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Energy utilization and efficiency analysis for hydrogen fuel cell vehicles

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Abstract

This paper presents the results of an energy analysis for load-following versus battery-hybrid direct-hydrogen fuel cell vehicles. The analysis utilizes dynamic fuel cell vehicle simulation tools previously presented [R.M. Moore, K.H. Hauer, J. Cunningham, S. Ramaswamy, A dynamic simulation tool for the battery-hybrid hydrogen fuel cell vehicle, Fuel Cells, submitted for publication; R.M. Moore, K.H. Hauer, D.J. Friedman, J.M. Cunningham, P. Badrinarayanan, S.X. Ramaswamy, A. Eggert, A dynamic simulation tool for hydrogen fuel cell vehicles, J. Power Sources, 141 (2005) 272–285], and evaluates energy utilization and efficiency for standardized drive cycles used in the US, Europe and Japan.

Keywords: Fuel cell vehicle; Simulation; Direct-hydrogen system; Analysis

1. Introduction

The focus of this paper is on the direct-hydrogen fuel cell vehicle (DHFCV). Specifically, it presents the results from a comparison of the energy use for two battery-hybrid DHFCV designs with that of a load-following DHFCV design. This is the third paper of a three paper series on DHFCVs. The first two papers of the series presented dynamic simulation tools developed to realistically analyze battery-hybrid and load-following DHFCVs [1,2].

Hybridizing the DHFCV is generally assumed to be a viable technique for improving the vehicle energy use and efficiency—largely based on the ability to recover and reuse regenerative braking energy. However, there are also negative aspects of hybridization, including additional complexity, additional packaging constraints, and potentially higher cost—especially when the hybrid design is configured for maximum recovery and reuse of regenerative braking energy. Balancing these negative attributes are potential benefits of hybridization, e.g., improvement in start-up performance, improved performance (acceleration), potential efficiency improvements for the fuel cell system operation, and durability and efficiency benefits from operating the fuel cell stack in a less dynamic mode.

This paper presents simulation results, and a detailed quantitative analysis, of energy flows and energy efficiency for the hybrid and load-following DHFCV designs. Vehicle energy use and efficiency is compared amongst the load-following and two battery-hybrid DHFCV designs. Vehicle emissions are not considered here, since no emissions other than water are present. In addition, upstream energy losses and emissions associated with the production, distribution and marketing of hydrogen fuel are not addressed. This is because the use of a common fuel renders this a moot issue for purposes of comparison amongst alternative DHFCV designs.

It should be noted that the battery-hybrid DHFCV designs analyzed here are specifically selected to optimize the recovery and reuse of regenerative braking energy to the maximum extent that is realistically feasible. These battery-hybrid designs have already been presented in terms of their detailed pros

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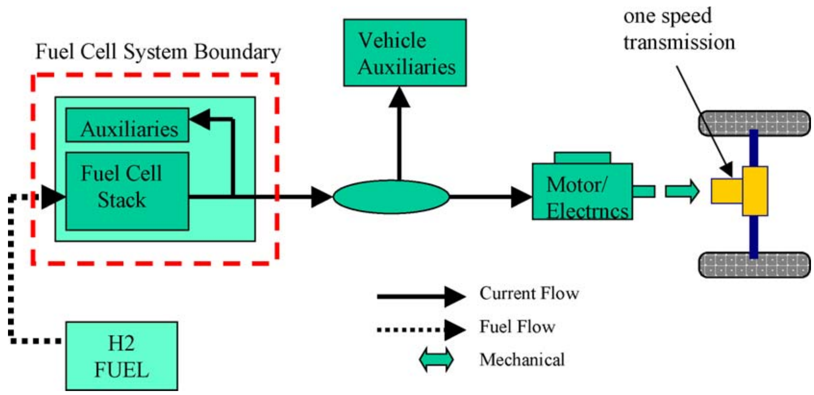

Fig. 1. Configuration of the load-following vehicle (LF).

and cons, as compared to several other battery-hybrid designs, and the details regarding the choice of these two alternatives and the simulation tools developed for their simulation and analysis have been presented in the literature [1,3]. A similarly detailed discussion of the load-following DHFCV design, and the associated simulation tool, is also in the literature [2]. These three designs will only be briefly reviewed here, since the details are available in the literature [1,2]. The alternative DHFCV designs that are compared in this paper are shown in Figs. 1–3.

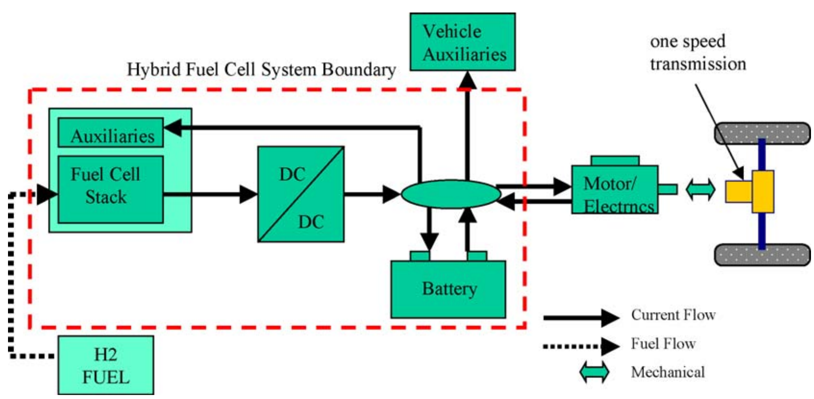

Fig. 2. First configuration for DHFCV battery-hybrid – Config1.

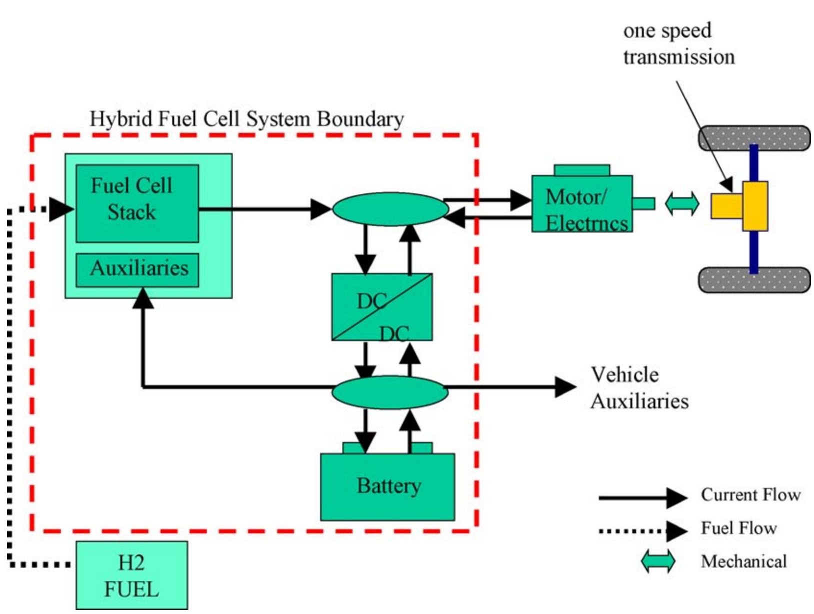

Fig. 3. Second configuration for DHFCV battery-hybrid – Config2.

1.1. Alternative DHFCV designs

The load-following DHFCV design is shown in Fig. 1 with the energy flows illustrated by arrows. Further details of this design, and of the details for the related simulation tool, are presented in [2].

Fig. 2 shows the first battery-hybrid vehicle design to be analyzed, with arrows indicating the direction of electrical power flows. This design is referred to as Config1 (shorthand for configuration 1). The key factor in this design is the placement of the dc–dc converter in the primary energy path between the fuel cell stack and the motor electronics. This design, and the related simulation tool, are presented and discussed in the literature [1].

Fig. 3 shows the general configuration of the second fuel cell battery-hybrid design, designated as "Config2" (shorthand for configuration 2). The key change from Config1 is the placement of the dc–dc converter in the charging path for the battery pack, rather than in the primary energy path between the fuel cell stack and the motor electronics. The arrows show the direction of electrical current flow amongst the major components. A detailed discussion of this design, and the simulation tool, is available in the literature [1].

The next subsection reviews the methodology for this study.

1.2. Methodology

When comparing the load-following and battery-hybrid DHFCVs in this study, care is taken to keep the vehicle parameters identical wherever possible. The only exception is when the hybridization requires that specific parameters or sub-system configurations be modified (e.g., vehicle curb weight incorporates the additional weight of the battery-hybrid fuel cell system, primarily associated with the battery pack and the dc–dc converter).

The load-following and battery-hybrid DHFCVs are designed on an "equal performance" basis. The Partnership for a New Generation of Vehicles[2] (PNGV) defined a set of vehicle targets which are generally followed in this study (the so-called "3X" car). Specifically, in this analysis a subset of the 3X performance parameters are incorporated within the DHFCV design criteria. This subset relates to the acceleration performance of the vehicle and is presented in Table 1. These vehicle acceleration parameters, plus the top speed requirement, constitute the dominant performance criteria used for sizing the system components in the load-following vehicle.

In simulating the vehicles analyzed here, it is necessary to specify values for a number of vehicle parameters. These are the input values that describe either the vehicle or, in certain cases, component properties. The parameters are either single-valued (e.g., the aerodynamic drag coefficient), tables (e.g., battery resistance as a function of the state of charge), or two-dimensional efficiency maps (e.g., motor and transmission efficiency).

[2] The Partnership for a New Generation of Vehicles (PNGV) was an public/private partnership between the US government (seven agencies and 20 federal laboratories) and Chrysler, Ford, and General Motors that aimed to strengthen the United States' competitiveness by developing technologies for a new generation of vehicles.

Table 1
Vehicle acceleration and maximum speed

	Target values	LF[a]	Config2	Config1[b]
0–60 mph (s)	12	12.2	11.9	13.2
Max. speed, min (mph)	85	94	94	94
0–30 mph (s)	Not a target	5.0	4.8	5.0

[a] Load-following.
[b] Results when the vehicle power demand (as seen by the fuel cell stack), is averaged over 20 s.

