to complete a single simulation, but more accurately depicts loads on components in the vehicle and powertrain.

In both models, the general structure and methodology for modeling hybrid gasoline and hydrogen fuel cell vehicles are quite similar. Both of them don't deal with balance-of-plant modeling issues associated with thermal, water, and air management for peripheral sub-systems. Rather, the fuel cell is treated as a unit system, defined by the system performance curve (system

efficiency vs. FC load). There are, however, major differences in modeling cold-start behaviors of FCVs, which are given by detailed discussions in Appendix B.

We use ADVISOR 2002 version and PSAT5.1 version for our FC vehicle simulations. Please note that both models are constantly evolving as we improve our understanding of FC systems. In our judgment, these models are better served for the purpose of trade-offs and trend analyses.

ADVISOR Results

As explained in Appendix B, in ADVISOR, there are two basic approaches to model FCV cold-start:

1. "Fast warm-up" mode - Assuming the FCVs being heated-up at maximum rate, or as quick as possible. In this mode, the FC will operate at maximum power capacity to heat up itself exclusively (no power output to drive the vehicle), and the battery pack will provide all the traction force, before the FC system achieves its operation temperature. This mode can be called "Fast Heat-Up" mode. Note that this approach, like the ADL partitioned reformer idea, means that the vehicle has much less power initially than when warmed up.

2. "Slow warm-up" mode - Assuming the FCVs will use normal warm-up approach that takes residual waste heat (based on efficiency) when the FC delivers power output to the drivetrain, and calculates the coolant and component temperatures based on mass flows and heat transfer coefficients. In this mode, no extra energy is used in heating up the system, so it's a "Slow Warm-Up" or "Energy Conserving" mode. The only energy penalty associated with cold-start is from FC inefficiency.

Based on the above distinctions, we decided to run Advisor on three cases: 1) a "slow warm-up" case, 2) a "fast warm-up" case; and 3) a "hot start" case where the FC starts at fully warmed up conditions.

As explained in Appendix B, the thermal model of the fuel cell used in ADVISOR is identical to that of its internal combustion engine thermal model. The ADVISOR FC thermal model is further being updated by the time this paper is presented. Thus in this analysis, we are less concerned about the absolute results of cold-start fuel economy effects. Rather, we focus on the comparison with hot-start results and the comparison between slow and fast warm-up modes. MIT conceded that they didn't include cold-start in their study. Thus their results should be compared with ADVISOR hot start results.

Tables 8 gives MIT results, the ADVISOR simulation results for the above three cases based on MIT vehicle specifications for a H2 hybrid FCV, and MPG penalties associated with slow and fast warm-up cases. There are several conclusions can be drawn from Table 8:

Table 8 – ADVISOR 2002 Simulation Results on H2 FCVs

H2 FCVs	*MPG*	**Advisor MPG**			*MPG Penalty (hot/cold –1)*	
Advisor	MIT	Slow Warm-up	Fast Heat-up	Hot	Slow Warm-up	Fast Heat-up
City	83.7	70.6	60.7	74.5	5.5%	22.7%
Hwy	111	89.9	89.9	89.9	0.0%	0.0%
CAFE	94.1	78.1	71.1	80.7	3.4%	13.5%

1) MPG penalty of a slow warm-up mode is about 5.5% for the City cycle. For the fast mode, it's about 23%. Thus the slow warm-up mode, which warms up the FC based on waste-heat, has about one fourth of energy penalties of the fast warm-up mode, which warms up the FC as fast as possible.

2) The above conclusion implies that there is a trade-off between minimizing the cold-start energy penalty and speed-up of the cold-start process.

3) MIT's fuel economy projections on the H2 FCV are better than ADVISOR 2002 results for both hot-start City and HWY cases.

We note that, for a conventional vehicle, in reality the same trade-off as identified in item 2 exists. Warming up the vehicle to operating temperature before departure will also increase energy use. We have not modeled this.

Similarly, Tables 9 gives MIT results, the ADVISOR simulation results for the above three cases based on MIT vehicle specifications for a gasoline reforming hybrid FCV, and MPG penalties associated with slow and fast warm-up cases.

Table 9 – ADVISOR 2000 Simulation of Gasoline FCVs

Gas FCVs	*MPG*	**Advisor MPG**			*MPG Penalty (hot/cold-1)*	
Advisor	MIT	Slow Warm-up	Fast Warm-up	Hot	Slow Warm-up	Fast Warm-up
City	37.2	49.6	42.5	51.2	3.2%	20.5%
Hwy	50.9	71.9	71.9	71.9	0.0%	0.0%
CAFE	42.3	57.7	52.1	58.8	1.9%	12.9%

There are also several conclusions can be drawn from Table 9:

4) MPG penalty of a slow-warm-up mode is about 3.2% for the City cycle. For the fast mode, it's about 20.5%. Thus the fast" mode, which warms up the FC and reformer as fast as possible, has more than five times the energy penalty of the slow mode, which warms up the FC and reformer based on waste-heat. We again note that we have no comparable fast mode estimate for a CV.

