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The use of electric drive in urban driving conditions using a hydrogen powered vehicle – Toyota Mirai

Vehicles with electric propulsion systems are increasingly more often equipped with solutions that improve their drive system's efficiency. The latest vehicle model with a fuel cell hybrid system – Toyota Mirai was used in this experiment. The design of this vehicle is similar to that of hybrid vehicles in many aspects. However, new fuel cell technologies are being developed for automotive use, including compressed hydrogen tanks and control systems. The article presents an analysis of a fuel cell operation during vehicle start-up and driving, with particular emphasis on the hydrogen injection strategy of the three fuel injectors used in the fuel cell. The fuel cell interaction with the high-voltage battery has also been characterized. It has been shown that increase in the electrical supply voltage of the vehicle's electric motor can be observed at high torque values of the electric motor. The maximum voltage gain – approximately three times (up to about 650 V) – allows for double the torque of the drive system compared to the standard value.

Key words: *fuel cell, HEV vehicle, hydrogen fuel*

1. Introduction

The transport development strategy, approved for implementation by the European Commission, calls for the reduction of greenhouse gas emissions from the transport sector. Realization of these assumptions with the conventional drive systems will not be possible. Leading car manufacturers, aware of the challenges they face, to work intensively on alternative drives for passenger vehicles. The introduction of a hybrid drive in 1997 by the major car manufacturer, Toyota, was the effect of this new research strategy [8]. The combination of an electric and conventional drive system has made it possible to significantly reduce the atmospheric CO_2 emissions. In the first generation of Toyota Prius the average CO_2 emission was 120 g/km [1] while the latest version of its fourth generation produces merely 70 grams per kilometer [2]. This company estimates that since the introduction of the Prius, the replacement of 10 million conventional-type diesel cars with 10 million hybrid cars has reduced the CO_2 emissions by over 77 million tons. The fact that more and more manufacturers are using hybrid drives in Europe, North America and Asia serves as a confirmation of this drive's potential.

Despite the popularity of this kind of drive system, the requirements set by the European Commission to reduce carbon dioxide emissions will still be impossible to reach. It is only the task of creating a zero-emission vehicle, posed to the car manufacturers, that will eventually allow for the implementation of this transport development strategy. All leading manufacturers want to achieve these goals by putting vehicles with electric drives into mass production. The main issue is: what will be the energy carrier – automotive battery or hydrogen.

Hydrogen as an energy carrier allows a vehicle – at a standard refueling pressure of 70 MPa and a hydrogen mass of 5 kg – to cover a distance up to 550 km. The use of such high pressure requires special tank designs that are already mass-produced. The established hydrogen refueling standards for passenger cars also requires a larger investment in the construction of a hydrogen refueling stations. The main advantage of this standard is the time of refueling 5 kilograms of hydrogen, i.e. filling the tank from 0 to 100% which takes about 3 minutes. This is the main argument for this type of energy carrier, as opposed to the time consuming charging of electric vehicles. The safety of using fuel cell powered vehicles is also supported by the fact that they are actually refueled by drivers without any supervision. The construction of self-service stations was adopted as a standard solution.

Does this energy carrier already provide a clear and unambiguous alternative to conventional propulsion? The hydrogen production process itself is known and popular. It can be produced, from coal, through the electrolysis of clean water, even by composting municipal waste. The challenge remains to find and popularize a method that meets two mutually exclusive criteria: the purity of hydrogen and its price. At present, the cost of hydrogen is about 9 Euro per kilogram, which makes the cost of operation comparable to the operating costs of a vehicle with a 1.8 dm^3 displacement petrol engine.

The widespread use of hydrogen as a source of energy requires, in some parts of the world, the further development of the hydrogen refueling station infrastructure and, in many other parts, building and establishing this infrastructure from scratch.

The use of a high-voltage battery as an automotive energy carrier requires finding a solutions to the fundamental problems of the vehicle's range and battery charging time. Although research aiming to eliminate these problems has been ongoing for over a century, they have yet to be effectively overcome. The latest generation of batteries, not only used by Tesla, provide a range of 150–200 km after just 30 minutes of charging time. The maximum range of the vehicle is up to 450 km, but it takes at least a few hours to charge the battery to full (with three-phase power supply) or even upwards to 30 hours (for normal household use). In order to reach the 200 km range after only 30-minute charging it becomes necessary to use super-fast chargers. Their charging time shortens the full recharge time to 4.5 hours. The power requirement for one station, however, is 480 V/ 200 A×3.

Undoubtedly, the construction of fast charging stations, usually referred to as superchargers, and the use of supercapacitors are currently considered as the best solution for obtaining a large range of the vehicle with a fully charged battery. Nevertheless, this technology also requires the construction of a charging station infrastructure. It is also extremely important to provide energy for the infrastructure to do its job. It is necessary to build a power grid with a very efficient current source – which is also a technical and economic challenge.