It is important to remember that the values of these parameters, or the technologies used (with their inherent parameters), are chosen so that the complete vehicle is able to meet the vehicle performance requirements. Therefore, the process of "designing" the vehicle is inherently iterative, and the parameter values for each design are selected through this iteration process.

For example, the vehicle mechanical properties (such as aerodynamic drag coefficient, frontal area, tire diameter, and tire friction) are invariant for all three vehicles (see Appendix B). In contrast, the overall vehicle mass varies, i.e., for the two battery-hybrid designs the NiMH battery pack and the dc–dc converter both add significant mass to the vehicle curb weight.

In addition, some parameters are fixed, such as the aerodynamic drag and the frontal area (these are PNGV "3X car" requirements). Also, various vehicle component parameters are fixed, e.g., the shape and the values of the motor efficiency map, and the transmission efficiency map. In contrast, other vehicle parameters such as the gear ratio and the fuel cell system net output power are the direct result of the design iteration process required to satisfy Table 1. The battery-hybrid vehicles use the same fuel cell stack, auxiliaries, and electric power train as used in the load-following vehicle platform. It is therefore not particularly surprising that the performance of the load-following and hybrid DHFCVs evaluated here are very similar.

The major differences amongst the three DHFCV configurations evaluated in this study occur in the fuel cell system designs. For the battery-hybrids these fuel cell system designs include two additional components, a dc–dc converter and a large battery pack, and an additional controller (described here as the battery controller) to manage these additional components together with the fuel cell stack. These additional components enable regenerative braking to be implemented at the vehicle level and provide for storage and reuse of this regenerative energy.

1.3. SOC correction

For battery-hybrid vehicles, it is important to properly account for the net energy stored in (or extracted from) the energy storage device (battery, ultracapacitor) when evaluating the efficiency of the vehicle over a drive cycle. The central idea behind this exercise is that for long-term performance testing (which is the "proper" metric for evaluating performance) the energy stored in the battery should be irrelevant as far as the miles kWh^{-1} numbers are concerned. Since simulating long-term performance over specific drive cycles would imply very long simulation times (due to "*n*" repeats of the driving cycle), it is easier to correct the miles kWh^{-1} numbers for single cycle runs by an appropriate amount (which if determined correctly would yield a result similar to one obtained after long-term testing).

For batteries if the SOC (state of charge) at the beginning of the cycle and the end of the cycle are equal, then the efficiency numbers do not have to be corrected in any way. Since this is often not the case, the correct efficiency is calculated by taking into account the difference in initial SOC and the final SOC.

The standard methods of evaluating the SOC correction for battery-hybrid vehicles and the SOC correction method adopted in this current study have been presented and discussed in the literature and the reader is referred to this discussion for details [1].

1.4. Organization of paper

The detailed results of this study are now presented in a series of detailed discussions. This includes total energy usage of the vehicles on various drive cycles, as well as detailed analysis of energy usage in the different fuel cell system components, highlighting where energy is consumed. Finally the overall study is discussed and conclusions are presented. The main body of the paper is supplemented with two appendices. Appendix A defines the nomenclature used in the study, and Appendix B presents the vehicle parameters used in the study.

2. Energy analysis overview for Config1 and Config2

This section briefly summarizes the results of the comparison between the energy utilization and energy efficiency of the two battery-hybrid DHFCV designs (Config1 and Config2) and the load-following (LF) DHFCV design. Although it is generally expected that the recovery and reuse of regenerative braking energy will benefit the energy utilization of a DHFCV, it can also be said that, in general, hybridizing a fuel cell vehicle is not expected to show as much of an improvement in fuel economy as is obtained by hybridizing an internal combustion engine vehicle (ICE). This is a result of the net system efficiency relationship versus net power of a fuel cell system, where peak efficiency occurs at a low power levels and is thus efficiently exploited by an LF (load-following) design for typical drive cycles. Again, it is important to emphasize that there may be reasons other than energy utilization to adopt a battery-hybrid design for a DHFCV.

For clarity in presenting the results for Config1 and Config2, each of these battery-hybrid designs are first individually compared to the LF design before discussing the more complex comparison among the three DHFCV options. The metric used in all energy utilization comparisons is "miles kWh^{-1}-LHV (H_2)". [Note that a fully warmed up vehicle achieving a fuel economy of 25 mpg (9.41 L/100 km) would equate to 0.74 miles kWh^{-1}, and a fuel economy of 35 mpg (6.72 L/100 km) would equate to 1.04 miles kWh^{-1} using conventional gasoline.]

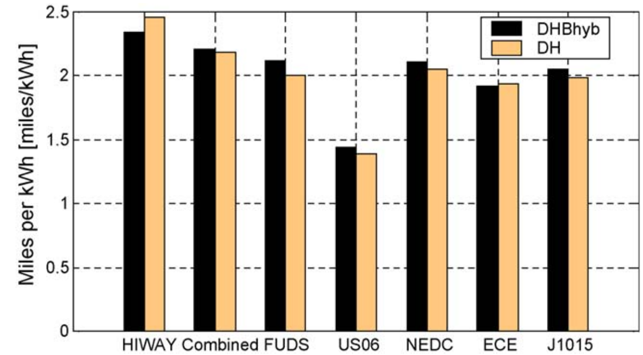

Fig. 4. Vehicle fuel economy for alternative international driving cycles. *Note*: "DH" is load-following and "DHBhyb" is Config1.

2.1. Config1

In comparing the energy utilization of the LF fuel cell vehicle to that of the Config1 battery-hybrid DHFCV, vehicle parameters are kept the same except where the hybridization requires a specific change due to sub-system configurations (e.g.; the Config1 vehicle curb weight incorporates additional weight for the battery hybridized fuel cell sub-system, due to the battery pack and dc–dc converter).

The overall fuel economy results for Config1 are shown in Fig. 4, referencing seven internationally used drive cycles. Note that these results assume the vehicles are fully warmed up before beginning the drive cycle.

Several trends can be observed in Fig. 4. For the US EPA cycles, the load-following vehicle outperformed the Config1 hybrid on the HIWAY sequence (5% lower fuel economy for the hybrid vehicle), but the hybrid had better results on the FUDS cycle (6% larger). The resulting combined cycle results are very similar for both platforms, with the hybrid vehicle showing only a negligible improvement in combined cycle fuel economy.

The numerical values of the miles kWh^{-1} values plotted in Fig. 4 are presented in Table 2, along with the % change versus the LF design.

Examining the percent difference row in Table 2, the LF vehicle outperforms the Config1 hybrid on the HIWAY sequence (5% lower fuel economy for the hybrid vehicle), but the hybrid has better results on the FUDS cycle (6% larger). The resulting combined cycle results are very similar for both platforms, with

Table 2
Vehicle fuel economy (miles kWh^{-1})

Miles kWh^{-1}	HIWAY	Combined	FUDS	US06	NEDC	ECE	J1015
LF	2.46	2.18	2.00	1.39	2.06	1.93	1.99
Config1	2.34	2.21	2.12	1.44	2.11	1.92	2.05
Percentage difference	−4.9	+1.4	+6	+3.6	+2.4	−0.5	+3.0

the hybrid vehicle showing a negligible 1.4% improvement in fuel economy. On the more aggressive US06 cycle, the hybrid showed only a 3.6% improvement in the fuel economy results, a relatively small improvement. In looking at the European and Japanese drive cycles, the advantage of the Config1 hybrid is again either quite minor or even negative (e.g., the ECE cycle). There are four primary factors that combine to produce these results: dc–dc converter loss, vehicle weight effect, fuel cell system efficiency and regenerative braking.

The dc–dc converter loss is the primary negative attribute of the Config1 design vis-à-vis the LF design, when comparing these alternative DHFCV designs solely on the basis of fuel efficiency. The loss due to the dc–dc converter occurs in the primary energy conversion path (the output of the fuel cell stack) and creates a significant deficit vis-à-vis the LF design—where the stack output is applied directly to the electric drive train.

The Config1 battery-hybrid vehicle is 9% heavier than the load-following platform, due to the 130 kg weight of the battery pack plus dc–dc converter. This additional weight has a noticeable negative effect on fuel economy.

In addition, the overall fuel cell system efficiency tends to be lower for the hybrid vehicle, primarily due to losses in the dc–dc converter and battery components. Although not specifically discussed in this paper, this lower fuel cell system efficiency also has a negative effect on fuel economy for the Config1 hybrid platform.

The basic design goal for the hybrid designs evaluated in this study is the recovery and reuse of regenerative braking energy to the maximum extent that is realistically possible.

However, the magnitude of the regenerative braking energy is strongly drive cycle dependent. For example, on the FUDS driving sequence almost twice the energy is recovered at the wheel as is the case for the US06 cycle. It is important to note, however, that this is only the energy recovered at the wheel. In order for this energy to be useful for motive power (and therefore to affect the vehicles energy efficiency) a "round trip" efficiency needs to be accounted for—where the energy passes through the transmission and motor to the battery pack and then back through the same chain to the wheels. This reduces the benefit of regenerative energy recovery and reuse. In addition, the added weight of the hybrid sub-system in Config1, and the inefficiencies associated with the battery pack "round trip" plus dc–dc converter losses combine to significantly diminish the actual benefit of regenerative braking energy reuse.

All of these negative effects are partially balanced by the regenerative braking, which has a very noticeable positive effect on the hybrid vehicle's fuel usage. Therefore, cycles with a large amount of braking (i.e., FUDS) tend to show improvements for the hybrid efficiency versus the load-following DHFCV. However, these individual effects must be realistically simulated in order to reach valid conclusions re-energy usage.

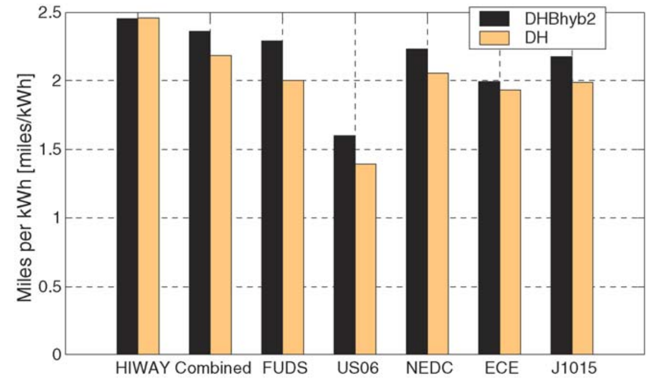

Fig. 5. Vehicle fuel economy for multiple driving cycles. *Note*: "DH" is load-following and "DHBhyb2" is Config2.

