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Effects of drivetrain hybridization on fuel economy, performance and costs of a fuel cell hybrid electric vehicle

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HIGHLIGHTS

- A 13.6% reduction in the 0–60 mph acceleration time has been achieved.
- Hybridization led to an increase in fuel economy by up to 7.7%.
- A reduction of up to 25% in the purchase price of the vehicle is achieved.
- Hybridization led to an 18.8% reduction in the total cost of the vehicle.

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ABSTRACT

Fuel cell hybrid electric vehicles (FCHEVs) are considered to be the most attractive long-term option for passenger cars. Several barriers, such as cost, durability and hydrogen refueling infrastructure, must be overcome for a wider use of FCHEVs. In this paper, a mid-sized FCHEV is modeled and simulated in ADVISOR to analyze the influence of hybridization factor on vehicle performance and costs. The results are compared with those of the Toyota Mirai in order to find the optimum size of the fuel cell stack and the number of battery modules that meet various driving requirements, minimize hydrogen consumption and vehicle cost. The best results are obtained by reducing the fuel cell stack power by 58%. A 7.7% increase in equivalent fuel economy (71.6 MPGe) and a reduction of 25% in the vehicle cost is achieved.

Introduction

There is a growing concern about air pollution and climate change due to vehicle emissions. Transport is the main factor responsible for greenhouse gas emissions in large urban areas. In 2019, emissions from the transport sector accounted for almost 25% of global CO_2 emissions [1]. Despite the efforts of Governments to improve air quality in large cities, air pollution remains a pressing problem. According to the Global Burden of Disease report, 3.1 million people died prematurely in 2017 due to air pollution [2].

If significant reductions in CO_2 emissions are to be sought in the transport sector, biofuels and renewable hydrogen are

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two main options that can be pursued [3–6]. To reduce fossil fuel consumption and greenhouse gas emissions, several countries have encouraged the use of alternative fuels: biodiesel, bioethanol, hydrogen and biogas [7,8]. However, large-scale production of biofuels implies large land requirements for feedstock production. Critics point out that biofuels compete with food resources and contribute to deforestation, as some of these crops demand large amounts of land, so forested areas must be cut to make room for agricultural expansion [9–13].

Hydrogen is considered one of the best alternatives to fossil fuels and can have an important contribution to long-term decarbonization [14–16]. It appears in all eight of the European Commission's net-zero emissions scenarios for 2050 [17]. Germany, the United States, China, Japan and Scandinavia are encouraging the use of hydrogen in the transport sector. A wide variety of feedstocks can be used to produce hydrogen, including renewable sources, nuclear, and fossil fuels. Currently, hydrogen production is expensive, but the International Energy Agency (IEA) analysis concludes that the cost of hydrogen production could fall 30% by 2030 as a result of declining costs from renewable sources and increased hydrogen production [18].

Over the past two decades, vehicles have become more efficient and new technologies have been successfully introduced. Many governments around the world are introducing incentive programs to encourage the adoption of zero-emission vehicles, such as battery electric vehicles (BEVs) and fuel cell hybrid electric vehicles (FCHEVs) [19,20]. There are several benefits of FCHEVs, including improved fuel economy and easy maintenance, compared to internal combustion engine vehicles (ICEVs) [21]. FCHEVs are twice as efficient as conventional ones. Toyota Mirai, the most selling FCHEV, has a combined cycle fuel economy rating of 67 miles per gallon equivalent (MPGe), or 3.51 L/100 km [22].

The adoption of BEVs and FCHEVs can achieve a deep decarbonization of all transport segments [23]. Although FCHEVs and BEVs are presented as competing technologies, they are in fact complementary [24]. BEVs have higher energy efficiency, but batteries have less energy density by weight, making them suitable for lighter vehicles and short distances [25]. The specific energy of hydrogen is 142 MJ/kg, more than three times that of gasoline (46 MJ/kg), and more than 200 times that of Lithium-ion batteries (about 0.6 MJ/kg) [26]. The high specific energy allows FCHEVs to travel greater distances, in addition to allowing fast refueling (2–5 min) [27,28].

There are several barriers to FCHEVs adoption: high vehicle cost, high hydrogen cost [29], durability, and limited refueling infrastructure [30]. Despite this, more than 18,000 hydrogen FCHEVs were sold in 2019 and the sales projection is that 6.56 million FCHEVs will be sold globally in the 2014–2032 period [31]. By 2030, the price of an FCHEVs is expected to be competitive with ICEVs [32]. According to the IEA, FCHEV's market share could reach 17% by 2050 [33].

The dynamic response of the fuel cell system (FCS) during transient and instantaneous peak energy demands is relatively slow [34,35]. This is due to the considerable response time of air compressors and flow controllers. To improve the performance of the FCS, during transient and instantaneous peak power demands, it is always associated with energy storage system (ESS) [35,36]. The ESS, usually batteries and/or supercapacitors, supplies the vehicle with power during periods of peak power demand, in addition to providing power for the fuel cell startup. Hence, the stress on the FCS will be diminished and the transient performance of the power train and the energy storage efficiency will be improved [37]. Other reasons for hybridization include reducing the vehicle cost, capturing regenerative brake energy and extend the fuel cell lifetime [38,39].