For the person owning and driving a car, the important are parameters such as: the price of fuel, the vehicle range, the availability of fuel and the ease of refueling. For the considered energy carriers, the current price and availability of speak for the use of batteries. This is due to the fact that the initiative of construction of the electric vehicle charging infrastructure had already been undertaken as well as the incentive in the form of a reduced cost recharging or even free sources of electricity that have been provided.

By contrast, hydrogen as an energy carrier that is being distributed to fuel cells in the automotive industry has an undoubtful advantage in the form of fast refueling and a much larger vehicle range after refueling. The poor availability of hydrogen refueling stations is due to the very short history of this technology and as a result of its dynamic development. Hydrogen as fuel looks to have a huge future ahead, merely by the fact that it is possible to produce it in the process of waste disposal, and waste is a big problem for our civilization.

Production of the Toyota Mirai vehicles started in Japan in December of 2014, and the sales in the US in the following year. In Europe, the first vehicles were sold in 2015 in Great Britain, Germany and Denmark, and in 2016 also in Belgium. In the same year Toyota Mirai was launched in Norway and Sweden. There are 5 hydrogen refueling stations in Norway. It is estimated that by 2020 there will be more than 20 of them. Sweden has hydrogen refueling stations in Stockholm, Gothenburg and Malmo. Based on Toyota data, it is estimated that 700 hydrogen-powered vehicles were sold in 2015 and about 2,000 in 2016. The sale values are expected to reach about 3,000 vehicles in 2017, with an increase to 30,000 in 2020.

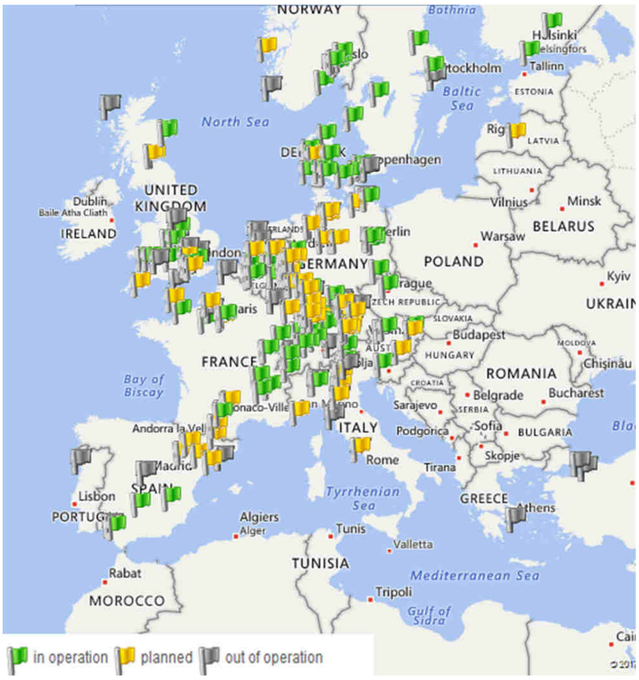


Fig. 1. Map of hydrogen refueling stations in Europe [4]

Two hydrogen tanks with a pressure of 70 MPa were used in the Toyota Mirai vehicle (Fig. 2). Thus the largest unit mass density of compressed hydrogen was obtained. The voltage from the fuel cell stack is converted to 650 volts and fed to the electric AC motor. Technical fuel system data of the vehicle with fuel cells is presented in Table 2.

Table 1. Fuel cell vehicles available on the automotive market

	Toyota Mirai	**Hyundai ix35 Fuel Cell**	**Honda Clarity Fuel Cell**
			
Acceleration 0-60 mph	9.6 s	12.5 s	11 s
Fuel Cell power	113 kW	100 kW	103 kW
Engine power	113 kW	100 kW	130 kW
Top speed	179 km/h	161 km/h	200 km/h
Range	ca. 550 km (NEDC test)	594 km	482 km
H_2 storage	70 MPa	70 MPa	70 MPa

The latest fuel cell drive solutions include more electronic controls than their predecessors. Previous versions of drive development (Fig. 3 – left) had a fuel cell and an inverter that connected directly to the electric motor and fed with the same voltage. The current solution uses a voltage boost, which allows to increase the electric motor supply voltage up to 650 V.

In the new generation of fuel cells, some parts were eliminated and others significantly consolidated, which simplified the whole device structure (Fig. 4).