The Config1 battery-hybrid simulation tool used in this study includes all of these tradeoffs, in as realistic a fashion as possible [1]. The analysis result for the Config1 DHFCV design is that only for cycles with a relatively high amount of regenerative braking at low to medium power levels (e.g., the FUDS cycle) are there distinct advantages for Config1 over the LF design, in terms of vehicle fuel economy. For the other cycles, advantages may lie in non-quantitative advantages associated with the less stringent dynamic performance requirements placed on the Config1 fuel cell system, but this is not specifically considered in this analysis.

In summary, for the Config1 DHFCV design there does not appear to be any substantive benefit vis-à-vis the LF design in terms of fuel efficiency (although there may be other operational benefits not specifically evaluated in this study).

2.2. *Config2*

Config2 battery-hybrid DHFCV fuel economy results are presented in Fig. 5 for several drive cycles. Both systems are characterized in terms of 'miles kWh^{-1}' (LHV of H_2) for each drive cycle. These results assume the vehicles are fully warmed up before starting the drive cycle.

Numerical values corresponding to Fig. 5 are presented in Table 3.

Looking at Fig. 5 and Table 3, several trends can be observed. On the US EPA cycles, the LF vehicle has approximately the same fuel efficiency as the hybrid on the HIWAY sequence, but the hybrid had better results on the FUDS cycle (14.5% higher 'miles kWh^{-1}'). The resulting combined cycle results showed the hybrid platform outperforming the LF vehicle (higher fuel economy values) with an 8.3% improvement. On the more

Table 3
Vehicle fuel economy

Miles kWh^{-1}	HIWAY	Combined	FUDS	US06	NEDC	ECE	J1015
LH	2.46	2.18	2.00	1.39	2.06	1.93	1.99
Config2	2.46	2.36	2.29	1.60	2.23	1.99	2.18
Percentage difference	0	+8.3	+14.5	+15.1	+8.3	+3.1	+9.5

aggressive US06 cycle, the hybrid showed a 15.1% improvement in the fuel economy results. In looking at the European and Japanese drive cycles, the increases for the hybrid in fuel economy are less, although still improved versus the LF design for each of these driving cycles.

The dominant factor affecting fuel economy improvements on the hybrid vehicle is the regenerative braking. On the FUDS cycle, an urban driving sequence with relatively large amounts of regenerative braking energy available, nearly 50% of the driving energy at the wheel was recovered. Not all of this energy is reusable for driving; however, because of the component energy losses that occur as the energy is transferred from the wheel to the battery pack and returned. Although the energy recovery is not as large on the HIWAY cycle, benefits are still evident for the Config2 design.

2.3. Summary—Config1 versus Config2

The Config2 DHFCV design has improved fuel economy versus the LF design on every drive cycle except for the HIWAY cycle. The cycle with the largest benefits observed was the US06 urban driving cycle with a 15% increase in the 'miles kWh^{-1}' performance. This improvement is primarily a result of the regenerative braking capability, slightly lower fuel cell stack average power, and reduced battery and dc–dc converter energy losses. However, the stack auxiliaries also show improvements in energy usage for Config2. These improvements are due to the lower average operating power levels for the hybridized system. [All of these effects for the Config2 design are discussed in detail in the following sections.]

Comparing these results to those observed with Config1, some differences are notable. The Config1 vehicle only showed a +1.4% improvement in fuel economy compared to the LF vehicle on the combined cycle (+6% on FUDS and −5% on HIWAY). In contrast, the Config2 results show a +8.3% rise above the LF combined cycle results (+14.6% on FUDS and +0% on HIWAY). When the two hybrid platforms are compared directly, the Config2 vehicle showed improved stack average efficiencies, even though it operates in a more dynamic manner. In terms of losses associated with specific components, the battery and dc–dc converter losses are substantially reduced on the Config2 platform, compared to the equivalent component losses for Config1.

Overall, there are three main factors that combine to produce these results, they are: vehicle weight, fuel cell system efficiency, and regeneration capabilities. In the case of this study,

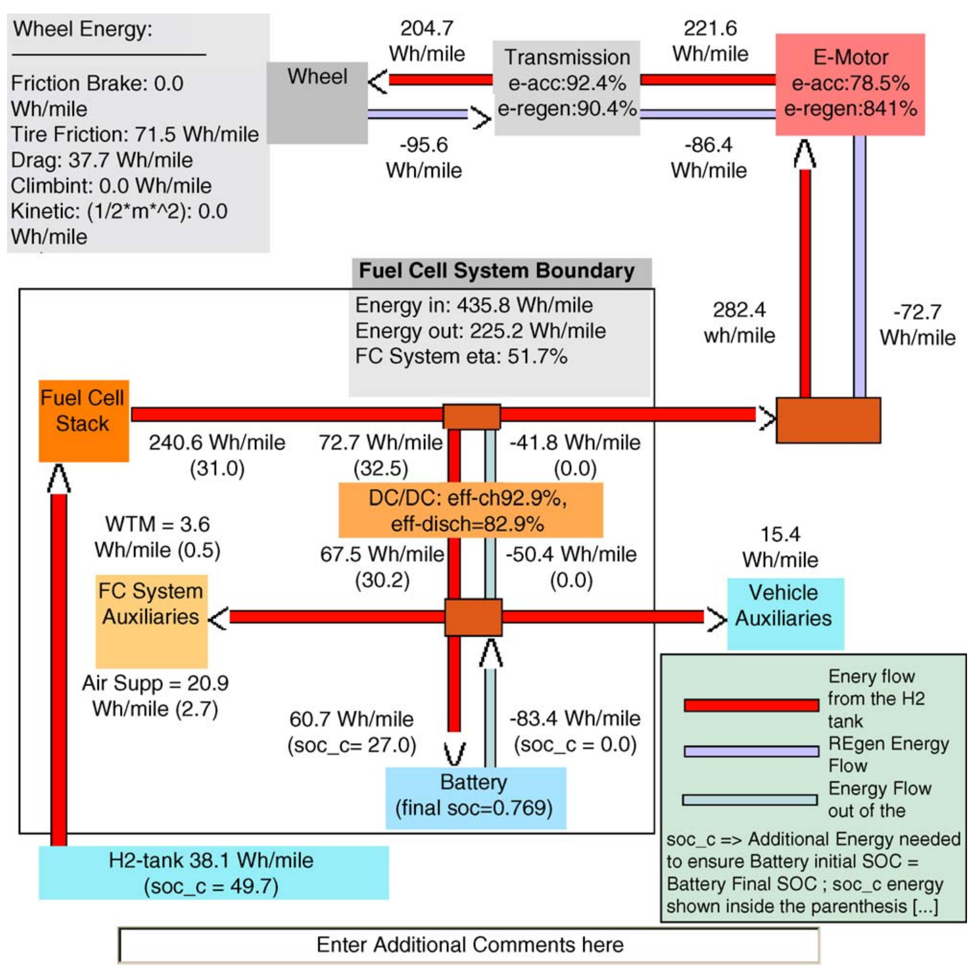

Fig. 6. Energy flow within the Config2 battery-hybrid DHFCV, FUDS. *Note*: total energy associated with each block is sum of drive cycle energy + (soc_correction energy).

the Config2 DHFCV vehicle is 9% heavier than the LF design (130 kg additional mass), negatively affecting overall performance. However, on many of the drive cycles, fuel cell system performance is improved, as will be discussed later in more detail. Specifically, total system losses are reduced for the hybrid vehicle due to more efficient operation of the fuel cell stack (even after accounting for battery and dc–dc converter losses). At the vehicle level, the regenerative braking capability makes a positive impact on the fuel economy of the Config2 hybrid platform.

Because of the very limited improvements in energy efficiency obtained for the Config1 battery-hybrid design, this design is not given any further detailed consideration in this paper. The remaining sections of this paper are focused on a detailed analysis and explanation of the reasons for the substantial energy utilization and energy efficiency improvements associated with the Config2 battery-hybrid DHFCV design (although the Config1 results are introduced where useful for contrast and understanding).

3. Preview of energy analysis results for Config2

As a prelude to the detailed energy analysis for the Config2 design in the following sections, this section focuses on a preview of the energy analysis for the Config2 battery-hybrid design. Fig. 6 shows the integrated energy flow diagram within the Config2 DHFCV for one drive cycle, the FUDS sequence.

From this figure it can be seen that although there is significant energy recovered at the wheel due to regenerative breaking (95.6 Wh mile^{-1} for this case), not all of this recovered wheel energy is ultimately available for reuse by the motor in subsequent accelerations because of the energy losses that occur in the round trip through the transmission, motor, motor electronics, dc–dc converter, and battery.

This diagram emphasizes the complex pattern of net energy flow for a hybrid DHCV during a drive cycle. It should be noted that these energy flow diagrams do not reflect the instantaneous power flows during any specific part of a drive cycle, but instead are the net flows integrated over the entire drive cycle. At any given point in time, the power is flowing in or out of the battery. Also, at different times this power is coming from the regenerative braking and may be flowing to the fuel cell auxiliaries (if the maximum current limits for the battery are met).

Note also that since the final SOC after the FUDS cycle was 0.77 (SOC_ini = 0.8), the apparent vehicle performance numbers at the end of the simulation are corrected to account for this difference in SOC [1]. For example, as shown in this figure, the *corrected fuel energy consumed* over the drive cycle is 386.1 + (49.7) = 435.8 Wh mile^{-1}. It should also be noted that the numbers in the parenthesis (...) in the energy flow diagram are the estimated numbers for the SOC correction. The numbers not enclosed in the parenthesis are the results from the simulation without SOC correction.