Several studies show that the hybridization factor (HF) is an important feature of the FCHEVs [39–41]. HF is the ratio between the battery maximum power to the powertrain total power. Huang et al. investigated the effect of HF of a FCHEV on fuel economy and vehicle dynamic performance [37]. Kim et al. [42] proposed a control strategy based on fuzzy logic to optimally distribute the relative power between the FC and the battery for a fuel cell/battery hybrid mini-bus. Fathabadi [43]developed a new energy source composed of battery, supercapacitor and fuel cell for a FCHEV. The vehicle achieved high energy efficiency and 545 km of autonomy.

Hybridization allows to reduce the size of the FCS and operate it more efficiently. By reducing the FCS maximum power, the FCHEV's purchase price decreases as does the hydrogen consumption, which results in lower operating costs [44].

The HF depends on the vehicle's design and influences both its performance and cost. Aiming primarily for cost reduction that can be achieved by reducing FCS power, this paper analyzes the influence of HF on the total costs and fuel economy of a FCHEV: the Toyota Mirai. Once an optimized configuration of the modeled FCHEV is defined, an economic comparison of this vehicle with the original Mirai is done.

Methodology

Current work uses the Advanced Vehicle Simulator (ADVISOR) to analyze the influence of the HF on the performance and cost of a mid-size FCHEV. ADVISOR is a model written in the MATLAB/Simulink software environment that allows quick performance and fuel economy analysis of conventional and alternative vehicles (BEV, FCHEV) [45]. ADVISOR uses powertrain component characteristics to estimate emissions and fuel economy for certain driving cycles and other quantitative performance metrics (i.e., acceleration at maximum effort, gradeability). Approximately 30 different driving cycles and several complex test procedures can be applied to assess fuel economy and emissions under various simulated test conditions [46] [–] [48].

The vehicle chosen for this study is the Toyota Mirai. ADVISOR is used to evaluate the fuel economy for different combinations of FCS and battery size operating on two different driving cycles (UDDS - Urban Dynamometer Driving Schedule, and HWFET- Highway Fuel Economy Test). Combined fuel economy is the most used by automakers and better reproduces the combination of vehicle use in the city and on the highway [49]. For all configurations, the powertrain total power is maintained constant, just changing the proportion of the power available from the battery and the FCS. All vehicle configurations must satisfy the Partnership for a New Generation of Vehicles (PNGV) minimum performance

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requirements (see item 4.2). The costs and fuel economy results of the different configurations (different HFs) are compared to those of the original vehicle.

Fuel cell hybrid electric vehicles

A FCHEV combines two propulsion systems: the fuel cell system and the energy storage system (ESS). The most used ESS in FCHEV applications are batteries and ultracapacitors. Fig. 1 shows a diagram of the FCHEV modeled in this work.

As can be seen in Fig. 1, the main components of the powertrain are the FCS, the battery pack (BP), converter/inverter, the electric motor and transmission. The BP and the FCS supply electrical power to the electric motor. Power conversion in an FCHEV has two stages: DC-DC conversion and DC-AC conversion. First, low voltage DC power from sources is converted into high voltage DC and then the high voltage DC is converted into AC by the inverter. The FCS is the main power source of an FCHEV, and the ESS is the auxiliary power source to assist the propulsion of the vehicle during transients and to recuperate energy during regenerative braking.

Vehicle specifications

In 2014, Toyota launched the first large-scale production FCHEV: the Toyota Mirai. Mirai stands out for its zero local carbon emissions, high autonomy (502 km) and fast refueling (less than 5 min) [49]. Mirai is the best-selling FCHEV and reached a cumulative total of 6293 sales [50]. The most relevant features of the vehicle are summarized in Table 1.

Mirai's powertrain consists of a 114 kW PEMFC (Proton-Exchange Membrane Fuel Cell) supplied from onboard compressed hydrogen tanks, and a nickel–metal hydride BP. The characteristics of the fuel cell system are presented in Table 2.

The FCS is composed of a PEM fuel cell stack, hydrogen supply subsystem, water management subsystem, air supply subsystem and control systems. The maximum fuel cell efficiency assumed for the Toyota Mirai simulation was 62%.

The BP consists of 34 low voltage (7.2 V) NiMH battery modules connected in series to produce approximately 244.8 V. The main characteristics of the batteries are summarized in Table 3.

Table 1 – Toyota Mirai specifications [51].

	Parameters	Value
Vehicle	Drag coefficient	0.29
	Curb weight	1850 kg
Fuel converter	Fuel Cell Stack (PEMFC)	114 kW
Wheels	Tire radius	0.33 m
	Rolling resistance coefficient	0.0076
Battery	Type	Ni–MH
	Capacity	6.5 A h
Electric Motor	Motor power	113 kW
Performance parameters		
Fuel Economy - EPA MPGe/(L/100 km)		67/(3.51)
Maximum Speed mph (km/h)		111 (179)
0-60 mph acceleration time (s)		9.0
Vehicle range miles (km)		312 (502)

Table 2 – Fuel cell system specifications [51].