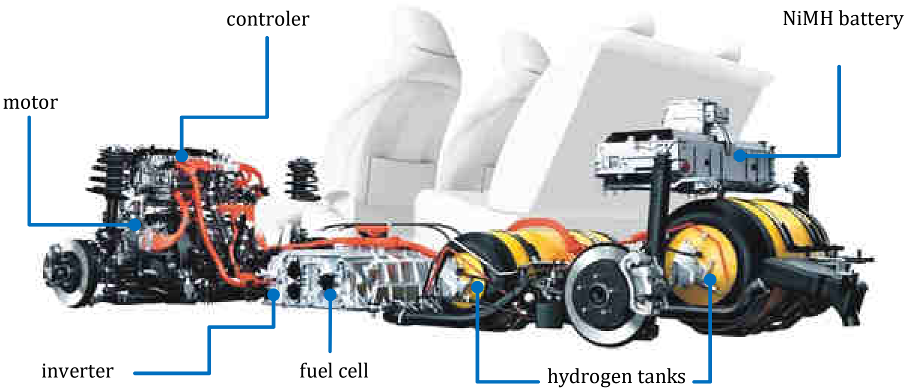


Fig. 2. Components distribution of the Toyota Mirai hydrogen system [6, 7]

Table 2. Toyota Mirai vehicle drive system characteristics [7]

Parameter		Value
Vehicle	mass	1850 kg
	maximum speed	179 km/h
Vehicle range	type approval cycle	approx. 550 km (NEDC test)
Fuel cell	type	PEM (polymer electrolyte)
	power	114 kW
	power density	2.0 kW/kg; 3.1 kW/dm^3
	cell number	370
	humidification	Internal circulation
Electric motor	type	synchronous AC
	maximum power	113 kW
	maximum torque	335 N·m
Battery	type	NiMH
Hydrogen storage	volume of tanks pressure/mass	front – 60 dm^3, back – 62,4 dm^3 70 MPa/5 kg H_2
Refueling	time	3 min

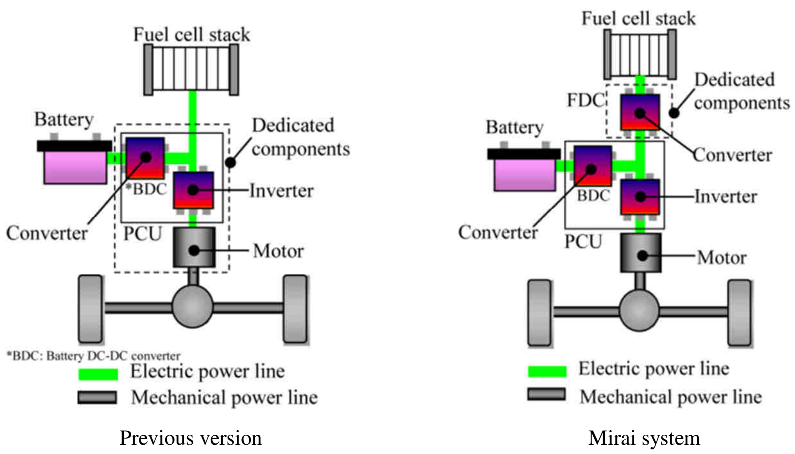


Fig. 3. Generations of Toyota vehicles fuel cell configuration [3]

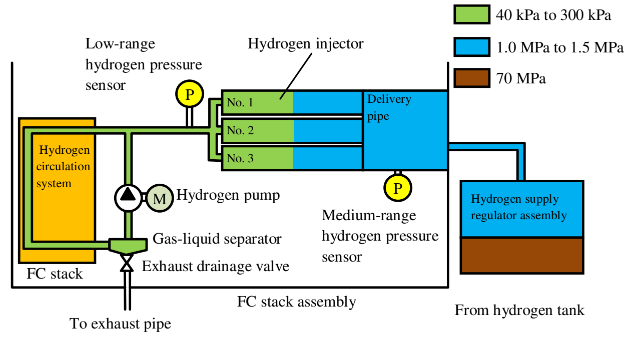


Fig. 4. The fuel cell power supply system schematic [5, 9]

Toyota Fuel Cell System (TFCS) is the world's first fuel cell system without an external humidifier. The fuel cell stack control and the control system was refined so that the water formed at the bottom of the cathode was transported to the front of the upper cathode part via internal circulation through the anode. The characteristic feature of the fuel cell system used in the tested vehicle is the three hydrogen injectors, that operate depending on the load on the system and their operation is the basis for the analysis carried out in the article.

Figure 5 shows the possible driving modes of the first mass-produced fuel cell vehicle. These modes are analogous to modes in hybrid vehicles, except that the function of the energy generator is to fill the fuel cell stack (as opposed to the diesel engine in HEV vehicles). The modes are: standstill loading, starting, normal driving, braking (energy recovery) and acceleration. Block diagrams indicate the systems used to drive the vehicle when in the driving mode. Two directions of energy flow are possible: the use of energy – in the form of hydrogen or electricity stored in a high-voltage battery, and the recovery of energy to charge the HV battery.

