

## SESSION A:

## EARTH MOVING AND TRANSPORTATION MACHINERY

## Experimental study of energy efficiency of a hydrogen vehicle

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### ARTICLE INFO

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### ABSTRACT

This study aims to determine the fuel economy of a hydrogen vehicle by analyzing its energy efficiency in real road conditions. The object of the study is a fuel cell vehicle. Hyundai NEXO, in which hydrogen is an energy carrier, from which electrical energy is obtained for the drive. The purpose of the development is to determine the hydrogen consumption and the corresponding energy intensity (kWh/km) in different driving modes, as well as to analyze the influence of speed, driving dynamics and road conditions on the efficiency of the vehicle. The experimental study is carried out in a real road environment on the territory of Sofia and the adjacent expressways. Two main road cycles are defined: urban and mixed, which reflect the typical modes of operation of cars. A GPS-based system for measuring dynamic parameters is used to collect data, and hydrogen consumption is determined by the vehicle's on-board instruments. The assessment of economy is carried out using indicators such as hydrogen consumption (kg/100 km) and energy consumption (kWh/km), which allows comparison between different driving modes. Particular attention is paid to the influence of different speeds on energy efficiency, as well as the differences between urban and extra-urban traffic. The results obtained contribute to a detailed study of the real-world operational efficiency of hydrogen vehicles and can be used to assess their role in sustainable transport. The study has practical significance in the context of the growing interest in hydrogen technologies and policies for the decarbonization of the transport sector.

### KEYWORDS

Hydrogen car, Hydrogen fuel cell, hydrogen, hydrogen consumption, FCEV.

### 1. INTRODUCTION

The increasing demands for decarbonization of the transport sector stimulate the development of alternative propulsion systems with low or zero local emissions [1]. Among them are hydrogen fuel cell electric vehicles (FCEV), which represent a promising solution for achieving long range, short charging time and high energy efficiency under real operating conditions. These facts prove the potential of hydrogen vehicles and confirm the need for their detailed study in order to improve the control algorithms of individual powertrain nodes and the design of this type of vehicle. In-depth study of their dynamic and economic indicators will help users determine the optimal operating mode of their vehicles, which will lead to a reduction in energy costs and an extension of the service life of vehicles [2], [3].

The aim of this study is to develop and experimentally apply a methodology for assessing the energy efficiency of a hydrogen vehicle in real road conditions.

### 2. THE RESEARCH

Worldwide, bench tests are mainly conducted, which aim to make a comparison between different vehicles and, above all, to determine the harmful emissions. Tests in real conditions are significantly less, and they are more applicable to determining the fuel consumption of vehicles. It is important to note that the advantage of bench tests is that they can be reproduced many times for different vehicles, while road tests in real conditions cannot provide full repeatability.

The present study was developed for regional conditions in the Sofia region. In addition to the selected routes, a decisive factor for its successful implementation is the equipment used. For the accurate determination of speed regimes, overcome displacements, accelerations and distance traveled, GPS-based equipment was used, which performs detailed recordings

of various parameters in real time during the process of conducting individual studies. Due to limited access to the internal parameters of the fuel cell through standard diagnostics, the study uses a tank-to-wheel approach, based on measuring the actual hydrogen consumption and dynamic parameters of the vehicle.

### 3. OBJECT OF THE RESEARCH

The object of the study is a Hyundai Nexo passenger car using fuel cell (Fuel Cell Electric Vehicle – FCEV), in which electrical energy is produced on board through an electrochemical reaction between hydrogen and oxygen. The hydrogen is stored under a high pressure of 700 bar in three special vessels located in the rear of the vehicle, and with the help of a reducing valve and a pipeline, the hydrogen reaches the fuel cell in the front of the vehicle. When the fuel cell operates, electrical energy, water and heat are released without any harmful emissions. The electrical energy produced powers the vehicle's on-board network, and a high-voltage battery is used to regulate the electrical system. Its functions focus on assisting acceleration, energy recovery and stabilizing the power balance of the entire vehicle [4].