Fuel Cell type	PEMFC
Maximum Power	114 kW
Specific Power	2 kW/kg
Fuel cell stack weight	56 kg
Fuel converter time to full power	5 s
Hydrogen tanks weight	87.5 kg
Fueling time	300 s
Hydrogen tanks capacity	5 kg of H_2
Hydrogen tanks normal operating pressure	70 MPa

Control strategies

The control strategy evaluates the traction power and decides whether FCS or battery supplies the requested power. Several control strategies can be used in FCHEVs.

FCHEV's battery typically operates in two distinct modes: charge depleting (CD) mode, and charge sustaining (CS) mode [53]. In CD mode, the battery discharges continuously, up to the minimum state of charge (SOCmin) defined in the control strategy. In (CS) mode, the battery's state of charge (SOC) may fluctuate but is kept above the SOCmin. According to Ahluwalia et al. [40], the battery of an FCHEV should operate in charge sustaining mode. In this mode, the SOC of the battery is maintained sufficiently above the SOCmin, so that the battery can always supply sufficient charge autonomously for

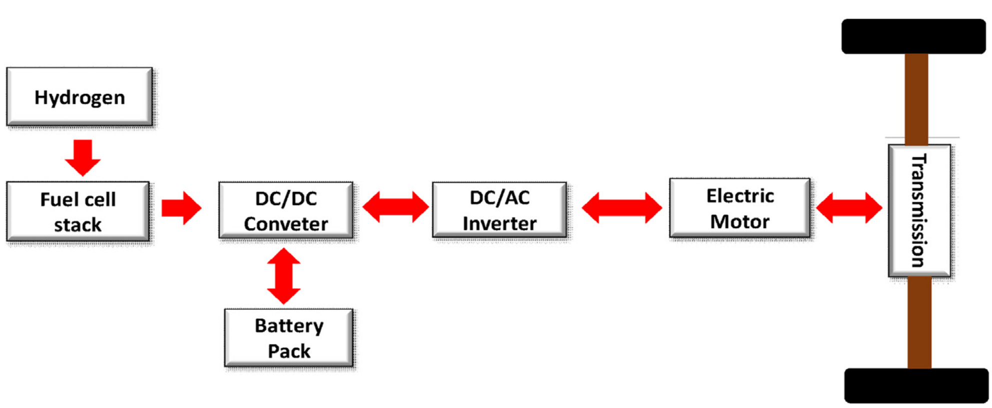

Fig. 1 – FCHEV powertrain and energy flow.

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Table 3 – Battery pack specifications [52].

Number of modules in the pack	34
Battery module nominal voltage	7.2 V
Battery pack nominal voltage	244.8 V
Battery module nominal capacity	6.5 A h
Battery module output	1.35 kW
Battery module weight	1.04 kg
Specific power	1.30 kW/kg
Energy Density	0.045 kWh/kg

acceleration events. Therefore, this is the appropriate strategy for FCHEVs since fuel cells are unable to respond quickly to energy transients.

Fig. 2 shows the FCS efficiency as a function of the required power. As can be seen in this figure, the fuel cell efficiency decreases dramatically at low power. Since a PEMFC has low efficiency when operating at low power, the electric motor should be driven by the BP to obtain a better performance of the propulsion system. For this reason, the minimum power of 15 kW was adopted to activate the FCS. Thus, for powers below 15 kW, the fuel cell remains off, and the electric motor is powered exclusively by batteries.

For peak power demand, both the FCS and the ESS supply propulsion power to the electric motor drive. When braking, the electric motor, working as a generator, converts part of the braking energy into electrical energy and stores it in the ESS.

Fig. 3 presents the results of the fuel cell specific fuel consumption as a function of the required power. There is an exponential increase in specific fuel consumption as the required power decreases.

According to Kostopoulos et al. [54], continuously operating the BEV's battery below 20% and beyond 80% of the SOC proved to be very harmful and dangerous as well. Thus, in the present work, the control strategy established that the battery SOC is kept within the following limits: $0.4 \leq \text{SOC} \leq 0.8$.

Hybridization factor

For an FECHV, the hybridization factor (HF) is the ratio between the battery maximum power to the powertrain total power. Equation (1) defines the HF:

$$HF = \frac{P_{ess,max}}{P_{fcs,max} + P_{ess,max}} \times 100\ [\%] \quad (1)$$

where $P_{ess,max}$ is the storage system maximum power and $P_{fcs,max}$ is the FCS maximum power.

The HF ranges from 0% to 100%. When HF is 0%, the energy is fully supplied by FCS, while it is fully supplied by BP when HF is 100%. The HF depends on the vehicle's design and influences both its performance and cost. In the present work, an analysis of HF is performed by varying the FCS and ESS power. $P_{fcs,max}$ power is reduced, while $P_{ess,max}$ is increased to compensate for the decrease in FCS power, keeping the vehicle's installed power $(P_{fcs,\ max} + P_{ess,\ max})$ constant at 159.9 kW. The hydrogen tank weight is about 5% of the vehicle's total weight and was kept constant in this work.

Vehicle performance

FCHEVs must satisfy the following requirements:

a) FCS alone must be capable of maintaining the vehicle at 55-mph speed (88.5 km/h) at 6.5% grade for 20 min [55];
b) According to the Partnership for a New Generation of Vehicles (PNGV), the vehicle must be capable of accelerating from 0 to 60 mph (96.6 km/h) in 12 s [56].