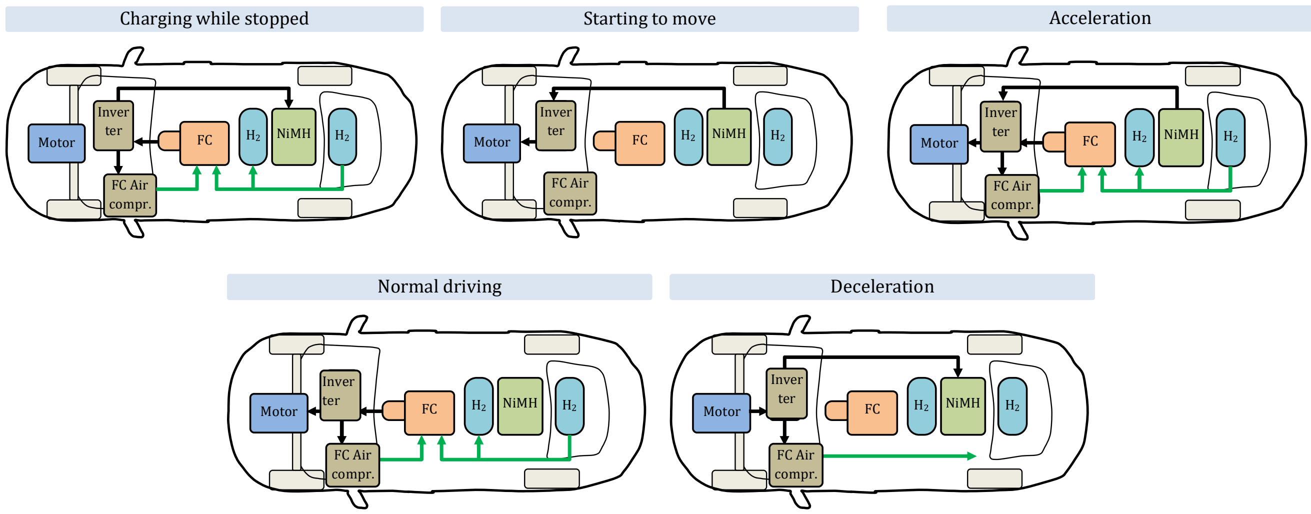


Fig. 5. Drive mode of Toyota Mirai [6]

2. Fuel cell tests

The aim of the fuel cell tests for the vehicle was to analyze the operating conditions of the fuel cell in relation to its power supply. Due to the use of three hydrogen injectors in the supply system, the control method was interesting.

The study was conducted in several vehicle operating states, in each case analyzing:

a) starting the fuel cells,

b) standard operating conditions of a fuel cell,

c) cooperation of the fuel cell with energy storage systems.

3. Fuel cell start

The fuel cell analysis was performed during the first test drive of the Toyota Mirai vehicle in Poland (the vehicle mileage was approximately 3,000 km at the time). Because of the limited amount of hydrogen and the short time of vehicle availability, the study was performed during the vehicle presentation in Warsaw. Drive data registration was based on the use of diagnostic monitors (FC – Fuel Cell and FCDC – Fuel Cell Direct Current) implemented in the OBD system. Recording of selected cell parameters from the presented diagnostic monitors was done using an OBD connector and a computer equipped with TechStream software. The number of recorded parameters affects the frequency of data recording. In the presented studies this frequency was:

– 8 to 20 Hz when recording 51 parameters of the FC monitor,

– 8 to 16 Hz when recording 91 parameters of the FCDC monitor.

The Toyota Mirai vehicle drive system analysis was performed in fuel cell start-up conditions. The first 20 seconds of operation after the system start were analyzed.

The fuel cell start-up began from the state of being switched off completely (as seen by the level of minimum voltage in Fig. 6). Within seconds (2–3 seconds), the value of the voltage generated by the cell stack was 315 V with a current of 32 A. The rated power (10 kW) is 10% of its maximum power. After a 10 second period, the current generated from the fuel cell increased (up to 40 A), which increased the power to about 13 kW. These conditions require only hydrogen injection by one injector placed in the power supply (Fig. 4).