5) The above conclusion implies that there is an even larger trade-off between conserving cold-start energy and slow vs. rapid warm-up processes for GFCVs.

6) MIT's fuel economy projection on the gasoline hybrid FCVs is significantly lower (about 28%) than what is predicted by ADVISOR 2002 based on hot-start City and HWY cycles.

7) Comparing Table 8 and Table 9, it appears that ADVISOR predicts similar percentage cold-start MPG penalties for both H2 and Gasoline FCVs. This is somewhat anti-intuitive, because the gasoline reformer and associated catalysts should require more energy to warm up the FC system than a H2 system. On the other hand, since the GFCV is less efficient, this could explain why the percentage effects are similar. In our judgment, one obvious shortcoming of the ADVISOR 2002 cold-start model is the apparent neglect of reformer warm-up and catalyst light-off effects.

8) The above results show that MIT over-predicts ADVISOR 2002 for hot-start H2 FCVs, but under-predicts ADVISOR for the hot-start GFCV case. MIT didn't consider the cold-start effects for both H2 and gasoline reformer based hybrid FCVs, but other assumptions appear to dominate the differences in estimates.

<u>PSAT Results:</u>

In PSAT, unlike ADVISOR, there is only one option to model cold-start effects.

As explained in Appendix B, PSAT's approach to model FCV cold start is completely different from that of ADVISOR. For modeling hydrogen FCVs, it relies on cold and hot FC maps and corresponding maximum power output. Unlike thermal models based on block thermal conduction, convection and radiation used by ADVISOR, PSAT assumes the fuel cell warm-up based on accumulated fuel flow and an engine coolant warm-up time constant, which is defined as coolant warm-up time if full FC power output is applied from the very beginning to fully warmed-up conditions (default value to be 600 seconds). However, under this mode, the FC is basically warmed up based on FC waste heat. In this sense, the PSAT cold-start modeling approach for H2 FCVs is similar to ADVISOR's "Slow warm-up" approach.

The modeling methodology for the gasoline reformer FCVs is very different. In addition to a cold FC map that is different from the hot map, PSAT introduced the catalyst light-up time and reformer warm-up time to feed H2 to fuel cell, and fuel penalties designated to start both the reformer catalyst (10g) and reformer itself (93.6 g). On top of this, the maximum available fuel cell power output is a function of coolant temperature, and fuel consumption is scaled between cold and hot FC maps based on coolant temperature as well. PSAT specifically designates the light-up time for the catalyst to be 20 seconds, and warm-up time for the reformer to be 30 seconds, and warm-up rate for FC stack (coolant temperature) to be 128 seconds when heated by maximum FC power. The FC system dedicates its first 30 seconds of operation to exclusively heat-up itself. Battery power is the only traction force available in the first 30 seconds. Thus, for gasoline FCVs, the PSAT cold-start modeling approach is similar to ADVISOR's "Fast warm-up" approach. However, the PSAT model is not at all sensitive to FC mass. So this is a problem that should be addressed in the later version.

In this analysis, we run PSAT on two cases: 1) a cold-start case as the default SAE test procedure; and 2) a "hot start" case where the FC starts in a fully warmed up condition. Table 10 gives the results for the H2 FCVs and Table 11 for the gasoline FCVs.

Table 10 – PSAT Simulation of H2 FCVs (slow warm-up)

Gas FCVs	*MPG*			*MPG Penalty*
PSAT	MIT	PSAT SAE	PSAT hot	Hot/cold-1
City	83.7	85.7	93.7	9.3%
Hwy	111.0	112.3	112.3	0.0%
CAFE	94.1	95.9	101.2	5.5%

Table 11 – PSAT Simulation of Gasoline FCVs (fast warm-up)

Gas FCVs	*MPG*			*MPG Penalty*
PSAT	MIT	PSAT SAE	PSAT hot	Hot/cold-1
City	37.2	36.5	44.9	23.0%
Hwy	50.9	78.5	78.5	0.0%
CAFE	42.3	48.1	55.6	13.8%

Generally speaking, PSAT shows better fuel economy projections for H2 FCVs than that of both the MIT study

and ADVISOR modeling results. For the H2 FCV, the cold-start MPG penalty is about 9% for the City cycle, which is far less than what ADVISOR projects, but is similar to the conventional ICE cases.

For the GFCVs, PSAT shows a higher fuel economy projection than that of the MIT study, but a worse result than ADVISOR 2002, for either cold or hot-start cases. The GFCVs' cold-start MPG penalty from PSAT is about 23% for the City cycle, which is slightly higher than the ADVISOR projection.