A performance and cost analysis for vehicles with different degrees of hybridization will be performed in results and discussion (Results & discussion), only for vehicle configurations that meet the requirements mentioned in this section (Vehicle performance).

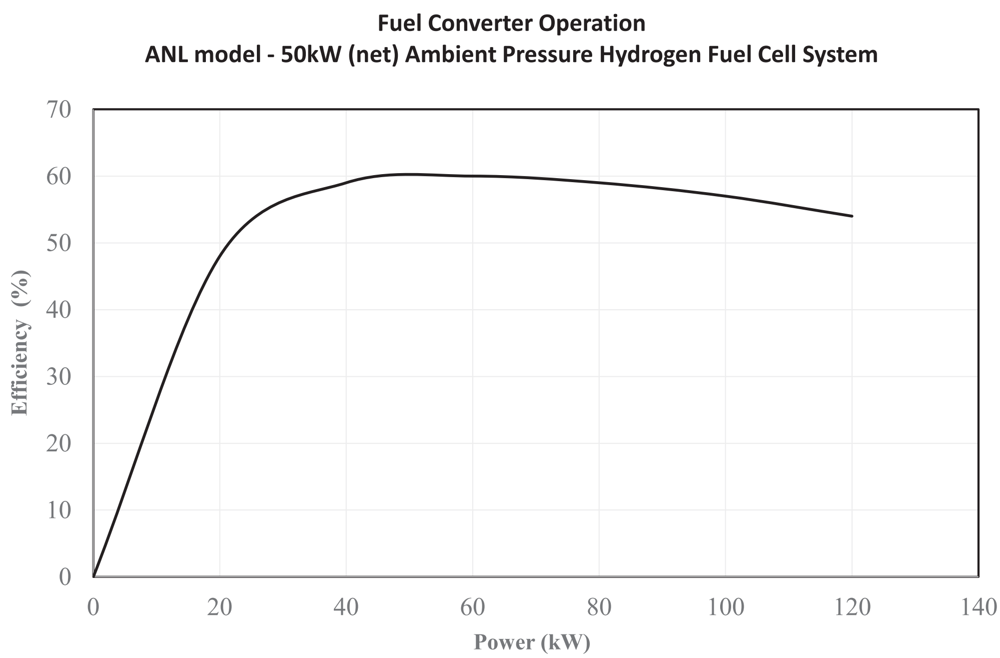

Fig. 2 – Fuel cell system efficiency map from the ADVISOR model.

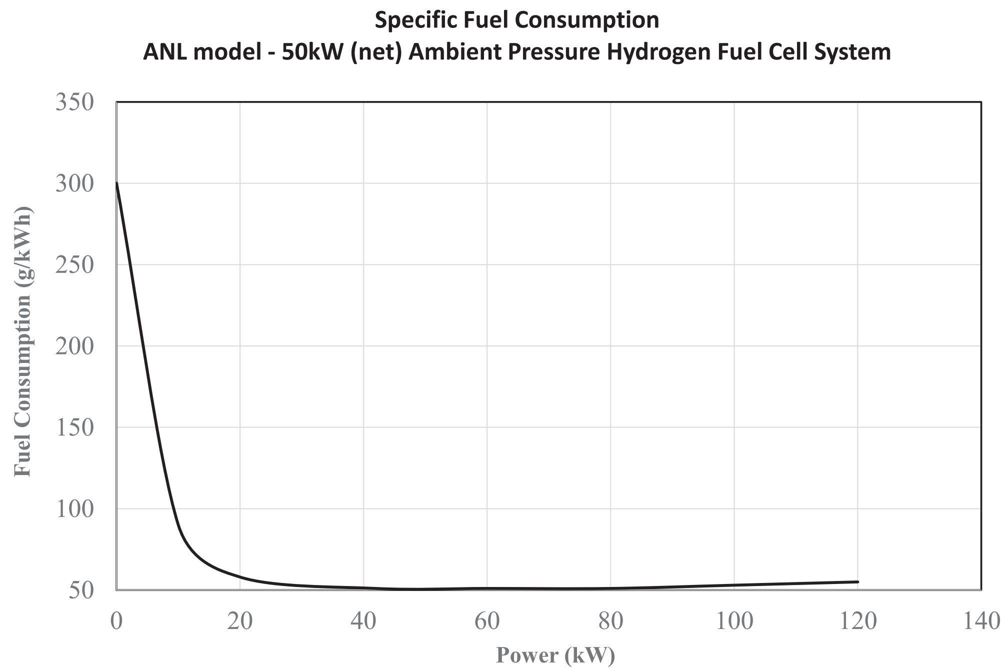

Fig. 3 — Hydrogen consumption map of the FCS from the ADVISOR model.

Results & discussion

The Toyota Mirai simulations were done by varying the vehicle's HF. Table 4 presents the variable size battery and FCS components studied in this work.

The total power of the propulsion system (Pfcs,max + Pess,max) was kept constant (159.9 kW). The FCS power decreased from 130 kW to 47 kW and the HF went from 18.7% to 70.6%. Mirai's original HF value is 28.7%. The HF values were obtained by increasing the number of battery modules.

It can be seen from Table 4 that the increase in the HF results in an increase in vehicle mass since the specific power of the Ni-MH battery is lower than that of the fuel cell.