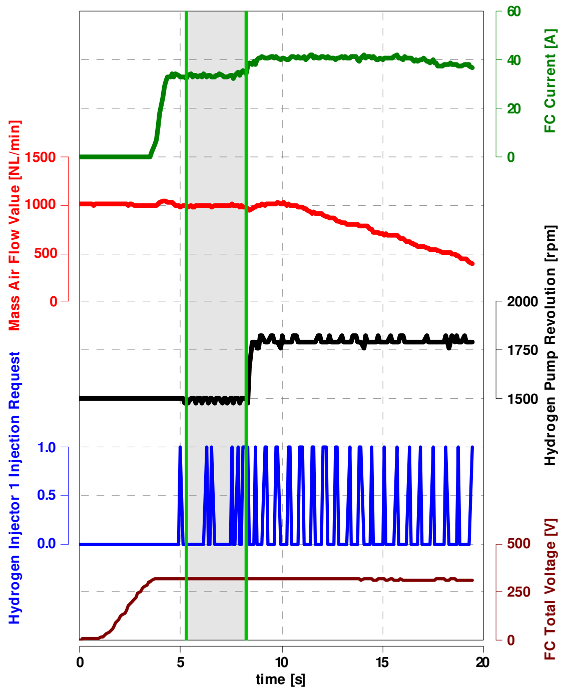


Fig. 6. Changes in fuel cell operating parameters during start-up (vehicle stopped)

Maintaining the operating parameters of the cell after its start-up requires an increased rotational speed of the hydrogen pump (from 1500 to 1800 rpm) and a much higher frequency of hydrogen injection by the injector 1. The supply of hydrogen is performed at a pressure of 122 kPa and the air pressure is maintained at 100 kPa.

4. Fuel cell driving operating conditions

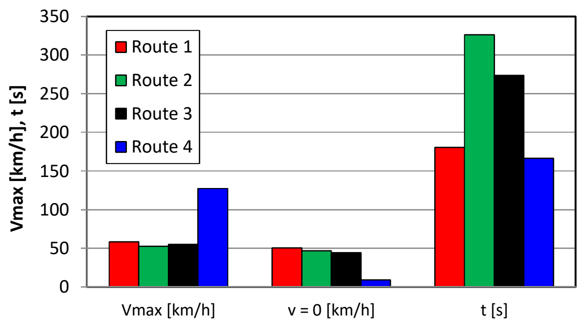
4.1. Analysis of a fuel cell operation

The drive operation evaluation began with an analysis of the test vehicle traffic conditions. Figure 7 shows the comparison of the conditions of the four Toyota Mirai routes. For three of those routes (routes 1, 2 and 3) the maximum traveling speeds are comparable and reach 50 km/h. On these routes the time spent stationary is also close in value (equal to 50% of the total test time) – Fig. 7a. Route 4 is characterized by an increased maximum vehicle speed. The test duration values are varied and range from 160 to 330 seconds respectively. The analysis of the time density of three driving phases, divided into: driving without acceleration (a = 0), acceleration (a > 0) and braking (a < 0) indicates that each drive had a similar driving parameters. In particular, routes 1–3 have a time density of up to 10% at constant speed and about 20% at acceleration and deceleration each.

The fuel cell power analysis shown in Fig. 8 during vehicle acceleration indicates a high level of its performance.

Maximum power of the fuel cell during acceleration is reached after 3.5 seconds. Hydrogen injectors are switched on gradually with the power demand. The third injector was used only after obtaining about 70 kW cell power generation. With the increase in electric current, the maximum voltage of the cell is reduced, which is in line with the typical characteristics of its operation. Resistance losses then increase, thus limiting the voltage value when increasing the current output [5]. The maximum current of the cell is 468 A at 244 V. The vehicle speed under these conditions was only 40 km/h.

a)



b)

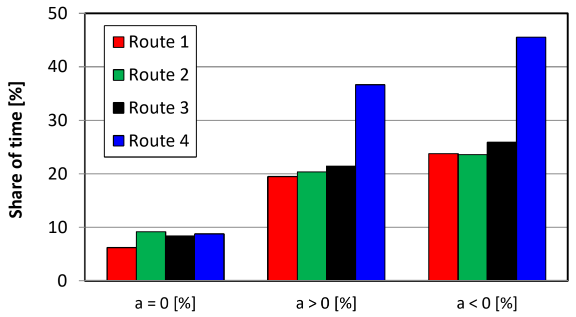


Fig. 7. Road test results of the Toyota Mirai vehicle: a) the vehicle speed, b) the vehicle acceleration time density (excluding the vehicle being stationary)

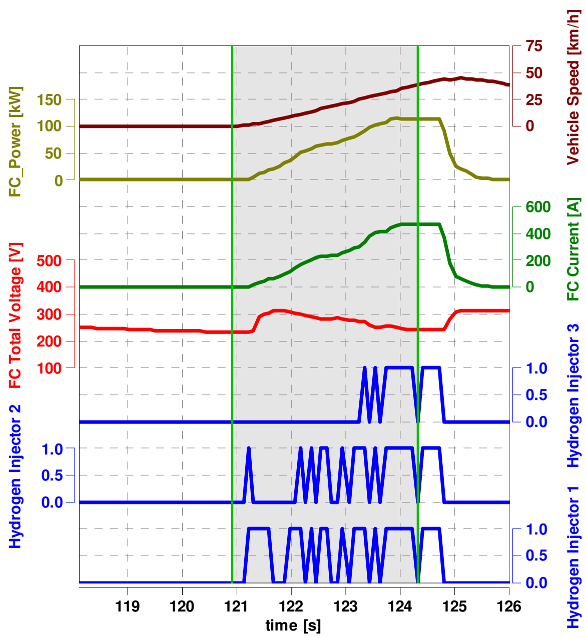


Fig. 8. Example of changes in hydrogen fuel supply (three injectors) against speed variations (average speed) of driving a Toyota Mirai (route 1)