For the modeling of GFCVs, PSAT explicitly dedicates an amount of fuel penalties to start reformer catalyst (10g) and reformer itself (93.6 g)[3]. Similarly to the ADL approach (not exactly since these figures in PSAT are insensitive to power level of the reformer), we can directly calculate fuel penalties associated with cold-start, as given by Table 12.

Table 12 – PSAT Analysis on Cold-Start Energy and MPG Penalties for Gasoline FCVs

PSAT	*PSAT hot* Equivalent Gasoline		*Cold-start Penalty (103.6g, 4,558 kJ)*	
	in Grams	In kJ	Energy	MPG
City	454.8	20,010	19%	23%
HWY	505.9	22,435	0	0
CAFE	250.1	21,101	10%	13%

In Table 12, we estimate that the total amount of fuel use based on the "hot" city cycle is about 455 grams or 20,101 kJ (derived from 44.9 MPG), thus the cold-start energy penalty of 103.6 g, or 4,558 kJ, is about 19% of total, or the MPG penalty of about 23%, which is consistent with Table11. This is slightly larger than the 19% estimate by ADL. The above analysis can't be performed for the H2 FCVs, since no dedicated fuel penalties are given for H2 FCV cold-start. As the above process indicates, the energy penalty results are not results of simulation or modeling, rather, it's pre-determined as inputs prior to the simulation run. We are not convinced that "a dedicated fuel penalty" is a good way to simulate the cold-start energy penalty. This does not give flexibility in assessing cold start impacts of different sizes of system, as well as different starting driving conditions.

SUMMARY OF KEY FINDINGS

This section summarizes what we have discussed so far. First, we have discussed the differences between a "fast warm-up" approach and "slow warm-up" approach. Table 13 presents the estimated time for the FC to reach operation temperatures based on the FUDS (City) drive cycle. The estimates are given for both H2 and gasoline reforming FCVs, based on ADVISOR and PSAT.

Table 13 – Cold Start Times to Reach Operation Temperature

Warm-up approach	*H2 FCVs*	*Gasoline FCVs*
ADVISOR (Fast)	~ 250 sec.	~ 250 sec.
ADVISOR (Slow)	~ 2,500 sec.	1,000 sec.
PSAT (Fast)	Not Available	Catalyst - 20 sec, Reformer –30 sec., Stack > 128 sec.
PSAT (Slow)	Stack >> 600 sec. ~ 600 sec. with full FC power	Not Available

For ADVISOR's "Fast" mode, both H2 and Gasoline FCVs can reach operation temperature in about 250 seconds, or 4 min. For ADVISOR's "Slow" mode, the H2 FCVs reach operation temperature in about 2,500 seconds, or 40 min., and gasoline FCVs reach operation temperature in about 1000 seconds, or about 20 min.

It appears that PSAT has a fast warm-up mode for GFCV, but a slow warm-up mode for H2FCV. For PSAT H2 FCV cold start simulations, the coolant temperature increases slowly, taking far more than 600 seconds to reach its operation temperature. For PSAT's simulation of GFCVs, the assumed light-up time for the catalyst is fast, at 20 seconds, warm-up time for the reformer is also fast, at 30 seconds, while warm-up time for the FC stack (coolant) is more than 128 seconds. We note that the GFCV FC stack should be able to heat up faster than the H2FCV FC stack, due to the existence of waste heat generated by the reformer. Thus, PSAT's simulated shorter warm-up of the FC stack in the quickly warmed up GFCV than in the slowly warmed up H2 FCV is plausible.

Table 14 summarizes the modeling results based on ADVISOR and PSAT for the MIT H2 and gasoline FCVs. Since MIT's results don't include cold-start effects, we only compare them with ADVISOR and PSAT's "hot-start" results.

Table 14 clearly shows that the fuel economy results vary with cold start modes (cold vs. hot, fast vs. slow) and models (ADVISOR vs. PSAT). Generally speaking, PSAT gives the most optimistic prediction for the H2 FCVs, while MIT give most pessimistic projections for the gasoline FCVs. For H2 FCVs results, MIT's result is between ADVISOR's "hot-start" and PSAT "hot-start" results. For the gasoline FCVs, MIT under-estimates

[3] These figures are based on Argonne's 50 kW POX Gasoline reforming fuel cell system.

both ADVISOR (by 28%) and PSAT (by 14%) "hot-start" results.

Table 14 – Comparing MIT H2 and Gasoline FCVs Fuel Economies with Advisor and PSAT Modeling Results

MPGGE	*H2 FCV*			*Gas FCV*		
	MIT	ANL	Diff.	MIT	ANL	Diff.
ADVISOR Fast		71.1			52.1	
ADVISOR Slow		78.1			57.7	
ADVISOR Hot	94.1	80.7	17%	42.3	58.8	-28%
PSAT Fast		N/A			43.0	
PSAT Slow		95.9			N/A	
PSAT Hot	94.1	101.2	-7%	42.3	49.0	-14%

Table 15 compares City, HWY and Combined (based on SAE test procedure) fuel economies of baseline and gasoline reforming GFCVs. Since MIT only gives "hot-start" results for all of their FCVs, we estimated "MIT Cold Start" fuel economy by discounting MIT's City MPG by 23% based on Table 11. So the adjusted MIT figure is 37 MPG. The modeling results based on ADVISOR and PSAT range from 43 to 58 MPG. For comparison purposes, Table 15 also presents MIT 2020 baseline and MIT adj. 1996 baseline, as defined earlier.