Vehicle's performance results

To calculate the vehicle's performance at different degrees of hybridizations the Advanced Vehicle Simulator (ADVISOR) is used. The results of Toyota Mirai's acceleration and uphill tests for different HFs are presented in Table 5.

As can be seen in Table 5, increasing the HF implies a decrease in acceleration time. Likewise, the increase in HF reduces the maximum grade at which the FCS alone can maintain the vehicle at 88.5 km/h (55 mph) speed for 20 min.

From the previously established constraints, it was possible to determine a range of acceptable HFs. The lower limit of the HF was set at 19.3% because below this value the vehicle could not reach acceleration within the set time (12 s). On the other hand, the upper limit of the HF was set at 70% since, at 70.6%, the maximum grade that the fuel cell system is capable of sustaining does not meet the minimum value set (6.5%).

Simulations were performed to analyze the influence of the HF on vehicle performance and costs. Table 6 summarizes the results of the simulations of different HFs within the established limits.

The simulation results show that there are consistent performance gains by increasing the HF to the upper limit of

Table 4 — FCHEV platforms studied.

Hybridization Factor	Fuel cell power (kW)	NiMH battery power (kW)	Number of battery modules	Battery pack weight (kg)	Fuel cell stack weight (kg)	Gross vehicle weight (kg)
18.7%	130	29.9	22	23	64	1982
19.3%	129	30.9	23	24	63	1982
28.7%	114	45.9	34	35	56	1986
40.0%	96	63.9	47	49	47	1991
50.0%	80	79.9	59	61	39	1995
60.0%	64	95.9	71	74	31	2000
70.0%	48	111.9	83	86	24	2005
70.6%	47	112.9	84	87	23	2005

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Table 5 – Results of acceleration and uphill tests for configurations studied.

Hybridization Factor	18.7%	19.3%	28.7%	40.0%	50.0%	60.0%	70.0%	70.6%
Gradeability[a]	12.9%	13.5%	17.8%	15.0%	12.4%	9.5%	6.6%	**(6.4%)**
0–96.6 km/h acceleration time[b] (s)	**(12.4)**	11.8	8.8	7.9	7.6	7.6	7.6	7.6

Values in bold and in parentheses do not satisfy the previously established restrictions (Vehicle performance a and b).
[a] The highest grade the vehicle only powered by FCS can ascend while maintaining at 88.5 km/h (55 mph) speed by 20 min.
[b] 0–96.6 km/h acceleration response time with FCS and ESS supplying power to the vehicle.

Table 6 – Summary of simulation results.

Hybridization Factor	19.3%	28.7%	40.0%	50.0%	60.0%	70.0%
Fuel Economy – Combined Cycle (MPGE)	63.6	66.9	67.4	68.9	70.2	71.6
Maximum speed (mph)	98.1	97.6	97.5	97.5	97.4	97.4
0-60 mph acceleration time (s)	11.8	8.8	7.9	7.6	7.6	7.6

70%. Fuel economy improves with increasing HF due to better braking energy recovery. The configuration with the highest HF (70%) has the best fuel economy (71.6 MPGe). Compared to the vehicle's original configuration (HF = 28.7%, 63.6 MPGe), there is an estimated savings of 7.7% in fuel economy in the combined cycle.

In addition, the configuration with the highest HF (70%) achieved a reduction in acceleration time of 1.4 s compared to the original configuration, i.e. a reduction of approximately 13.6%.

Fig. 4 shows the vehicle's energy consumption as a function of HF for different drive cycles.

Compared to the original vehicle configuration (HF = 28.7%), there is a 7.3% reduction in the vehicle's energy consumption in the combined cycle for the HF = 70%.

Influence of hybridization factor on vehicle's costs

Considering the high cost of the FCS, a reduction in the maximum power of the FCS decreases the FCHEV's purchase price, as does the consumption of hydrogen, which results in lower operating costs.

The vehicle's purchase price, the consumer's fuel expenses and other costs (taxes, profit margins, etc.) are considered in the cost analysis of the different configurations of the FCHEV. Vehicle maintenance costs are not considered in this study. The impact of HF on the vehicle's total cost is analyzed below.

Vehicle's total cost

FASTSim (Future Automotive Systems Technology Simulator), a vehicle simulator tool with a large and reliable dataset of