The Hyundai NEXO fuel cell is one of the most advanced series-produced PEM (Proton Exchange Membrane) systems in the automotive industry and is often used as a reference example in scientific publications on FCEV technologies. The reason for this is the relatively compact design of the stack, which is characterized by a high volumetric power density, which means that the cell generates relatively high power in a small volume. This indicator is measured in kW per unit volume and is denoted by kW/L. In the Hyundai Nexo cell, it is 1 kW/L, while in the company's previous hydrogen car, the IX 35 Hydrogen, it was 0.8 kW/L. Better efficiency of the cell is achieved through thinner membranes, better catalysts in the cell itself with high reaction activity. To increase the performance of the fuel cell, it is necessary to improve the distribution and supply of gases in the cell, as well as to improve its temperature balance. An air compressor is used to supply air to the cell. Such indicators reduce the weight of the fuel cell itself and the vehicle as a whole, freeing up additional volume for other units on board. In addition, energy efficiency and dynamic characteristics are improved. This type of cell is suitable for use in cars, as they develop a low operating temperature and start quickly, even at low temperatures [5]. The fuel cell consists of several stacks, with their total power amounting to 95 kW, while the engine has a power of 120 kW, and to reach its maximum power at peak loads, electrical energy from the battery is used. During operation of the cell and before activation, it must be well hydrated. This is a necessary condition for the effective passage of  $H^+$  protons through the membrane. Otherwise, the result is that the internal resistance increases, leading to a drop in voltage and a decrease in efficiency, but also the temperature increases locally, which can lead to cracking of the membrane and its chemical aging. To protect the cell from drying out, a system for humidifying the inlet air is used, using part of the water obtained as an end product from the operation of the cell itself. In this process, moisture is transferred without direct mixing of gases from the outlet and inlet tract. Before reaching maximum load on the fuel cell, the system monitors the temperature, humidity and activates the air system, stabilizing the cell. Cold start is also not without problems. At extremely low temperatures, freezing of the water in the cell can occur, the membrane dries out and its proton permeability decreases. Therefore, cells used in vehicles have a temperature control system, which consists of a hydrator and an electric heater. If the cell becomes overly humid and filled with water, this can block the passage of various gases through it and stop it from working [6].

These facts show that before conducting research with hydrogen cars, it is necessary to select appropriate conditions, such as bringing the fuel cell to operating temperature and ensuring its humidification.

Proton-conducting fuel cells used in cars are very sensitive to contamination and deviations in the parameters of hydrogen. Its purity must be 99.97% or higher. Carbon monoxide (CO), sulfur compounds, ammonia or hydrocarbons can lead to catalyst poisoning, reduced efficiency or accelerated degradation of the cell. In passenger cars, hydrogen is stored in special vessels at a pressure of 700 bar, while in trucks and buses it is 350 bar. Regardless of the type of car, the pressure in the cylinders must be stable and reduced when it is fed to the fuel cell, to the required levels.

The temperature during vehicle refueling can affect the density of the hydrogen fuel and safety. The rate of refueling increases the temperature in the fuel cylinders. A number of procedures have been developed for the actual refueling of vehicles with hydrogen, specifying temperature compensations, operating pressure during refueling and corresponding drop levels, as well as a number of other safety measures [8]. Other regulations specify requirements for hydrogen stations, covering their infrastructure, safety features and specialized technical requirements [7].

Table 1: Permissible levels of hydrogen contamination in fuel cells ISO 14687 [9]

| Pollutant                  | Maximum permissible concentration | Impact on fuel cell      |
|----------------------------|-----------------------------------|--------------------------|
| Carbon monoxide (CO)       | 0.2 ppm                           | Catalyst poisoning       |
| Total sulfur compounds     | 0.004 ppm                         | Irreversible degradation |
| H <sub>2</sub> S           | included in sulfur limit          | Catalyst deactivation    |
| Ammonia (NH <sub>3</sub> ) | 0.1 ppm                           | Membrane damage          |
| Formaldehyde               | 0.01 ppm                          | Membrane degradation     |

| Pollutant                          | Maximum permissible concentration | Impact on fuel cell             |
|------------------------------------|-----------------------------------|---------------------------------|
| Formic acid                        | 0.2 ppm                           | Corrosion                       |
| Water (H <sub>2</sub> O)           | 5 ppm                             | Flooding / corrosion            |
| Oxygen (O <sub>2</sub> )           | 5 ppm                             | Reduced efficiency              |
| Nitrogen (N <sub>2</sub> ) + argon | 300 ppm                           | Fuel dilution                   |
| Hydrocarbons                       | 2 ppm                             | Contamination of the electrodes |
| Particles                          | strictly limited                  | Blocking flow channels          |

#### 4. PREPARATION OF THE VEHICLE AND EQUIPMENT

Before the test, the vehicle must be prepared according to the manufacturer's recommendations. This means checking the tire pressure, size, condition, and suitability for the season in which the test is being conducted. It is also important to check the technical condition of all bodywork components that affect the vehicle's aerodynamics and fuel efficiency. It is important to ensure that sufficient fuel is available for the test in advance. All unnecessary energy consumers should be turned off and any unnecessary load removed from the vehicle [6].