The analysis of the hydrogen injectors operation relative to the driving conditions is shown in Fig. 9. For each test run of different instantaneous speeds and the resulting accelerator pedal position, the work of the individual hydrogen injectors is shown. On this basis, the use of injectors was evaluated based on the position of the accelerator pedal. It was assumed that this value was proportional to the load on the propulsion system.

The analysis was conducted for several acceleration pedal positions: 0%, 0-25%, 25-50%, 50-75%, and 75-100%. Data obtained from this analysis indicate the use of two injectors mainly. The third injector is only used during the final range of accelerator pedal position.

The results shown in Fig. 9 indicate the low speed of the vehicle forcing the third injector to operate.

An analysis was also carried out to summarize the effect of the speed and load on the operating conditions of hydrogen fuel injectors in the fuel cell. Injectors 1 and 2 are operated at each tested vehicle speed and for loads ranging from 0 to 100% (Fig. 10). The use of injector no. 3 is only required for loads exceeding 60%, which were respective of vehicle speeds in the range of 25 to 130 km/h.

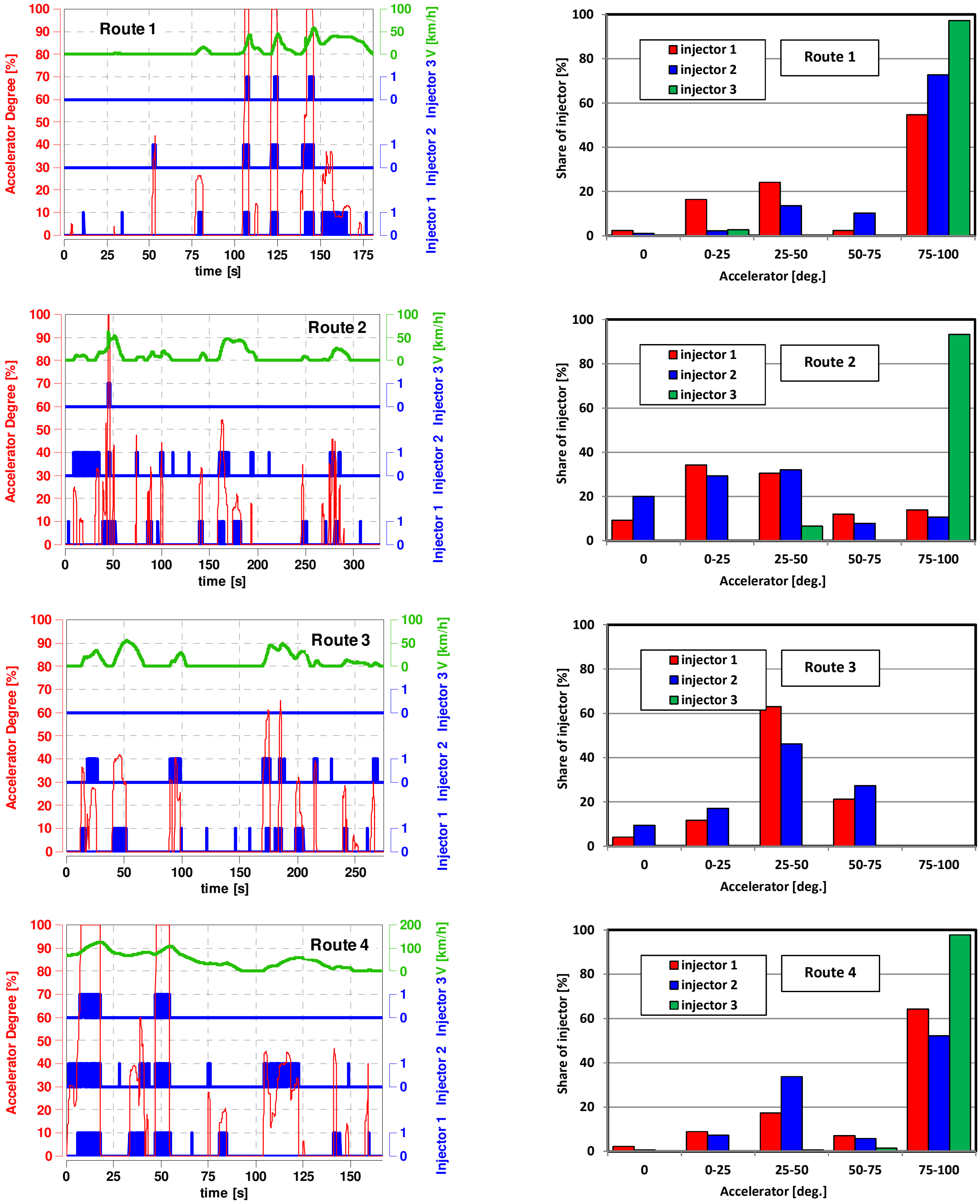


Fig. 9. Analysis of the fuel cell hydrogen power supply conditions by three injectors, along with the injector operating time densities (accelerator pedal positions)