Table 15 – City, HWY and SAE Fuel Economies of MIT Gasoline FCVs

	City	*HWY*	***SAE***
Original MIT 2020 Base CV	*42.4*	*60.8*	*49.1*
Original MIT Hot-Start GFCV	*37.2*	*50.9*	*42.3*
MIT Cold Start GFCV*	30.2	50.9	**37.0**
PSAT Cold Start GFCV	36.5	55.1	**43.0**
ADVISOR Fast Warm-up GFCV	42.5	71.9	**52.1**
ADVISOR Slow Warm-up GFCV	49.6	71.9	**57.6**

- Not in MIT study, our revision

Figure 5 illustrates the MPG ranges of different modeling approaches and baselines for GFCVs. Both "MIT 2020 CV" and "MIT Hot-Start" bars are shaded to serve as references. The four blue bars show that ADVISOR's slow warm-up mode gives the most optimistic projection, and the MIT projection adjusted by cold start effects is more pessimistic than all modeling results.

Table 16 lists fuel economy and its gains of these modeling results over the corresponding cold-start baseline vehicles for both H2FCVs and GFCVs, and for both MIT and GM adjusted cases. Since GM also only gives "hot-start" results for all of their FCVs, we have also adjusted GM results for "cold-start" comparison. We have discounted GM and MIT's H2 FCV combined (or SAE proc.) MPG figures by 6%, and gasoline reforming FCVs for 13%, based on Table 13, and compare these results, as given by Table 16. The baseline vehicles for MIT and GM studies are also listed in Table 16.

Figure 5 – Comparing Fuel Economies of MIT Gasoline FCVs

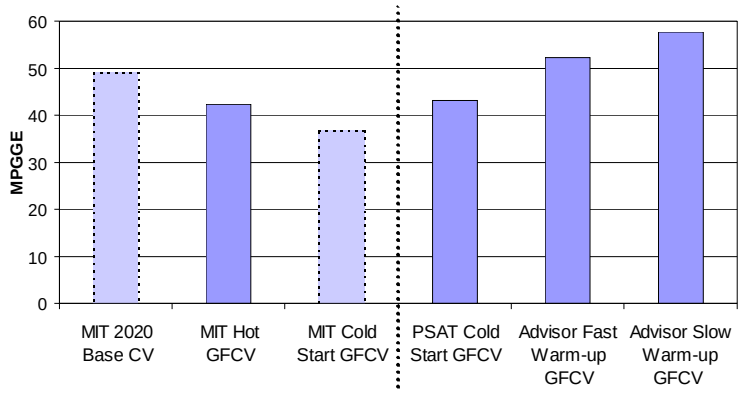


Table 16 - Comparing Fuel Economies of MIT and GM's H2 and Gasoline Reforming FCVs

MPG	*Base-Line CV*	*H2 FCV*	*Gain vs. Base*	*Gas FCV*	*Gain vs. Base*
Original MIT Hot		94.1	92%	42.3	-14%
MIT Cold Start Estimate*	49.1	88.8	81%	37.0	-25%
Warm-up Model Run:					
MIT ADVISOR Fast		71.1	45%	43.0	-12%
MIT ADVISOR Slow		78.1	59%	52.1	6%
MIT PSAT Fast		na	-	57.6	17%
MIT PSAT Slow		95.9	95%	na	-
GM Hot		*48.1*	*138%*	*30.2*	*50%*
GM Cold Start Estimate*	20.2	45.4	125%	27.0	34%

- Not in original study, based on our revisions, na = not available in PSAT model

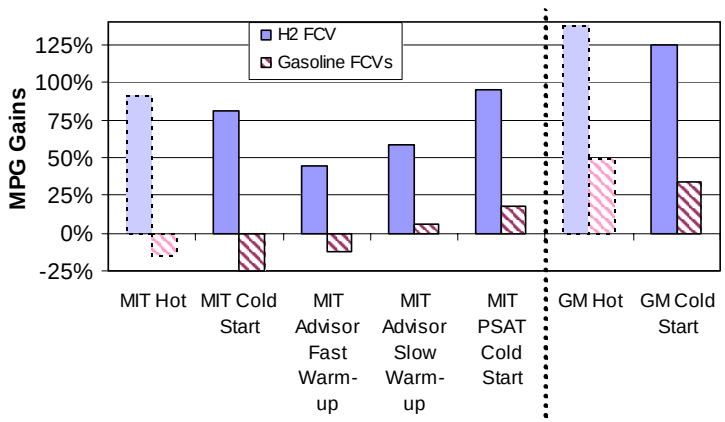
Table 16 indicates that MIT's own study, adjusted for cold-start effects, would project about 80% MPG gain for H2 FCV, and 25% MPG loss for gasoline FCV. Argonne modeling runs predict MPG gains of 45% to 95 % for the MIT H2 FCVs, and from -12% to 17% for the MIT gasoline FCVs. While MIT's projection for H2 FCVs is within the range of our modeling runs, MIT's projection for the GFCV is substantially lower than results of our modeling exercise.