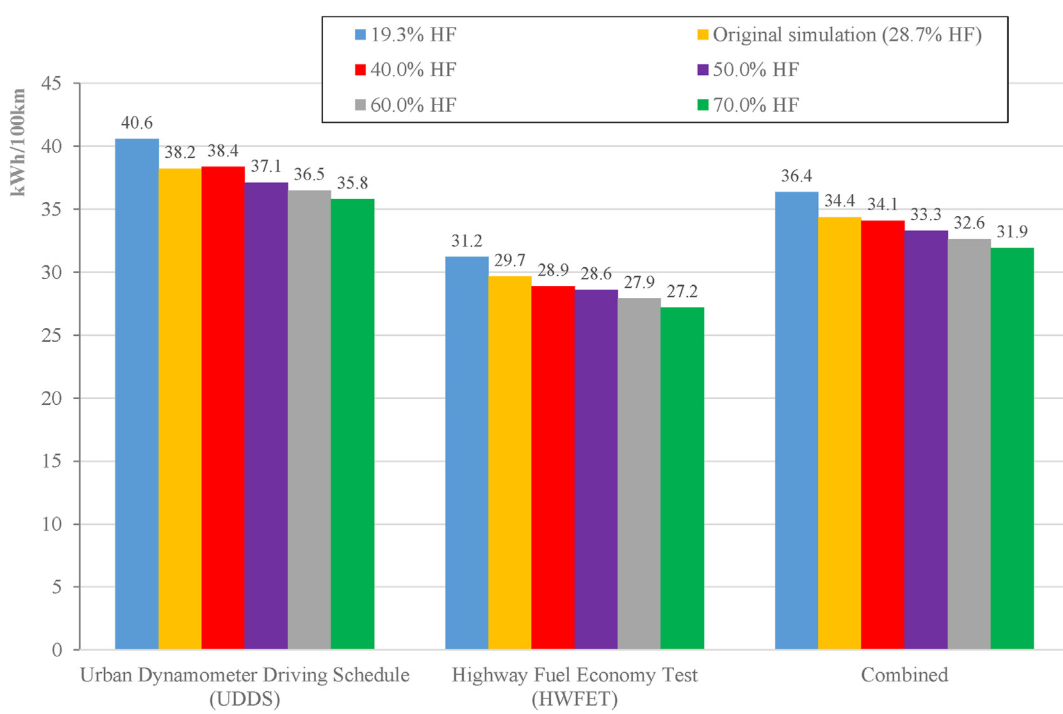

Fig. 4 – Energy consumption for different hybridization factors.

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Table 7 – Vehicle's component costs.

Component	Cost
Vehicle's base price (without FCS, battery, motor)	$ 17,014.00
Fuel cell stack cost	170.00 $/kWh
Hydrogen tank cost	16.00 $/kWh
Electric motor base cost	$ 425.00
Electric motor variable cost	21.70 $/kWh
NiMH battery pack base cost	$ 405.00
NiMH battery pack variable cost	145.00 $/kWh
Manufacturer's margin	12%
Retailer's margin	To be set between 5.0 and 15.0%
Sales tax	7.8%
Hydrogen price	15.82 $/GGE
Hydrogen price	15.53 $/kg
Discount rate	3.20%

costs and performance of real vehicles, is used to estimate the costs of FCHEV's components [57]. In addition to the vehicle's component costs, the manufacturer's profit margin, retailer's margin, and taxes must be considered in the vehicle's total cost. The retailer margin and the manufacturer's profit margin are 13.2% and 12.0%, respectively. These values are within the range suggested by Fries et al. [58]. The tax rate is estimated at 7.8% according to the values available in FASTSim dataset.

The main components of the FCEHV are the electric motor, FCS, hydrogen tank, BP and vehicle's glider. According to the FASTSim model, the Toyota Mirai's estimated base price (i.e., excluding electric motor, battery, fuel cell and fuel tank) is $ 17,014. The cost of fuel cell stack is 170 $/kW and the hydrogen tank is 16 $/kWh, according to the FASTSim database. The cost of the electric motor has a fixed value of $ 425 plus a variable value of 21.70 $/kW.

Fries et al. [58] state that the cost of BP should be divided into fixed costs, regardless of the size of BP, and variable costs (per kWh). The authors estimate that BP's fixed costs for hybrid electric vehicles are $ 405 plus a variable cost of 145 $/kWh.

The manufacturer's gross margin adopted was 12% [58]. According to the same authors, the retailer's sales margin ranges from 5 to 15%.

DOE periodically releases the average price of alternative fuels at US gas stations According to DOE, the average price of hydrogen is $ 15.82/GGE in 2018 [59]. The price of hydrogen is assumed to be constant over the vehicle's lifespan.

It is important to bring the future fuel costs to present value as overtime money loses value due to inflation. In this sense, Zhang [60] introduces the calculation for the conversion of future value to present value as follows in the equation:

$$\mathrm{PV} = \frac{FV}{(1+d)^n} \tag{2}$$

where PV is the present value; FV is the future value; d is the discount rate; and n is the time expressed in years.

According to FASTSim model, Toyota Mirai's lifespan is over ten years. Therefore, the assumed discount rate was 3.20% which refers to the ten-year US Treasury bond return rate [61].

Table 7 summarizes the vehicle's costs assumptions. Subsequently, these assumptions will be validated in relation to the Toyota Mirai purchase price to consumers.

Cost breakdown analysis

Table 8 presents Toyota Mirai's cost breakdown analysis. The FASTSim model was used to estimate vehicle's cost data, since Toyota does not provide Mirai costs, broken down by components [57]. The retailer's sales margin was assumed to be 13.2%, remaining in the range of 5.0–15.0%, defined by Fries et al. [58] and taking into account Mirai's purchase price. According to Toyota, the 2017 Mirai's market price in the United States is $ 57,500 [62].

In addition to the vehicle's market price, cost analysis must also incorporate operating costs. In the present study, only fuel costs were considered in operating costs. Table 9 shows the fuel costs for the original configuration over the vehicle's lifespan. Fuel costs were calculated from the manufacturer's fuel economy data (67 MPGe), considering the vehicle's

Table 8 – Toyota Mirai's cost breakdown analysis.