Figs. 7 and 8(a) and (b) show the relative breakdown of the vehicle side energy consumptions for two drive cycles (FUDS and HIWAY). One should note that plots (a) in Fig. 8 are drawn

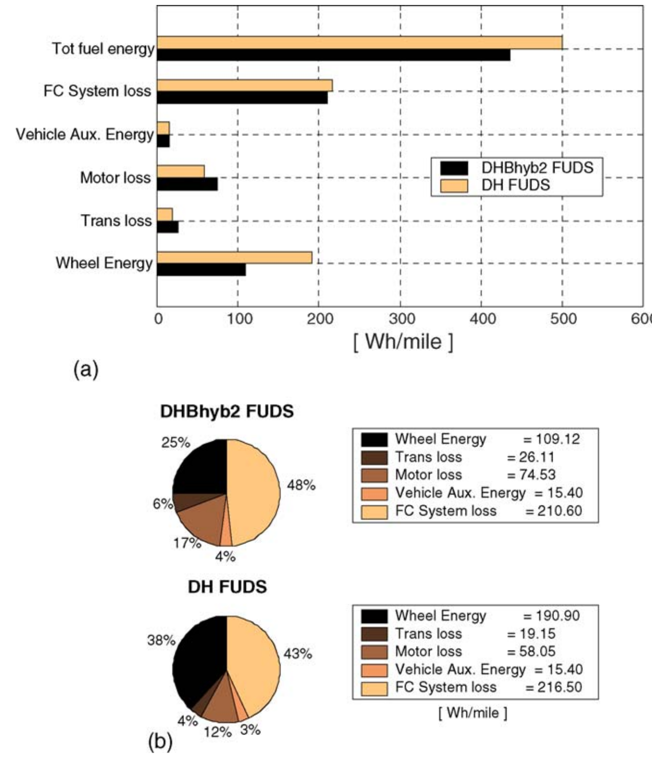

Fig. 7. Fuel cell vehicle energy loss, FUDS. (a) Total fuel usage and primary vehicle energy losses (Wh mile^{-1}), FUDS [DH = LF and DHBhyb2 = Config2] and (b) primary vehicle energy losses (Wh mile^{-1}), FUDS, total fuel usage: Hyb = 435.76; LF = 500.0.

to different scales to better illustrate the details of the vehicle-related losses. These details will be discussed in the sections to follow.

Although a detailed discussion will follow, it is worth briefly noting at this point some of the major effects presented in these figures. Fig. 7(a) and (b) compare the Config2 and LH vehicles on the FUDS urban drive cycle. The FC system loss is the largest factor in the total fuel energy consumed for the Config2 vehicle, accounting for a fraction of between 43 and 48% of the total losses for the two platforms (this is in contrast to over 70% for the Config1 hybrid platform). With the hybrid vehicle, the magnitude of the FC system loss was slightly smaller (discussed later).

Largely due to the reduced wheel energy as a result of regenerative braking, the total fuel energy for the hybrid vehicle was lower by approximately 13%. Looking at Fig. 7(a), the wheel energy parameter for the Config2 hybrid vehicle represents the energy necessary for driving at the wheel minus the regenerative braking energy recovered (also at the wheel). The component energy losses associated with this recovered braking energy, as the energy is transferred from the wheel to the battery pack, are also accounted for in the figure. This can be partly explained with larger motor and transmission loss parameters for the Config2 hybrid vehicle. Additional battery sub-system losses are accounted for in the FC system loss parameter, and will be discussed later.

Fig. 8(a) and (b) provide vehicle results for the HIWAY drive cycle. In this cycle, the trends are noticeably different from those

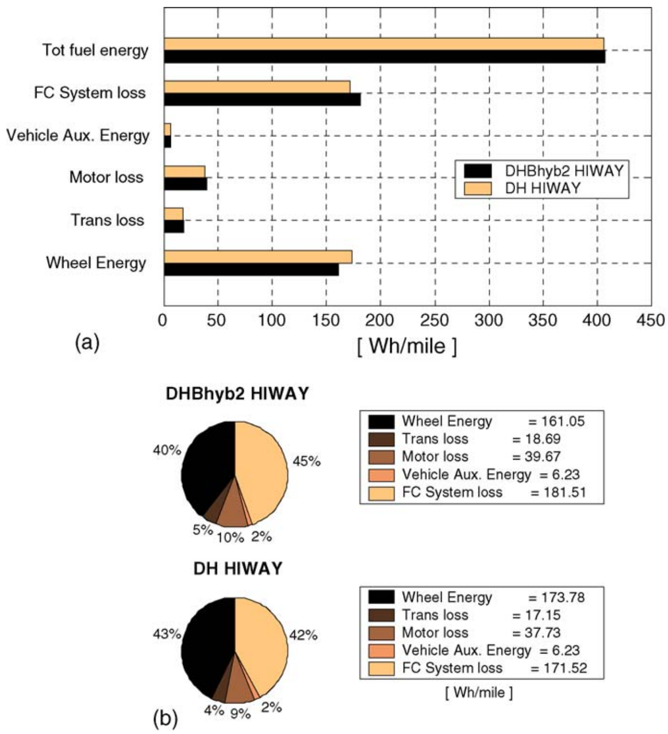

Fig. 8. Fuel cell vehicle energy characteristics, HIWAY. (a) Total fuel usage and primary vehicle energy losses (Wh mile^{-1}), HIWAY and (b) primary vehicle energy losses (Wh mile^{-1}), HIWAY, total fuel usage: Hyb = 407.15; LF = 406.40. *Notes*: the scales for the Wh mile^{-1} in Fig. 7 and this figure are different; the tot fuel energy is the *required* energy for the vehicle over the entire drive cycle; wheel energy = 'wheel driving energy' − 'wheel regen energy'.

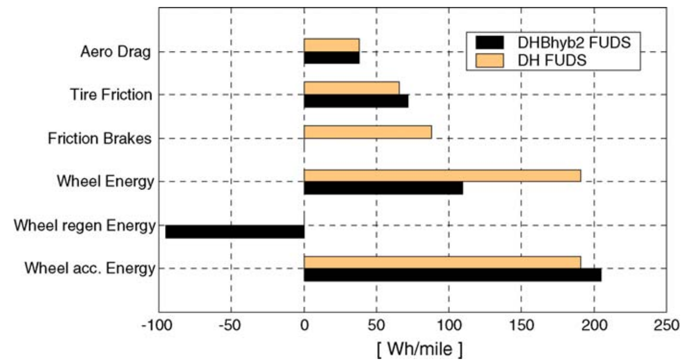

Fig. 9. Energy at the wheel in the FUDs cycle. *Note*: "DHBhyb2" = Config2 and "DH" = LF.

for the FUDS cycle (Fig. 7). First, the difference in wheel energy for the two designs is substantially smaller, largely as a result of reduced regenerative energy recovery. Second, the FC system loss is actually larger in magnitude for the hybrid vehicle compared to that of the LF vehicle. This results in a total fuel energy that is approximately equal for both vehicles. The fraction of the total fuel energy attributed to the FC system loss is about the same on both platforms for this drive cycle compared to the equivalent result for the FUDS cycle. Table 4 below resummarizes the magnitude of the losses shown in the previous figures.

As will be discussed in later sections, the improvement in FC system losses for the Config2 hybrid vehicle (on the FUDS cycle) comes about due to the lower stack losses and substantially reduced battery and DC/DC component losses.

In the following sections the detailed energy characteristics of the vehicle and sub-systems will be analyzed. The objective is to understand the variations in energy use between the Config2 hybrid and the LF vehicles and the corresponding differences in fuel economy. The investigation starts at the vehicle side, with the comparison of the energy losses at the wheel and the drive train. Following this, the energy use and losses in the fuel cell system are discussed. For brevity purposes, only three of the drive cycles are considered in this next section. These are the FUDs, the highway, and the US06 cycles. [Refer to Fig. 5 for the overall energy consumption of the Config2 and load-following DHFCVs on the seven different drive cycles that were used in this overall analysis.]

4. Vehicle level energy analysis

This section focuses on the vehicle level energy analysis of the Config2 battery-hybrid DHFCV design. First the "wheel energy" usage is examined (i.e., energy at the tire, friction brake energy, and wheel energy recovered from regenerative braking) and then the "drive train losses" are detailed (i.e., the energy lost between the motor electric terminals and the motor mechanical shaft).

4.1. Wheel energy

This section will focus on the energy usage at the wheels. This includes the energy at the tire, friction brake energy, and wheel energy recovered from regenerative braking. Figs. 9 and 10 show these energy characteristics for two drive cycles.

Table 4
Vehicle energy losses[a]

	FC system loss (Wh mile^{-1})	Wheel energy (Wh mile^{-1})	Trans loss (Wh mile^{-1})	Motor loss (Wh mile^{-1})	Vehicle Aux (Wh mile^{-1})	Delta SOC energy (Wh mile^{-1})
Config2 on FUDS	210.6	109.1	26.1	74.5	15.4	4.3
LF on FUDS	216.5	190.9	19.2	58.1	15.4	0
Config2 on HIWAY	181.5	161.1	18.7	39.7	6.2	2.2
LF on HIWAY	171.5	173.8	17.2	37.7	6.2	0

Note: delta SOC energy not shown in Fig. 8.
[a] Shown in Fig. 8.

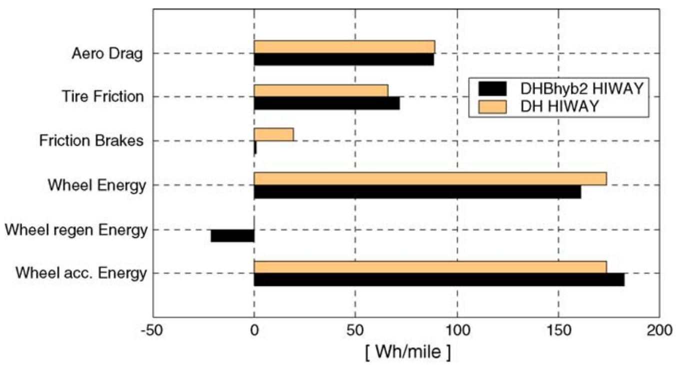

Fig. 10. Energy at the wheel, HIWAY cycle. *Note*: "DHBhyb2" = Config2 and "DH" = LF.