For the GM FCVs, the adjusted MPG gains are 125% for the H2 FCV and 34% for the gasoline FCV. Figure 6 graphically presents these results. The shaded bars are original MIT and GM results. The five blue bars are based on our cold-start adjustment and modeling results.

We stress that the cases constructed will never be exactly comparable. Power as a function of time from

start has not been examined here for these cases. Similarly, we have not generated estimates of cold start effects for conventional vehicles with fast warm-up strategies similar to those assumed in the PSAT and/or ADVISOR models. Ultimately, the vehicles designed will inevitably have different cold start behavior, and consumers will decide on the acceptability of those trade-offs for their purposes.

Figure 6 - Comparing MPG Gains of MIT and GM H2 and Gasoline FCVs by Various Modeling Approaches



CONCLUSIONS

This paper presented a comparative assessment of hydrogen and gasoline reforming hybrid fuel cell vehicles from recent major studies carried out by MIT, GM, DTI and ADL. We identified key issues associated with assessment of fuel cell technology vehicles. Detailed analysis reveals that the most probable estimates from these studies differ greatly on the implied benefits of fuel cell vehicles at the tank-to-wheel level (vehicle-powertrain efficiency and vehicle fuel economy), leading to great uncertainties in estimating well-to-wheel greenhouse gas (GHG) emission reduction potentials.

Having discussed some broader issues addressed in prior related papers, this paper focused on cold-start modeling of both hydrogen and gasoline reforming hybrid fuel cell vehicles. Cold starts play important roles in determining both fuel penalties and start-up time of fuel cell vehicles, but had been ignored by three of the four studies, and had not been included in reference mpg estimates for advanced technology vehicles in any of the studies. Relying on DOE's ADVISOR and PSAT vehicle simulation models, we discussed various methodologies of cold-start modeling, and modeled both H2 and gasoline FCVs based on MIT's vehicle specification. Using this information, we constructed an initial, illustrative estimate of the effect of readjusting the FCV mpg estimates in the reviewed studies to account for cold start energy use (Table 16).

The review of the two vehicle simulation models showed that there can be at least two optional approaches to setting up the warm-up strategy for an FCV - a "slow warm-up" mode, where the FC can be warmed-up based on use of the powertrain's waste heat, and a "fast warm-up" mode, where the FC (and reformer for GFCVs) can be heated-up as quickly as possible. One key observation is that there is a trade-off between the cold-start energy penalty realized and the time to fully warmed up operating conditions. Roughly, the results indicate that the shorter the desired time to fully warmed up conditions, the greater the energy penalty.

The PSAT model indicates that slow warm-up will have the drawback that only a percentage of full power will be available during the warm-up period. The slow warm-up strategy for FCVs was estimated in both the PSAT and ADVISOR models to take many minutes to reach fully warmed up conditions, but to provide the opportunity to have a proportionally smaller cold start energy penalty than for current conventional powertrains. Fast warm up was estimated to cause a percentage energy penalty two to three times larger than for slow warm up strategies of contemporary conventional powertrains as implemented in the FTP. We have not considered the energy penalty effects of warm up of conventional vehicles to operating temperature before departure.

This paper discussed, but did not focus on the percent of peak power available as a function of time from initiation of warm-up. This is an area for further investigation.

Finally, this paper adjusted previously published MIT and GM projections by introducing cold-start effects compared to and derived from ADVISOR and PSAT modeling results. Even though investigation of each modeling approach has identified flaws, the results provide some insight on cold-start energy use penalties. It shows that, after cold-start adjustments, MIT's projection for energy use of H2 FCVs is within the range of our PSAT and ADVISOR modeling runs. However, MIT's projection for the gasoline FCV is substantially lower than results of our PSAT and ADVISOR modeling exercises, as well as the GM prediction.

This paper provides an initial point of reference for those wishing to properly adjust and predict fuel consumption estimates of fuel cell vehicles for cold start and warm up effects. It appears that no single correct adjustment factor exists, since alternative cold start warm-up strategies and powertrain configurations could result in a wide range of (1) vehicle performance capabilities as a function of time from start-up and (2) associated cold start net energy penalties.