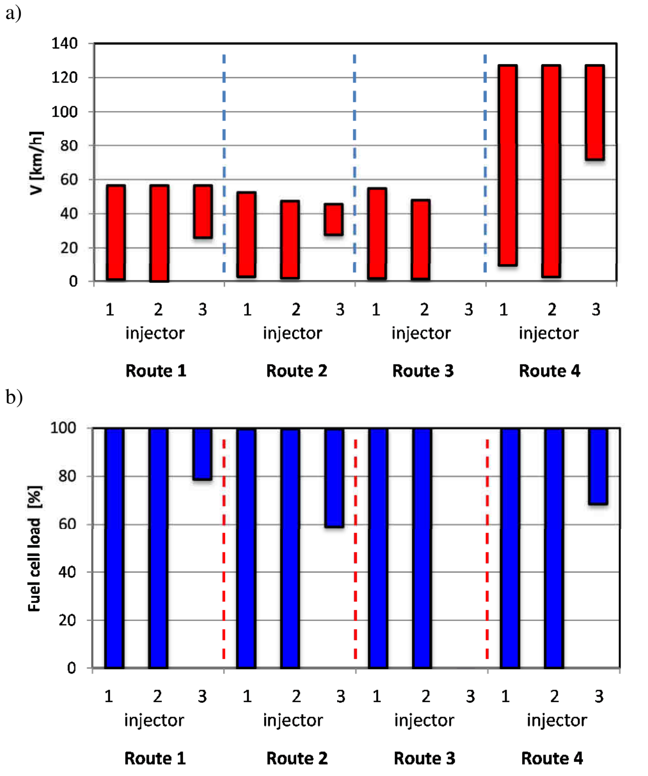


Fig. 10. The influence of vehicle speed (a) and fuel cell load (b) on operating conditions of the hydrogen fuel injectors in the fuel cell

3.2. The interaction of fuel cell and high-voltage battery

The hydrogen drive configurations shown in Fig. 3 indicate that the current systems will use so-called boosts (analogous to hybrid drives) to increase the voltage applied to the electric motor. The fuel cell DC-DC converter (FDC) increases the voltage from the fuel cell up from a maximum of 315 volts to 650 volts. This arrangement allows to double the power of the electric motor driving the vehicle. The conditions for this voltage gain during the operation of the Mirai Toyota system are shown in Fig. 11. It is evident that during vehicle acceleration, the input voltage to the FDC achieves a maximum value (about 315 V), while the output of the converter is above 600 V. Additionally, the high-voltage battery operation is noted to aid the fuel cells – discharging during acceleration (positive current values) and charging during most braking maneuvers. Despite varying driving conditions, the battery charge level is maintained at 52–62%. This level of charge is also used in hybrid vehicles, which extends the battery lifetime.

Based on the above relationships, the HV battery operating conditions have been analyzed. According to Fig. 12a, the charging of the battery is carried out at increased voltage to about 315 V (fuel cell operating voltage). Significant battery charge time applies to small charging currents up to 50 A. Its discharge consists in using a current of up to 20 A, however, the maximum values exceed 120 A.

The electric motor operating conditions indicate the use of its full characteristics (Fig. 12b). Regenerative braking mainly occurs in areas of small torque values and in the range of average speeds.