Fig. 9 shows the results for the FUDS cycle. Both vehicles have the same aerodynamic drag energy loss given the same vehicle design. The tire friction energy loss is slightly larger for the hybrid platform given the heavier vehicle. For the same reason, the total energy required for driving at the wheel is similar, but not the same, for both vehicles (larger vehicle mass for the hybrid platform).

The most important metric to extract from Fig. 9 is the net wheel energy (also shown in Fig. 8). The primary difference in the wheel energy use between the Config2 and LF platforms arises from the Config2 vehicle's ability to capture regenerative braking. For Config2 on this drive cycle, nearly all of the braking requirements were met with this capability (though a small amount of non-zero friction braking does exist). As a result, 47% of the wheel driving energy is recovered. It is difficult to decipher from the results how much of this energy returns to the wheel for future driving demands. However, the "return trip" energy losses are accounted for in the form of higher component losses (discussed below).

Fig. 10 shows the same trends for the US HIWAY driving cycle. Here, there is a substantially reduced braking requirement compared to the FUDS cycle in the previous figure (almost a quarter of the FUDS requirement). As a result, the regenerative braking energy is noticeably lower resulting in only a small improvement in the wheel energy demand for the hybrid vehicle compared to that of the load-following platform. The slightly higher wheel driving energy and tire friction for both the FUDS and HIWAY cycles can largely be attributed to the heavier vehicle for the hybrid platform.

Fig. 11 graphically depicts the flow of regenerative braking energy for the Config2 vehicle as it undergoes the round trip from the wheel to the battery pack and then back to the wheel to provide traction power.

Table 5
Transmission and motor energy losses, FUDS and HIWAY cycles

($Wh\,mile^{-1}$)	LF FUDS	Config2 FUDS	LF HIWAY	Config2 HIWAY
Trans acc loss	19.15	16.9	17.15	16.2
Trans regen loss	–	9.2 (35.2%)	–	2.5 (13.4%)
Trans total	19.15	26.1	17.15	18.7
Motor acc loss	58.06	60.8	37.73	36.4
Motor regen loss	–	13.7 (18.4%)	–	3.3 (8.3%)
Motor total	58.06	74.5	37.73	39.7

4.2. Drive train losses

Table 5 summarizes the transmission and electric motor losses associated with two driving cycles. The motor loss is defined as the energy lost (not transferred) between the motor electric terminals and the motor mechanical shaft. The transmission loss is the energy lost between the motor shaft and the wheel shaft.

On both drive cycles, the driving energy loss (energy lost during normal drive mode) for both the transmission and the electric motor was similar. In the case of the motor specifically, the hybrid vehicle had slightly higher driving energy losses. However, once regen braking is considered, adding additional energy transferred in the reverse direction, both the transmission and motor losses increase for the hybrid platform. The significance of this is that some of the total energy captured during regenerative braking is lost as it is transferred from the wheel to the electrical bus and battery.

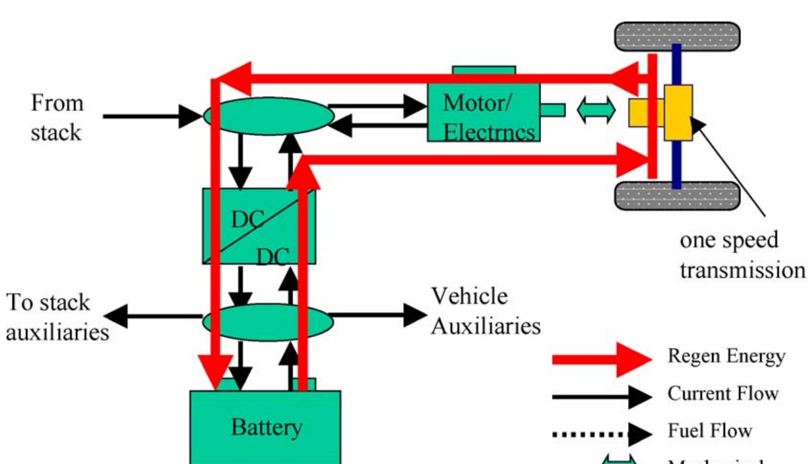

Fig. 11. Regenerative braking energy flow.

It can be seen that the hybrid vehicle transmission driving losses were, surprisingly, somewhat lower than the load-following case. This was due to differences in the response of the vehicles to the drive cycle differences that are within limits, but can still effect some intermediate energy consumption results.

4.2.1. Vehicle efficiency

Vehicle efficiency is defined as:

$$\text{vehicle efficiency} = \frac{\text{acceleration energy}}{\text{fuel energy consumed}} \times 100$$

where

driving energy

= climbing energy

+ energy needed to overcome aerodynamic drag

+ energy needed to overcome tire rolling resistance

+ kinetic energy remaining after drive cycle

and

fuel energy consumed = fuel LHV energy content.

This efficiency definition applies for both the load-following and hybrid cases since regenerative braking for the load-following vehicle is zero, and for the hybrid vehicle the regenerative braking energy is implicitly accounted for as a reduction in the fuel energy.

Due to the presence of the on-board energy storage system in the hybrid case, it is important to note that we do account for the change in state of charge (SOC) of the battery during the drive cycle. The total fuel energy consumed during the drive cycle is corrected by adding in an amount equal to the energy required to bring the battery SOC back to its initial level. All the energy and efficiency numbers reported in this paper have been corrected to account for the SOC difference (unless otherwise noted).

Fig. 12 displays the results for the efficiencies of the Config2 and LF designs. This is basically the same vehicle performance information as shown in Fig. 5, but in terms of the overall vehicle efficiency instead of the miles kWh^{-1} metric.

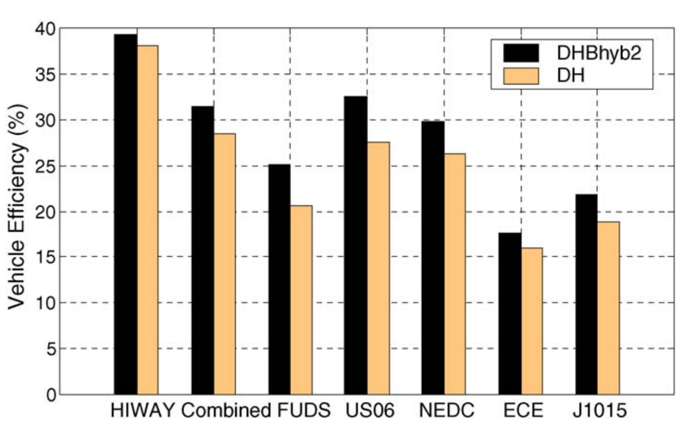

Fig. 12. Vehicle energy efficiency for several drive cycles. *Note*: "DHB-hyb2" = Config2 and "DH" = LF.

Table 6
Vehicle efficiency (%)

	LF	Config2	Config1
HIWAY	38.0	39.4	37.6
Combined	28.5	31.5	29.3
FUDS	20.7	25.0	23.1
US06	27.5	32.6	29.4
NEDC	26.3	29.9	28.3
ECE	16.0	17.7	17.1
J1015	18.8	21.9	20.6

The trends in Fig. 12 show that the Config2 hybrid vehicle has superior overall vehicle efficiency on every drive cycle tested (in contrast to the results for the Config1 vehicle, where the HIWAY cycle results were lower than the LF case). This simply means that, with Config2, for every unit of fuel energy consumed from the fuel tank a larger portion of that energy reaches the wheels, compared to the LF design (i.e., each unit of fuel energy is used more efficiently by the Config2 design). Note that this does not imply that less fuel will be used per mile; this aspect of vehicle performance is properly measured by the miles kWh^{-1} metric. For example, as a result of the heavier vehicle for the hybrid platforms, slightly more energy is required on all drive cycles for the hybrid designs. Given that the hybrid total vehicle efficiency is only slightly larger for the HIWAY cycle, for example, this results in nearly the same fuel usage overall for the Config2 and LF vehicles on that drive cycle.

Table 6 summarizes the values of the calculated vehicle efficiencies for all three DHFCV designs (LF, Config1 and Config2).

The improvements in the hybrid vehicle efficiency results, compared to the LF vehicle, are essentially due to the capture of regenerative braking energy. Drive cycles such as the FUDS and US06 that tend to have more braking (relative to other cycles) show a larger improvement in the vehicle efficiency for the hybrid results.

4.3. Vehicle range

The vehicle range depends on the fuel tank size and the specific energy consumption of each vehicle. In this study, a 37 L compressed hydrogen tank (5000 psi) is assumed. This tank size allows the LF design to travel nearly 300 miles. The assumed fuel mass carried, tank volume and tank weight are stated in Table 7, along with the resulting range (based on the simulated combined cycle fuel economy). In this context, the *combined*

Table 7
Fuel tank characteristics

	DH	Config2	Config1
Fuel economy, combined cycle (miles kWh^{-1})	2.18	2.36	2.21
Range (miles)	300	325	304
Fuel mass carried (kg)	4.13	4.13	4.13
Volume (L)	180	180	180
Tank weight, empty (kg)	64.7	64.7	64.7
Tank weight, full (kg)	68.8	68.8	68.8

cycle is the EPA certification test that takes the FUDS (without the warm-up period) and the HIWAY driving cycles into account using the 55/45 averaging split.

Since the hybrid vehicles have the same fuel tank as the load-following vehicle, the only factor affecting the vehicle range is the miles kWh^{-1} metric for the different vehicle designs. For the Config2 hybrid configuration the combined cycle fuel economy results are improved over that of the load-following vehicle by approximately 8.3%, therefore, the range is increased the same percentage.

5. Fuel cell system efficiency analysis

Before summarizing the results of the fuel cell system efficiency analysis, it is worth reviewing briefly the design and operational strategy of the Config2 battery-hybrid and the load-following fuel cell systems. In Fig. 13(a) and (b) respectively, the fuel cell systems for the load-following and Config2 battery-hybrid are delineated with a dashed box boundary.