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APPENDIX A - COLD START IMPACTS OF CONVENTIONAL ICE VEHICLES

Table A1 lists test results of conventional gasoline ICE vehicles conducted at CE-CERT testing facility at the University of California, Riverside between 1996-1998 [19]. The table presents cold start Bag 1 and warm-start Bag 3 fuel economies (in MPG) for four 4-cyinder, four 6-cylinder and five 8-cylinder vehicles. It shows that the differences between cold-start Bag 1 and warm-start Bag 3 fuel economies range from 12-25% for 4-cylinder vehicles, 12-16% for 6-cylinder vehicles, and 15-25% for 8-cylinder vehicles.

Table A1 – Cold Start Effects of Conventional SI-ICE Vehicles

	MPG			FTP City Drive Cycle		**MPG**	Energy
	Bag 1	Bag 3	diff.	Cold	Warm	**Penalty**	Penalty
4 Cylinders							
MY97 Honda Civic # 319	35.1	39.2	11.6%	33.5	35.2	5.0%	4.8%
MY93 Saturn # 106	32.2	38.1	18.4%	31.3	33.8	7.9%	7.3%
MY93 Corolla #307	28.7	34.3	19.5%	28.3	30.6	8.4%	7.7%
MY96 Altima #156	22.0	27.5	25.3%	22.4	24.9	11.0%	9.9%
average			*18.7%*			***8.1%***	*7.4%*
6 Cylinders							
MY97 Ford Taurus # 080	21.6	25.2	16.4%	21.2	22.7	7.1%	6.7%
MY96 Explorer # 203	19.4	22.2	14.5%	18.9	20.1	6.3%	6.0%
MY95 Caravan #036	20.9	24.2	15.6%	20.6	22.0	6.8%	6.4%
MY97 Malibu #324	22.1	24.8	12.4%	21.1	22.3	5.4%	5.1%
average			*14.7%*			***6.4%***	*6.0%*
8 Cylinders							
MY97 Suburban #330	15.2	17.5	15.0%	15.1	16.1	6.6%	6.2%
MY96 Ram 1500 #272	14.2	16.4	15.7%	14.0	14.9	6.9%	6.5%
MY95 Ford E250 Van #038	10.2	12.7	24.5%	10.8	12.0	11.2%	10.1%
MY95 C1500 SIERRA #318	15.0	17.5	16.6%	14.9	16.0	7.4%	6.9%
MY96 THUNDERBIRD 067	18.3	22.3	22.2%	18.2	19.9	9.6%	8.7%
average			*18.8%*			***8.3%***	*8.0%*

The last four columns of Table A1 give the impacts on the overall FTP city cycle. The cold FTP City Cycle includes Bag 1, Bag 2 and Bag 3 as presented by Equation 1. The warm FTP City Cycle excludes cold start by substituting Bag 1 with Bag 3 results. Thus the full FTP cycle cold start impacts are smaller than the Bag1 vs. Bag3 differences, as demonstrated by the last two columns. Generally speaking, the cold start MPG impacts over the FTP City Cycle average about 8.1% for I-4 engine vehicles, 6.4% for V-6 engine vehicles, and 8.3% for V-8 engine vehicles.

APPENDIX B - ARGONNE FCV MODELING APPROACHES

This section reviews modeling approaches used by ANL to simulate gasoline fuel cell vehicles (GFCVs). Specifically, ADVISOR (NREL, 2002 version) and PSAT (ANL) are evaluated.

Beyond differences between ADVISOR being a "backward" model and PSAT being a "forward" model, the general structure and methodology for modeling hybrid GFCVs are quite similar. In the current versions, both of them do not deal with balance-of-plant modeling issues associated thermal, water, and air management for peripheral sub-systems. Rather, the fuel cell is treated as a unitized system, defined by the system performance curve (system efficiency vs. FC load).

However, there are major differences between these two models regarding cold-start modeling methodology, as summarized by Table B1. One major difference is that for PSAT, for cold and hot fuel cell system efficiency curves are used for cold-start modeling, as shown by Figures B1-a and B1-b. For ADVISOR, only hot efficiency curves are used. PSAT also explicitly models catalyst and reformer light-up times. More detailed explanation of both modeling approach are given in the following sections.