Components	Value	Vehicle Parameters	Final Costs
Base vehicle price (without FCS, battery, motor)	$17,014.00	–	$17,014.00
Hydrogen tank cost	16.00 $/kWh	168.5 kWh	$2696.00
Electric motor base cost	$425.00	–	$425.00
Electric motor variable cost	21.70 $/kW	113 kW	$2452.00
Fuel cell stack cost	170.00 $/kW	114 kW	$19,380.00
NiMH BP base cost	$405.00	–	$405.00
NiMH BP variable cost	145.00 $/kWh	1.59 kWh	$231.00
Vehicle production costs	–	–	$42,603.00
Manufacturer's margin	12.0%	–	$5112.00
Retailer's margin[a]	13.2%		$5624.00
Sales tax[b]	7.8%	–	$4161.00
Suggested retail price (SRP)	–	–	$57,500.00

[a] Margins are considered as percentage of vehicle production costs.
[b] Sales tax is considered to be charged as a percentage of vehicle production costs plus manufacturer's and retailer's margins.

Table 9 – Analysis of Toyota Mirai's total costs.

Suggested retail price (SRP)	$ 57,500
Present value of fuel expenses	$ 32,652
Vehicles total costs[a]	**$ 90,152**

[a] Maintenance costs not included.

lifespan of 12 years and 19,916 km the average distance traveled per year.

The present value of fuel expenses over the vehicle's lifespan is quite significant in total vehicle expenses (57% of the vehicle's retail price).

Influence of hybridization factor in FCHEV's costs

As previously discussed, the objective of this paper is to analyze the influence of HF on the sale cost and operational cost of Toyota Mirai. Thus, the process of adjusting cost assumptions according to vehicle parameters for different HFs was repeated to obtain estimated results of production costs and suggested selling price, as well as the present value of fuel expenses for each configuration.

Table 10 presents the development of costs broken down by Mirai's components for several HFs. As can be seen in Table 10, the vehicle's final costs are strongly influenced by the FCS size and fuel costs. In the original vehicle configuration, fuel

Table 10 – Influence of the hybridization factor on vehicle cost.

Components	19.3% HF	28.7% HF[a]	40.0% HF	50.0% HF	60.0% HF	70.0% HF
Base vehicle price (without FCS, battery, motor) $	17,014					
Hydrogen tank cost $	2696					
Electric motor base cost $	425					
Electric motor variable cost $	2452					
NiMH BP base cost	405					
NiMH BP variable cost	167	247	341	428	515	602
Fuel cell stack cost $	21,930	19,380	16,320	13,600	10,880	8160
Vehicles production costs $	**45,089**	**42,619**	**39,653**	**37,020**	**34,387**	**31,754**
Manufacturer's margin $	5411	5114	4758	4442	4126	3811
Retailer's margin $	5952	5626	5235	4887	4539	4192
Sales tax $	4403	4163	3873	3616	3359	3101
Suggested retail price $	**60,855**	**57,522**	**53,519**	**49,965**	**46,411**	**42,858**
Present value of fuel expenses $	**34,552**	**32,652**	**32,393**	**31,635**	**31,003**	**30,335**
Vehicles total costs $ [b]	**95,407**	**90,174**	**85,912**	**81,600**	**77,414**	**73,193**

[a] Original configuration.
[b] Maintenance costs not included.

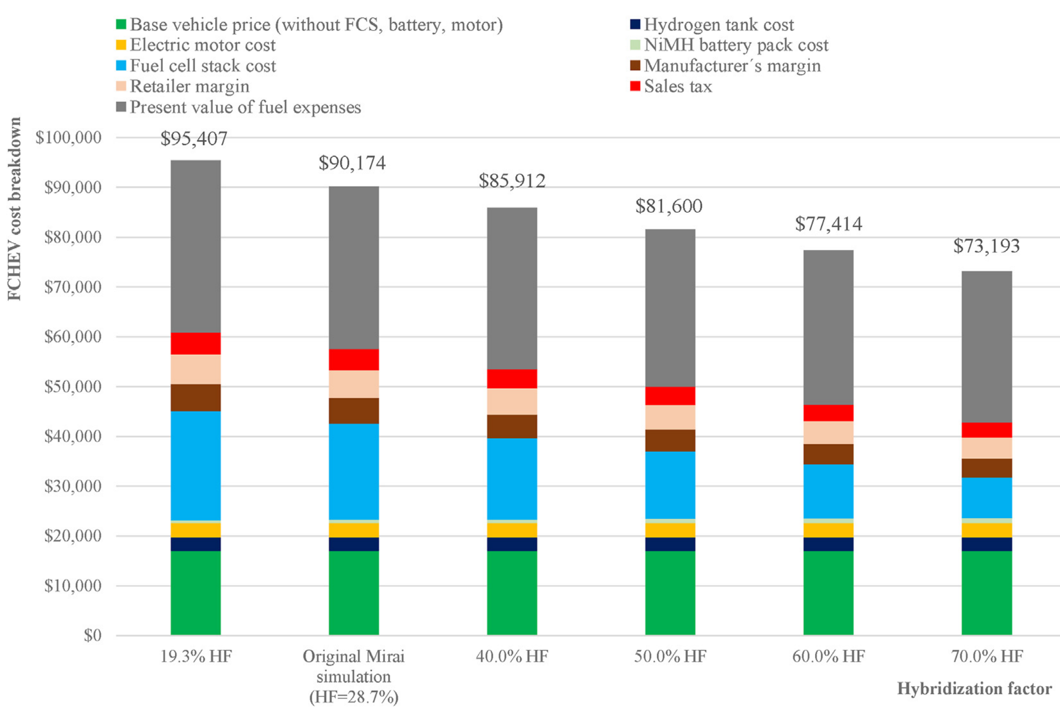

Fig. 5 – FCHEV's total cost as a function of the hybridization factor.