For the load-following vehicle, the fuel cell system is simply the fuel cell stack plus the associated auxiliaries. The net output electrical power is provided directly to the motor electronics for the vehicle drive. In the Config2 case, however, the fuel cell system now includes the battery pack and a power-conditioning device (dc–dc power converter). In both vehicles, the common attribute is that the system connects to the motor electronics.

In addition to required modifications in vehicle and system controls for the Config2 DHFCV, the hybrid vehicle fuel cell systems include two distinctly new components compared to the load-following vehicle: (1) a relatively large battery pack and (2) a dc–dc converter. The battery pack energy storage and peak power capabilities are chosen (through a design exercise using iterative simulations) to provide both a significant battery-only driving range (energy plus peak power) and the peak power acceptance requirements for regenerative braking energy recovery and reuse, respectively. In general, regenerative braking energy capture is maximized with a high energy storage and peak power battery pack, but an excessively large battery pack causes efficiency losses because of the added vehicle weight.

In contrast to the load-following DHFCV fuel cell system (where the auxiliary power requirements are met directly by the stack output power), in the Config2 battery-hybrid the energy

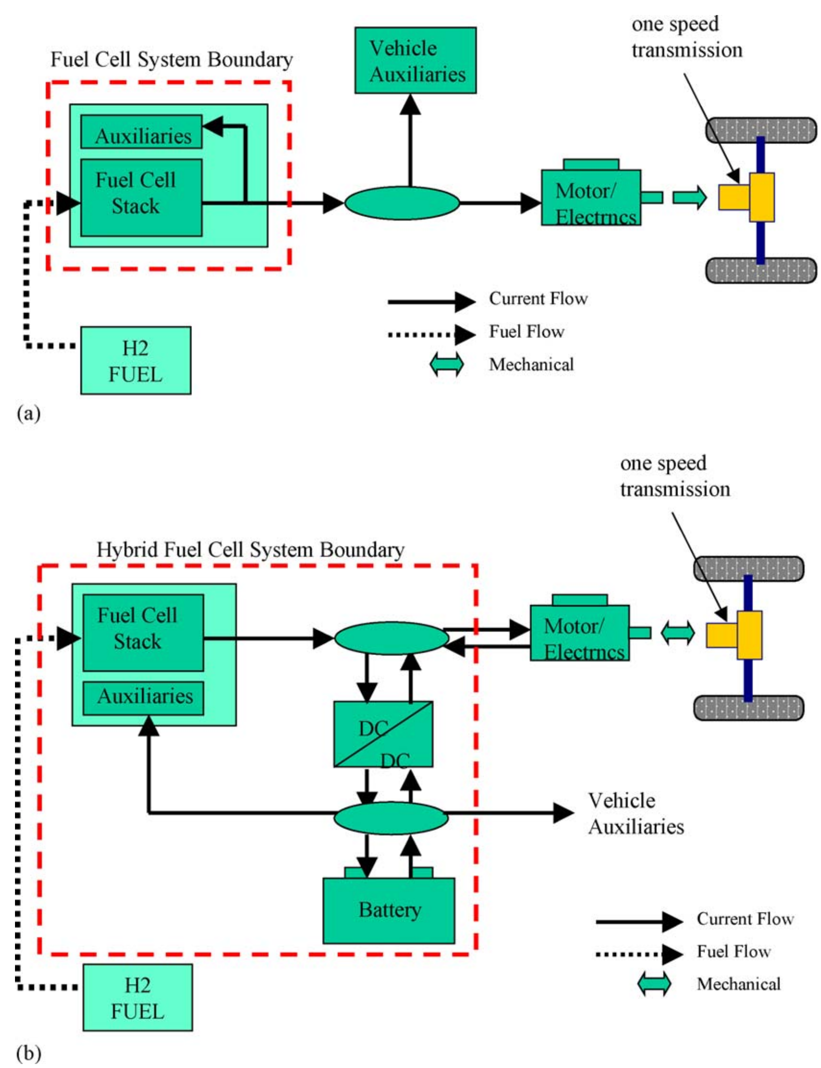

Fig. 13. Fuel cell systems for load-following and CONFIG2 DHFCVs. (a) Load-following vehicle and (b) Config2 battery-hybrid DHFCV.

for the fuel cell auxiliaries goes through a dc–dc converter (and possibly a round trip through the battery pack). Consequently there is an added energy loss in this component, compared to the load-following case.

On the upside for Config2, during dynamic operation the decoupling of the fuel cell system auxiliary power requirements from the stack (auxiliary power demands are met by the battery, not directly by the fuel cell stack) offers potential efficiency advantages that can be exploited through the use of an appropriate control strategy. For example, for Config2 the energy needed by the auxiliaries for high-power operation can be produced and stored in the battery during low stack power demand (hence high stack efficiency). This decreases the overall stack losses during a drive cycle (compared to a load-following case).

In contrast, for the load-following system the auxiliary current demand (supplied directly from the stack) increases the instantaneous stack current and forces the stack into a higher power (lower efficiency) region during high-power demand conditions. As noted above, in the Config2 case the current required for these auxiliaries originates from the battery, and this diminishes the resulting increase in stack current under these conditions (with a corresponding increase in instantaneous stack efficiency), compared to the load-following stack current.

5.1. Steady-state effects

When comparing fuel cell system operation and system efficiency between the load-following and Config2 battery-hybrid vehicle platforms, dynamic behavior (rapidly changing power demands) causes the major differences in system operation. However, before specifically addressing dynamic operation, it is useful to set the stage in terms of steady-state operation of the load-following fuel cell system. A steady-state fuel cell system analysis has been previously performed for the load-following DHFCV [2]. The results are presented in Fig. 14, which shows the steady-state efficiencies for the stack (“stack”) vis-à-vis the system, where the auxiliary parasitic loads are included (“net”).

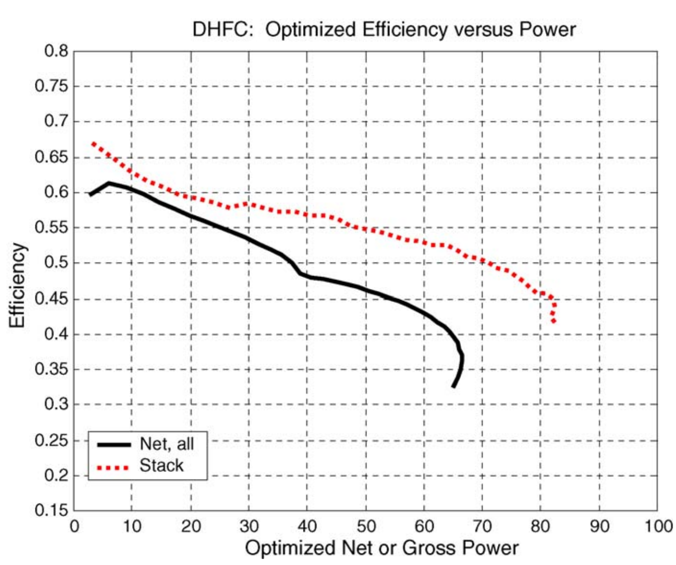

Fig. 14. Steady-state efficiency for the fuel cell system.

Several trends are important to note. First, the difference between the stack and net efficiency becomes larger at higher power loads, because of rapidly increasing power demand from the auxiliaries (particularly from the air supply system). Second, at low power the net efficiency also sharply decreases compared to the stack values. This occurs because the air compressor idle power (based on minimum compressor speed) is quite large relative to the very low stack power output. Third, the system peak power capability is significantly less than the stack peak power (83 kW) because of the auxiliary parasitic loads (a reduction of 15 kW in this example).

5.2. Dynamic effects

When the load-following and Config2 DHFCVs are simulated over dynamic driving cycles, the fuel cell stacks are subjected to quite significantly different dynamic demands. One measure of this difference is the values for the peak stack power, the average stack power, and the average stack efficiency over the drive cycle. Table 8 shows these three stack parameters for comparison purposes, based on results from three primary US driving cycles (FUDS, HIWAY, US06).

The first column shows the peak stack power draw over the drive cycles. This parameter provides an indication of the “dynamic range” of the power demand placed on the stack. For all three drive cycles, the peak power required was noticeably reduced for the Config2 hybrid platform (35% for the US06 cycle and 17% for the FUDS). This reduction in peak stack power occurs for two reasons: (1) battery power is available to supplement the drive motor current demand in the hybrid platform and (2) the auxiliaries are powered directly by the battery thereby reducing the direct stack load. Even after noting that these peak points are not required very often, the average stack power requirements were reduced by approximately 20% for all three drive cycles shown in Table 8.

For the resulting stack efficiency over the drive cycle, the average numbers are shown in the far right column of Table 8. For the FUDS and HIWAY cycles, the average efficiency was very similar for both platforms. On the US06 cycle, not surprisingly, the average efficiency improved for the hybrid vehicle.

Figs. 15 and 16 show the dynamic behavior of the fuel cell stack within each of the DHFCV designs when the Config2 and LF vehicles are operated over the FUDS drive cycle. Note that

Table 8
Fuel cell system dynamic characteristics

	Peak stack power (kW)	Ave stack power (kW)	Ave stack eff (%)
Config2 – FUDS	44.7	4.7	62.3
LF – FUDS	53.7	6.0	62.0
Config2 – HIWAY	32.3	9.8	61.8
LF – HIWAY	36.5	12.0	61.1
Config2 – US06	55.4	14.9	58.2
LF – US06	84.0	19.3	56.2

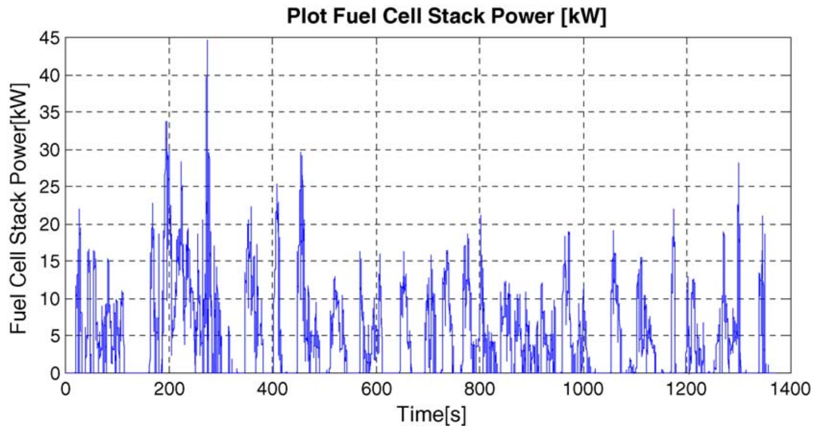

Fig. 15. Config2 stack gross power, kW (FUDS).

the vertical scales of these two figures are not the same. The scales were chosen to show the full dynamic range for each design, and the dynamic range of power demand is significantly lower for Config2 versus the LF design.