Table B1 – Cold-start Modeling Methodologies of ADVISOR and PSAT

	ADVISOR	*PSAT*
Hybridization	Yes	Yes
Balance-of-plant	No	No
Fuel cell engine	Unit system	Unit system
Hot FC efficiency curve	Yes	Yes
Cold FC Efficiency curve	No	Yes
Cold FC maximum power	No	Yes
FC polarization curve	No	Yes
Cold start	Yes	Yes
Thermal model	Same as IC engine	Based on cold FC map
Cold start options	2	1
Separate reformer module	No	Yes
Reformer catalyst light-up	No	Yes
Reformer light-up time	No	Yes

Figure B1-a. Argonne 50 kW H2 Fuel Cell Efficiency Curve

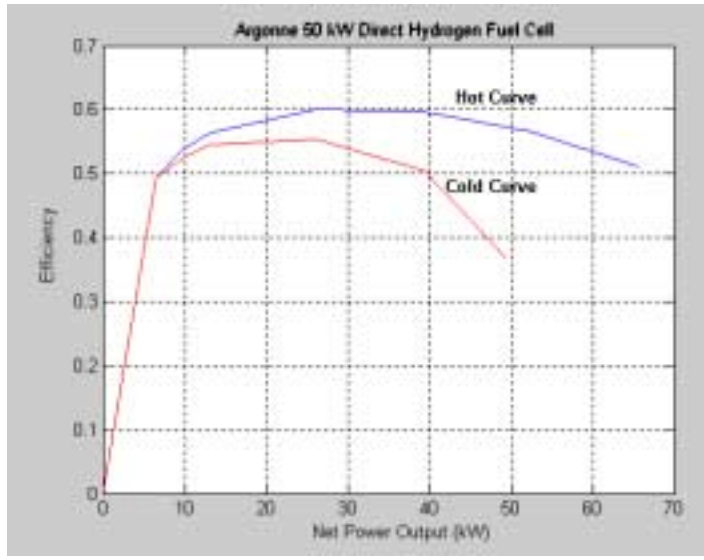
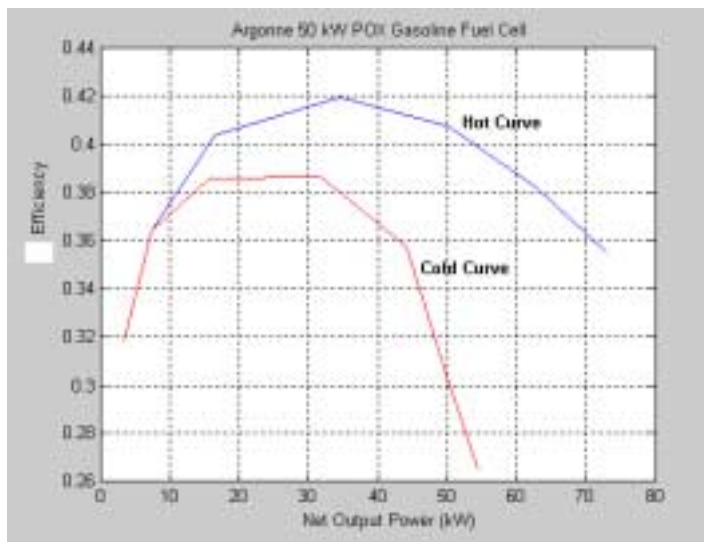


Figure B1-b. Argonne 50 kW POX Gasoline Fuel Cell Efficiency Curve



FCV Cold Start Modeling

<u>ADVISOR Approach</u>

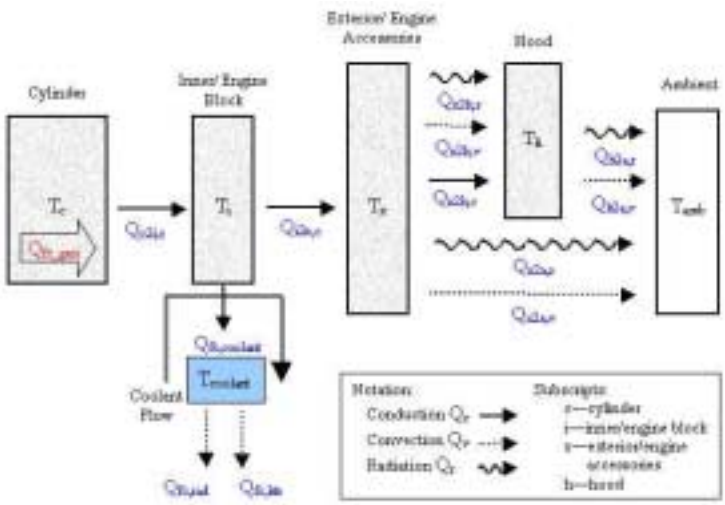
ADVISOR uses an engine thermal model to simulate cold-start effects of fuel cell vehicles.

Engine thermal model

The thermal model of the fuel cell is identical to that of an internal combustion engine, as demonstrated by

Figure B2. It breaks the engine assembly into four temperatures: the cylinder(s), the engine block, the exterior engine accessories, and the hood of the vehicle. The cylinder(s) and engine block serve as surrogates for a fuel cell stack. The coolant submodel simulates temperature levels controlled by a thermostat, with the setpoint (80°C for fuel cell) set by the user. Heat is generated by combustion (or generating electricity for the fuel cell case), conducted to the engine block (or fuel cell stack), and removed through forced liquid cooling, conduction, natural convection, and radiation. The calculations for the individual heat transfer paths are identical to the IC engine, with exactly the same thermal parameters being used. As of the time of completion of this paper, NREL was working with Virginia Tech to redefine the thermal network specifically for the fuel cell system and to update this part of the ADVISOR model.