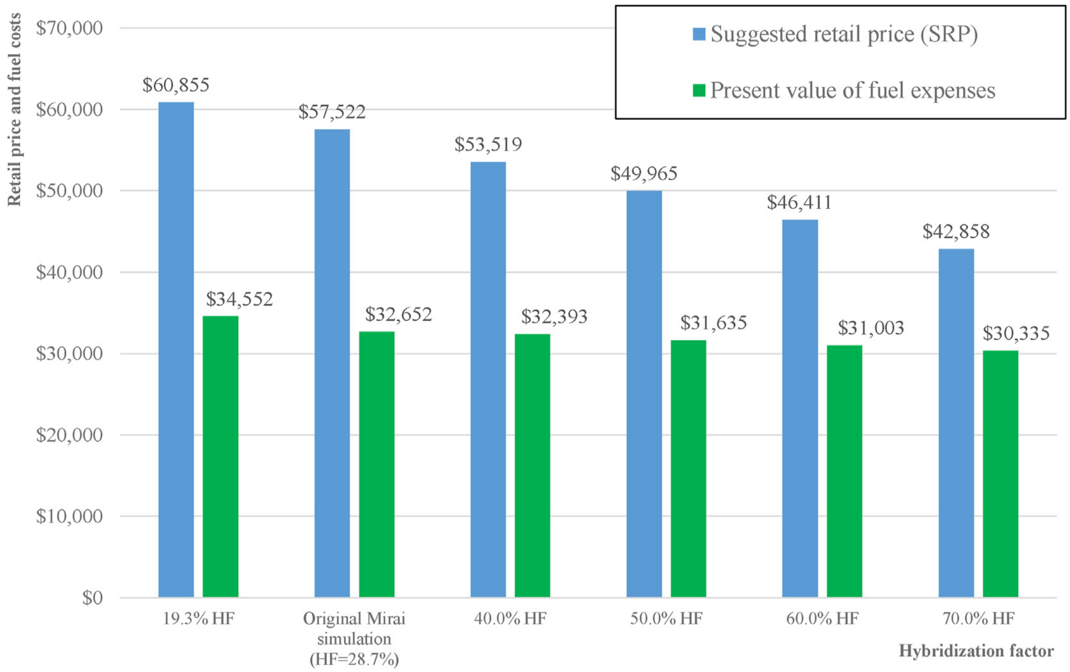

Fig. 6 – FCHEV's retail price and fuel cost as a function of the hybridization factor.

cell stack cost is about 50% of the vehicle's production cost. In the optimized configuration (HF = 70%), the cost decreases to 26%.

As explained before, increasing the HF implies expanding the maximum battery power and reducing fuel cell power. Since the cost of the fuel cell propulsion system is about ten times the cost of the BP, the total cost of the vehicle tends to decrease. This can be seen in Fig. 5.

Fig. 5 summarizes the FCHEV's total cost results for different HFs. The increase in HF from 28.7% (original vehicle) to 70.0% (upper limit) results in a reduction of $ 16,981.00, i.e., a decrease of 18.8% in the vehicle's total cost.

Fig. 6 shows the FCHEV's retail price (SRP) and the cost of hydrogen along vehicle's lifespan as a function of HF.

The increase in HF from 28.7% (original value) to 70.0% results in a reduction of $ 14,694.00, i.e., a decrease of 25% in the vehicle's purchase price. Likewise, there was a reduction in fuel costs of approximately 7% ($ 2317.00) with respect to the Toyota FCHEV benchmark (HF = 28.7%).

Conclusions

In this paper, a mid-sized FCHEV is modeled and simulated in ADVISOR to analyze the influence of hybridization factor on vehicle performance and costs. The proposed sizing methodology allows us to find the size of the FCS and the number of battery modules that meet various driving requirements, minimize hydrogen consumption and vehicle cost. The configuration with the highest hybridization (HF = 70%) showed a cost reduction of 25% in the vehicle's retail price compared to the original vehicle. FCS power is downsized from 114 to 48 kW (58% downsized) while the battery size is increased to 83 modules to compensate for the decrease of the fuel cell power. This configuration gives a better performance for the hybrid powertrain. A 7.7% increase in equivalent fuel economy (71.6 MPGe) is achieved in the Combined Cycle. A reduction of 1.4 s - about 13.6% - was achieved in the 0–60 mph acceleration time. When comparing all the results here, it is concluded that the increase in hybridization was beneficial for the performance and the decrease in the vehicle's overall costs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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