Looking at these two figures, the dynamic behavior of the fuel cell stack on both vehicle platforms is very similar. That is, the frequency of the changing power demand does not seem to be significantly different.

The primary trend to observe, as noted above, is the magnitude of the dynamic power range demanded from the stacks. For the Config2 design, the peak power demands are buffered by the use of the battery pack, reducing the peak power requirements of the fuel cell stack (to ∼45 kW for this example) compared to the LF (∼54 kW peak power demand). Additionally, note that for the hybrid the stack power drops to zero during vehicle idle conditions. This is possible because that the battery supplies the electrical current needs of the stack auxiliaries and vehicle auxiliaries, which can therefore be kept in a non-zero-power idle operating mode even if the stack is at zero power. However, as a practical matter, the control scheme would probably operate the stack at a at a low power rating. We expect our simulated control scheme to have a broader impact rather than just impacting efficiency.

6. Detailed loss analysis for the fuel cell system

This section focuses on the results from the detailed energy loss and flow analysis of the Config2 battery-hybrid fuel cell system vis-à-vis the LF (load-following) fuel cell system. In addition to the system level analysis, the results for the fuel cell system components (i.e., the battery pack and fuel cell stack) are also presented.

Net fuel cell system efficiency is defined below. It is important to note that significantly different physical and operational characteristics exist between the load-following and hybrid fuel cell systems. For example, net power of the fuel cell system for the load-following case accounts for the fuel cell stack, plus auxiliaries. However, in the hybrid case the net power now accounts for these losses plus the dc–dc converter and the battery pack. Though the detailed component structure within the systems is different, the net efficiency is still defined as the net energy supplied to the vehicle drive

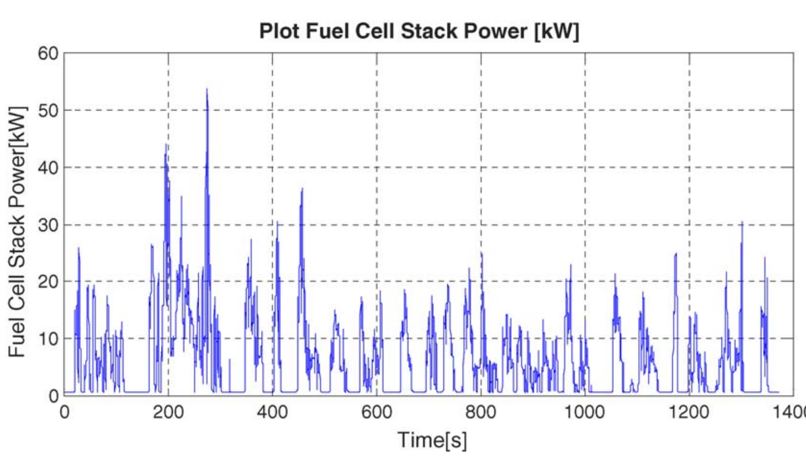

Fig. 16. LF stack gross power, kW (FUDS).

motor and vehicle auxiliaries, divided by the total fuel energy consumed.

$$\begin{aligned}\text{net electric energy} &= \text{driving energy to motor electronics}\\ &\quad -\text{regenerative energy recovered at the motor electronics}\\ &\quad +\text{energy consumed by the vehicle auxiliaries}\end{aligned}$$

$$\text{net efficiency} = \frac{\text{net electric energy}}{(\text{LHV}_{\text{H}_2})(\text{mass of hybrogenfuel consumed})}$$

In order to better understand the reasons behind the losses in the fuel cell systems for the load-following versus the Config1 and Config2 battery-hybrid DHFCVs, it is useful to look at the breakdown of the system losses in the three systems. This breakdown is shown in Fig. 17(a) and (b), in alternative formats.

For the FUDS cycle, the Config2 fuel cell system losses are lower overall compared to the LF case. The air compressor and WTM (water and thermal management) losses are slightly larger for the Config2 case but the differences are relatively minor. The real differences in the Config2 fuel cell system losses occur because of the dc–dc and battery pack losses—which are absent in the load-following system. However, the reduction in stack losses (compared to the load-following case) more than compensates for these additional component losses experienced for the Config2 design. The reason for the lower stack losses (and the higher compressor losses) will be discussed later, but they essentially occur because of the lower average power demanded of the stack. Additionally, the total demanded stack current (cumulative over the FUDS drive cycle) is lower for the Config2 hybrid platform, partly as a result of the energy recovered from regenerative braking and stored in the battery pack for use meeting subsequent drive motor power demands. Overall, the total fuel cell system loss was 2.8% less for Config2.

Comparing the two hybrid platforms on the FUDS cycle, the Config2 total systems losses are substantially reduced compared to the Config1 hybrid platform. The fuel cell system loss was 12% lower for the Config2 case. This is largely attributed to the reduced battery and dc–dc converter losses. The dc–dc converter loss is lower in Config2 because less overall current flows through the dc–dc converter (compared to Config1), since the stack current passes directly to the drive motor upon demand. The battery losses are lower in Config2 because less total energy is demanded of the battery pack during driving (this is largely due to the control algorithms used for Config2.

Slightly different trends are observed in Fig. 18(a) and (b), which shows the energy losses and loss breakdown for the HIWAY cycle.

The lower power demands of this cycle result in smaller differences between the load-following and Config2 loss numbers. On this drive cycle, the total system loss was only 6% larger for the hybrid vehicle.

As noted earlier, some of the component losses shown in these figures include energy lost as the regenerative braking energy is transferred from the wheels to the battery pack, and subsequently returned to the wheels for driving. In the case of Figs. 17 and 18, the battery and dc–dc converter losses account for inefficiencies of these energy flows.

Losses in the battery pack are due to the internal I^2R losses occurring both during charge and discharge periods (higher currents result in greater losses in the battery). Figs. 17 and 18 present the battery losses on the FUDS and HIWAY drive cycles, respectively. The results indicate that although the battery is useful for taking up the energy during regeneration, this comes at a price in terms of I^2R battery losses during both charge and discharge. Note that there is a net energy drain on the battery for both of the drive cycles in these figures. There is battery charge and discharge during the cycle, but most of the charging energy came from the regenerative braking energy recovery rather than from primary energy generated by the fuel cell stack from the hydrogen fuel. As a result, even though there is a net energy drain on the battery, the lower SOC limit of 0.7 is not reached during these test cycles.

For further clarification of this point, the battery pack SOC variation for the US06 cycle is presented in Fig. 19.

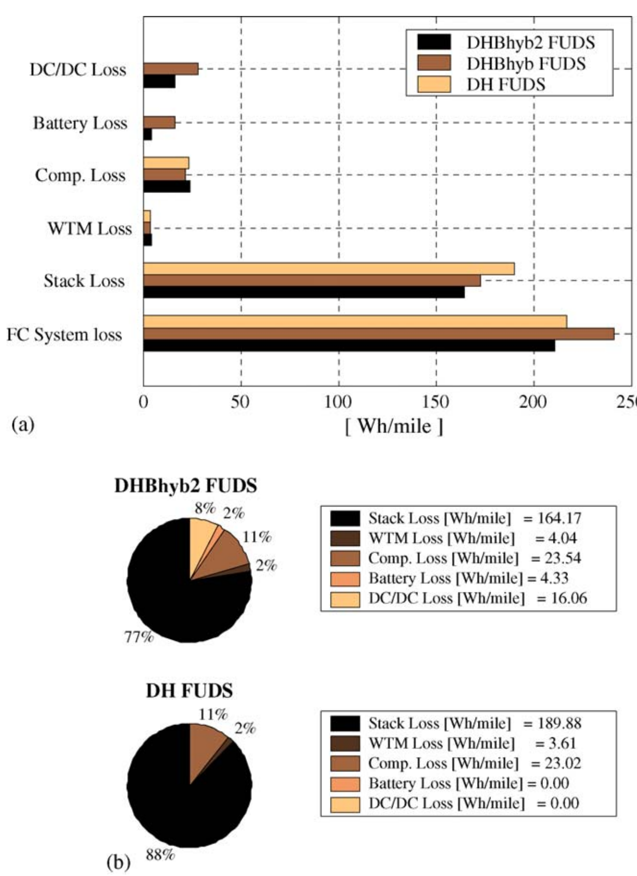

Fig. 17. Fuel cell system energy loss (Wh mile^{-1}), FUDS. (a) Total FC system energy loss. *Note*: DHBhyb = Config1, DHBhyb2 = Config2 and DH = LF. (b) Breakdown of FC system energy loss (Wh mile^{-1}), FUDS. *Note*: DHBhyb2 = Config2 and DH = LF.