Figure B2. ADVISOR Cold-start Model



Cold Start Strategies

In ADVISOR, there are two cold-start control strategies: setting parameter fc_fuclecell_warmup_bool equal to 0 or 1 designates them.

If bool is set equal to 0 then the fuel cell will use the normal warm-up approach that looks at the waste heat (based on efficiency) and calculates the coolant and component temperatures based on mass flows and heat transfer coefficients. The system fuel consumption will be scaled based on the coolant temperature. At the thermostat temperature the scale factor is 1, while at ambient temperature the scale factor is approximately 1.1. The input data map is assumed to be steady-state fully warm data. It will take about one FTP City cycle for the fuel cell to reach the thermostat temperature from ambient temp. This cold-start approach can be labeled as “slow warm-up” mode.

Alternatively, if it is set to 1 then the model basically forces the system to warm-up as quickly as possible and limits the power output capability of the system. Thus this mode can be called as “fast warm-up” mode. If the system is cold (<85% of the thermostat temp) and power is requested from the fuel cell, the fuel rate equivalent to full power operation will be requested while the fuel cell is assumed to provide no power output. In the model, all of the fuel energy converts to heat energy and dumped into the stack and coolant to bring the stack to operating temperature as quickly as possible. This is a very idealistic assumption but probably provides a reasonable estimate of one boundary. During this period, batteries will be necessary to satisfy vehicle traction power requirements. Once coolant reaches 85% of thermostat temperature then the system returns to normal operation and will provide the requested power to the motor. The efficiency correction factors as mentioned in the previous paragraph will be applied between 85% and 100% of thermostat temperature. Table B2 summarizes the differences between “fast warm-up” mode and “slow warm-up” mode.

Table B2 – Cold-start Effects of ADVISOR Modeling

When coolant T < 80°C	*Bool = 0 Slow Warm-up*	*Bool = 1 Fast Warm-up*
FC Battery Pack	Turn on Power assist	Turn on to maximum Pure electric power drive
FC warm-up	Gradual with waste heat, slow warm-up	Maximum rate with dedicated heat, rapid warm-up to 80°C
FC power output	Same as hot FC	Zero output to drivetrain, maximum for generating heat
Impact on FC efficiency	Modified by temperature correction equation	Maximum hot fuel use rate modified by temperature correction equation

Another important feature for ADVISOR is that there is no difference in modeling methodology between direct H2 FCVs and gasoline reformer FCVs. The only differences are 1) component masses; and 2) Hot FC system efficiency curves (Figures 1B-a and 1B-b). No cold curves are used, nor are catalyst or reformer light-up times used.

<u>PSAT Approach</u>

PSAT's approach to model FCV cold start is completely different from ADVISOR. It relies on cold and hot FC maps and maximum power output (Figures 1B), and catalyst light up time and reformer warm-up time to feed H2 to the fuel cell stack. As a result, the modeling of direct H2 FCVs is quite different from modeling of gasoline reformer GFCVs. Table B3 summarizes the PSAT cold-start modeling approach. Unlike the ADVISOR thermal model based on block thermal conduction, convection and radiation, PSAT assumes the fuel cell stack warm-up based on cumulative fuel flow and a coolant warm-up time constant *fc_temp_tau_hot*, which is defined as coolant warm-up time if full FC power output is applied from the very beginning to full warm-up. The default value of *fc_temp_tau_hot* equals to 600 sec. for the H2FCV system and 128 sec. for the GFCV system. In addition, there are exogenous default fuel penalties designated to start both reformer catalyst (10g) and reformer itself (93.6 g). On top of this, the maximum available fuel cell power output is a function of coolant temperature, and fuel consumption is scaled between cold and hot FC maps based on coolant temperature as well.

Table B3 – Cold-Start Effects of PSAT Modeling

	H2 FCVs	*Gasoline FCVs*
FC	Immediately on	Maximum on till 30 sec. No power output to drivetrain until after 30 sec.
Catalyst Warm-up	None	20 sec. (default value)
Reformer Warm-up time to feed H2 to fuel cell	None	30 sec. (default value)
Battery	Power assist	Pure electric power drive in first 30 sec.
Warming-up process	Fuel flow required for vehicle movement determines rate of warm up	Accelerated warm-up up to 30 sec, continued with fuel-flow for movement warm up
Fuel Impacts	Mix of hot and cold maps	Fuel penalty of 10 g (default) for catalyst warm-up, 93.6 g (default) reformer warm-up, plus mix of hot and cold maps
FC maximum power	Mix of hot and cold max. available power	Mix of hot and cold max. available power
Max. warm-up rate	600 sec. (10 min.) with full FC power	128 sec. (2+ min.) with full FC power