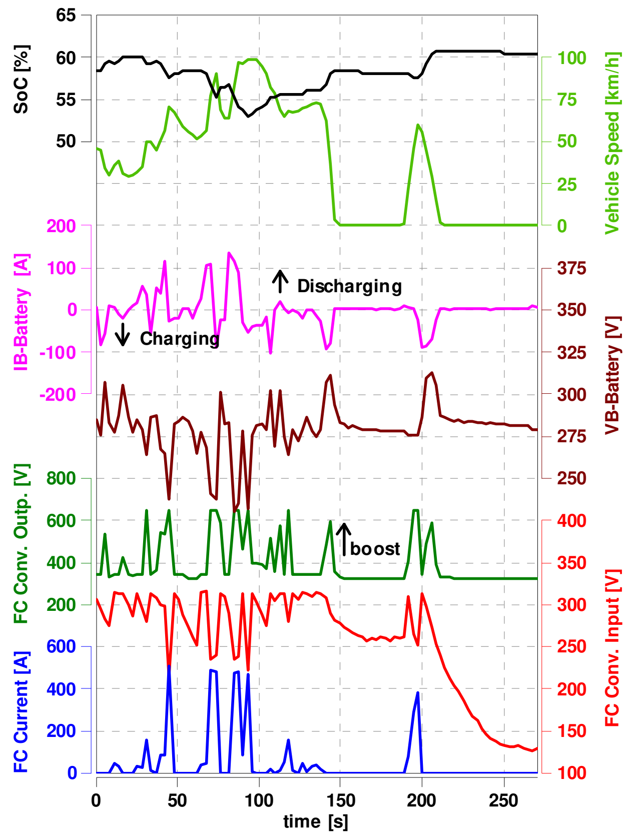


Fig. 11. Operating conditions for the voltage boost circuit for the voltage generated by the fuel cell

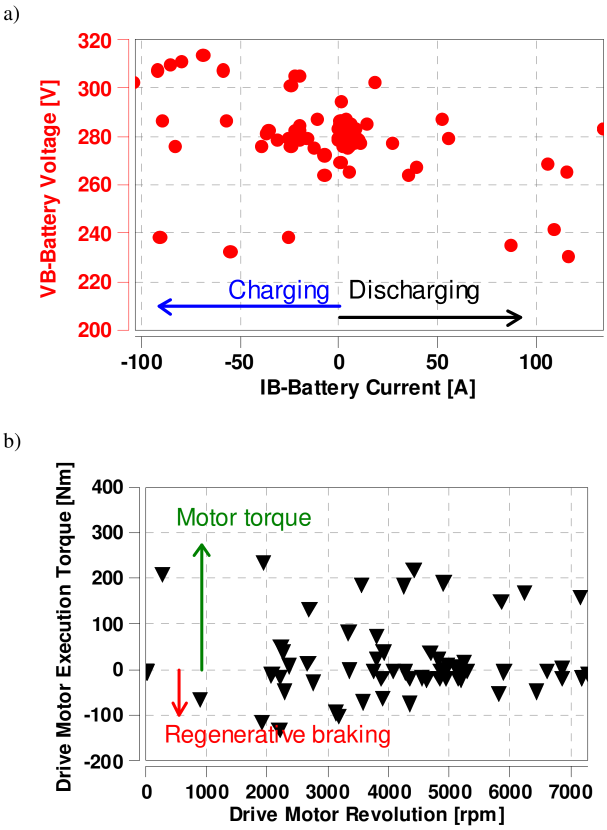


Fig. 12. Operating conditions of the systems: a) high-voltage battery, b) electric machine acting as a motor or generator

4. Conclusions

The Toyota Mirai is the first mass-produced vehicle to feature three independent fuel cell hydrogen injectors. An analysis of the fuel cell system in the vehicle in typical traffic conditions allows to pinpoint the key aspects of this system's operation:

1. The maximum value of the fuel cell voltage (315 V) when moving from zero is obtained after approximately 4 seconds during the vehicle start-up.
2. The full power of the fuel cell for vehicle acceleration is available after about 3.5 seconds after the vehicle has stopped (fixed operating conditions of the fuel cell).
3. The use of three hydrogen injectors allows for a wide range of possible ways of obtaining the desired flow of hydrogen for the fuel cell supply; The third injector is activated only during a high fuel cell load values at 75-100% of the accelerator pedal position. Analysis of the results indicates that the third injector is only running at speeds exceeding 35 km/h.
4. Equipping the power management system with a voltage boosting circuit for the electric motor power supply allows the voltage to be increased from 315 V to 650 V. The driving conditions that necessitate the operation of the so-called boost is rapid acceleration of the vehicle regardless of the charge level of the high-voltage battery.

Due to the limited time availability of the vehicle for the study future research will be conducted on both the chassis dynamometer in the standardized NEDC test as well as in real vehicle driving conditions at comparable distances. Then the results of the study will be comparable with the results from hybrid vehicles already tested by the Authors. This analysis will allow for a complete assessment of the propulsion system's energy consumption relative to other vehicles. The limitation in carrying out such tests is, however, that there is currently no infrastructure for refueling such vehicles in Poland.

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Nomenclature

a	acceleration	IB	battery current
AC	alternating current	NiMH	nickiel hydride battery
CO_2	carbon dioxide	OBD	on board diagnostic
FC	fuel cell	TFCS	Toyota Fuel Cell System
FCDC	fuel cell direct current	v	speed
FDC	fuell cell direct current converter	Vmax	maximum speed
HEV	hybrid electric vehicle	t	time
HV	high voltage	VB	battery voltage

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