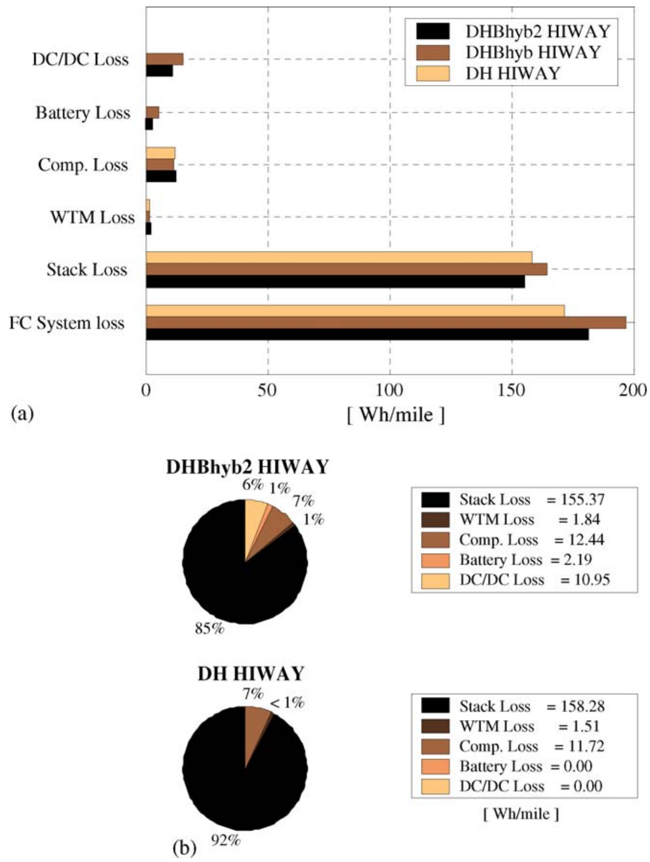

Fig. 18. Total fuel cell system energy loss (Wh mile^{-1}), HIWAY. (a) Total FC system energy loss. *Note*: DHBhyb = Config1, DHBhyb2 = Config2 and DH = LF. (b) Breakdown of FC system energy loss (Wh mile^{-1}), HIWAY. *Note*: DHBhyb2 = Config2 and DH = LF.

The US06 cycle is appropriate for evaluating battery stress because it is the most demanding of the US EPA driving cycles in terms of drive train power demand. It should be noted that the lower SOC limit of 0.7 is not reached for any of the cycles investigated (including FUDS, HIWAY, ECE, J1015, EUDC) when the initial battery SOC was set to 0.8, even for this very demanding US06 cycle. This is as a result of the specific control scheme used for the fuel cell system and battery pack control for the Config2 hybrid vehicle [1].

Note that the energy and loss numbers reported here do compensate for the energy stored or taken out of the energy storage system. This SOC correction is necessary in order to account for the energy supplied from the battery. In the absence of this correction, the resulting numbers will paint an incorrect and overly optimistic picture of the overall fuel efficiency. The method adopted in this study to make this correction is described in detail in the literature [1].

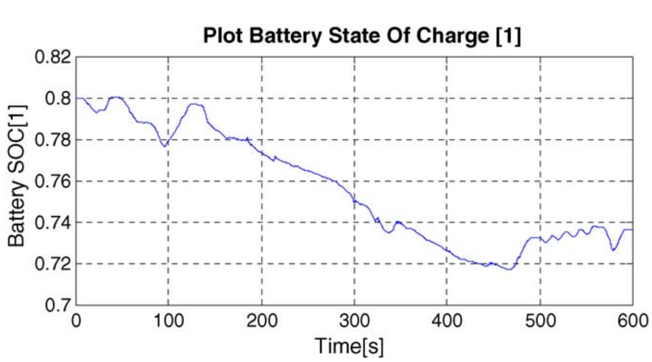

Fig. 19. Config2 Battery Pack SOC variation (US06 cycle).

7. Summary, discussion and conclusions

This paper utilizes the load-following and battery-hybrid direct-hydrogen versions of the existing *FCVSim* fuel cell vehicle simulation tool that has been developed to provide a dynamic and realistic FCV simulation tool [1,2]. This is the final paper of a three paper series that focuses on the simulation and analysis of the DHFCV (direct-hydrogen fuel cell vehicle). The first two papers presented the methodology and detailed construction of the dynamic simulation tool for the LF (load-following) and battery-hybrid DHFCV designs evaluated in this paper [1,2].

There are several elements that are unique to the battery-hybrid direct-hydrogen fuel cell system (i.e., not required for a load-following fuel cell system). They are: a dc–dc converter, the battery pack and associated battery pack controller, and the implementation of regenerative braking with the use of a regenerative braking controller. These additional elements enable the capture and reuse of regenerative braking energy by the hybrid designs to reduce the primary (fuel) energy use by the battery-hybrid DHFCV designs. The use of a battery pack also leads to the need for a post drive cycle battery SOC correction to the basic simulation results for energy use [1].

As is well known, regenerative braking energy capture is strongly drive cycle and vehicle design dependent. For example, on the FUDS driving sequence almost twice as much energy recovery per mile occurs at the wheel as for the case of the US06 cycle. These hybrid vehicle results are obviously dependent on the detailed design chosen for evaluation. For example, if a smaller than optimum battery pack is used, the regenerative braking benefits are reduced below the values determined in this study.

It is very important to note, however, that this calculation only accounts for the energy recovered at the wheel. In order for this energy to be useful for motive power (and therefore to affect the vehicles energy efficiency) a dynamic "round trip" efficiency needs to be evaluated (where the energy passes through the transmission and motor to charge the battery pack and then is discharged back through the same chain to the wheels). The added weight of the hybrid fuel cell system and the inefficiencies of the battery pack "round trip" and dc–dc converter all diminish the expected advantage of regenerative energy braking. The vehicle simulations in this study evaluated these additional losses for the battery-hybrid DHFCV configuration as realistically as possible [1].

In addition, the potentially beneficial tradeoff of improving the stack-auxiliary efficiency by limiting the dynamic operation of the fuel cell system does not yield significant improvement in the overall energy efficiency of the vehicle. Particularly, the average stack power and average stack efficiency are very similar for both the load-following and battery-hybrid DHFCV designs.

The major conclusion from this study is that only for cycles with a large amount of regenerative braking at low to mid power levels (e.g., the FUDS cycle) are there significant advantages in terms of overall fuel economy that can clearly be attributed to the hybrid configuration and regenerative braking energy recovery. For other drive cycles, advantages may lie in the intangibles associated with less stringent dynamic performance requirements placed on the fuel cell systems designed for use in hybrid vehicles, but such advantages do not manifest themselves in improved fuel economy for the battery-hybrid DHFCV designs considered in this paper.

Finally, it is important to add a strong disclaimer regarding any attempt to blindly generalize the results of this specific study to apply to all possible FCV hybrid designs. The results of this study apply only to the two specific battery-hybrid DHFCV designs, system configurations and component arrangements specifically analyzed (Figs. 2 and 3). Other components (e.g., ultra-capacitors) or component architectures and system designs may yield fuel economy gains in excess of those shown in this study. Also the loss characteristics assumed for the hybrid components in this study are key in determining the detailed results of the study, and any improvements in these component loss characteristics will change the detailed results. Lastly, alternate control architecture and tuning parameters will have a strong influence on the results.

Acknowledgements

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Appendix A

Acc acceleration
Aero aerodynamic
Aux auxiliary
Batt battery
Comp compressor
CONFIG configuration
DHFCV direct-hydrogen fuel cell vehicle
DHBhyb direct-hydrogen battery-hybrid system
ECE a standard European drive cycle
Eff efficiency
EPA federal environmental protection agency
FC fuel cell
FCV fuel cell vehicle
FUDS federal urban driving schedule (US)
HIWAY federal highway cycle (US)
Hyb Hybrid type vehicle
ICE internal combustion engine
J10-15 A standard Japanese driving cycle
LF load-following type vehicle
LHV low heating values
Motor loss motor energy loss
NiMH nickel metal hydride battery
PNGV partnership for a new generation vehicle
Propulsion energy required for vehicle propulsion
Regen regenerative braking
s seconds
SOC state of charge
soc_c energy required to correct for the battery SOC at the end of a drive cycle
t time
Tot fuel energy energy of total fuel into vehicle
Trans loss drive train energy loss
US06 an additional US driving cycle
WTM water and thermal management system

Appendix B. Vehicle parameters

Vehicle type	Load-following DH	Hybrid Config2	Comments
Vehicle			Comparable to mid size veh
Drag coefficient	0.3	No change	Comparable to mid size veh
Frontal area	2.20 m^2	No change	Comparable to mid size veh
Wheels		No change	14′ wheel radius
Wheel radius	0.3556 m		
Total wheel inertia	4 kg m^2		
Rolling friction coefficient	0.01		
Vehicle hotel load	0.3 kW	No change	
Max mechanical brake force	10.000 Ns	No change	
Test weight	See end of table	No change	

Appendix B (*Continued*)

Vehicle type	Load-following DH	Hybrid Config2	Comments
Fuel cell system			
Net power	66.5 kW	No change	
Power density	0.35 kW kg^{-1}		
Static efficiency map	Fig. 14		
Fuel cell stack technology	PEM	No change	
Number of cells	450		
Cell area	360 cm^2		
Membrane resistance	0.07 Ω cm^2		
Open circuit voltage	0.9 V $cell^{-1}$		
Compressor	Vairex twinscrew	No change	Without expander
Water and thermal management system (WTM)	Water sustainable 80 °C stack temp	No change	
Transmission			
Number of gears	1	No change	
Total gear ratio incl. differential	8.9	No change	
Transmission efficiency	Performance map	No change	Transmission designed for EV
Electric motor			
Technology	75 kW induction motor	No change	
Maximum torque	260 Nm	No change	
Maximum speed	10.000 rpm	No change	
Characteristic speed	2750 rpm at nominal voltage	No change	
Nominal voltage	312 V	No change	
Motor efficiency	Performance map	No change	
Torque as a function of voltage	Performance map	No change	
Motor inertia	0.1 kg m^2	No change	
Scale factor (for torque only)	1.0	0.9	Reduced scalar affected performance, but not weight.
Mass balance			
Shell mass	1000 kg	No change	
Payload			
Driver	75 kg	No change	From PNGV 300 lb payload
Luggage	60 kg		
Fuel cell system mass[a]	190 kg	No change	
Motor mass (including power electronic and transmission)	112.5 kg	No change	Based on Ford Ecostar 68 kW, scaled
Fuel (full tank assumed)	4.13 kg hydrogen equivalent to 68.8 kg full tank mass	No change	Compressed hydrogen storage capacity: 6 % weight @ 5000 psi
Battery management system	N/A	130 kg	NiMH battery pack: 100 kg, DC/DC conditioner: 30 kg
"Test" weight incl. driver	1500 kg	1630 kg	

[a] Includes water and thermal management system. Excludes fuel tank, fuel and dc–dc converter.

References

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