In case the vehicle has not been used immediately before the test, it is necessary to make a short trip of 10 to 15 minutes in order to reach the operating temperature of the cell and to ensure its humidification. This ensures the correct operation of the fuel cell and the recharging of the auxiliary battery. Before starting the test itself, the vehicle's on-board computer should be reset and various indicators should be recorded in the protocol, such as the temperature of the cell, the odometer reading, the setting of the air conditioning system, etc. The fuel tanks should be filled to the maximum, because the pressure in them affects the density of hydrogen, its temperature. When pre-setting it, it is also necessary to note the level of recuperation that will be used while driving. Only at the zero level is the recuperation activated when the brake pedal is pressed, while at the other three levels the recuperative mode of operation of the system is activated at the moment the driver releases the accelerator pedal.

#### 5. THE ROUTES

The test routes are pre-determined on the territory of the city of Sofia and the expressways around it. They are of three types: urban, suburban and mixed. The leading criterion for selecting the routes is to study the fuel efficiency of the vehicle when operating on different types of roads. They are of different lengths, with the urban route being shorter and the mixed route being longer. Both routes start and end at the same place in order to eliminate the influence of elevation changes. They are also selected so that they do not pass through tunnels in which the records of the GPS-based measurement system would be disturbed.

The urban cycle is 14.9 km long, covering a section of an urban highway with a maximum permitted speed of 80 km/h. In this way, the specific study covers all classes of roads in the urban environment and the movement of the vehicle in a fixed driving mode, and not only in transient modes. This reduces the influence of energy recovery and increases the influence of speed.

The mixed cycle is 30.9 km long, covering both city streets and the Northern Speed Tangent, where the speed of movement is 120 km/h, in addition, a certain part of it passes through the ring road with a maximum speed of 90 km/h. This cycle covers a wide range of traffic modes, which makes it maximally dynamic.

#### 6. GPS-BASED EQUIPMENT

A GPS-based VBOX type measuring system is used to record the speed, mileage and dynamic parameters of the vehicle. The device uses satellite positioning with a high sampling rate to determine the speed, distance traveled, time and coordinates of movement. The use of a GPS measuring system allows for high accuracy and independence from the vehicle's factory measuring systems.

The Vbox Racelogic used is a professional device for measurements in car racing, various road studies in real conditions and measurement of dynamic characteristics during braking and acceleration of vehicles. This type of devices is used by a number of universities, scientific organizations, automobile manufacturers, test centers and engineers in motor sports. The equipment is distinguished by particularly high accuracy in measuring speed, time and distance. According to the manufacturer, the deviation of the measuring system in speed measurements is up to  $\pm 0.1$  km/h [10]. Accuracy is higher on open country routes, due to the lack of tall buildings that would interfere with satellite signals. Suitable for the present study is the property of the device to draw the route traveled on a digital map, and it can be traced in which section of the route the car was moving at what speed and what distance it was traveling. The listed properties of the system prove that it is particularly suitable for performing measurements in real road conditions.

During the tests, in addition to the automatic recording of GPS data, manual notes were also kept on external conditions and events that could have an impact on the measurement results. Parameters such as weather conditions, traffic, temporary traffic restrictions and other factors affecting the vehicle's operating mode were recorded.

## 7. RESULTS

The test results are presented in tables, graphs and route profiles to visualize the operating modes and hydrogen consumption under different driving conditions. Parameters such as average speed, maximum speed, driving time and specific hydrogen consumption were analyzed.

Due to the impossibility of direct access to the data on the fuel cell parameters, the average fuel consumption was taken from the readings of the vehicle's on-board computer in the study. These data are not distinguished by high accuracy and precision, but for conducting real road conditions they provide good enough information about the fuel consumed during the test. One of the main factors that indicate the influence of the test data is traffic. Depending on its intensity, the hydrogen consumption could change significantly. Conducting multiple studies in different time ranges would provide more accurate data on hydrogen consumption.

In urban driving mode, the measured average consumption is 0.9 kg/100km, for 14,866 km traveled, this means that the actual fuel consumed is 0.134 kg of hydrogen. In terms of energy value, it is equal to 4,456 kW/h. Figure 2 shows clearly pronounced transient modes with stops and accelerations, as well as sections with established traffic.

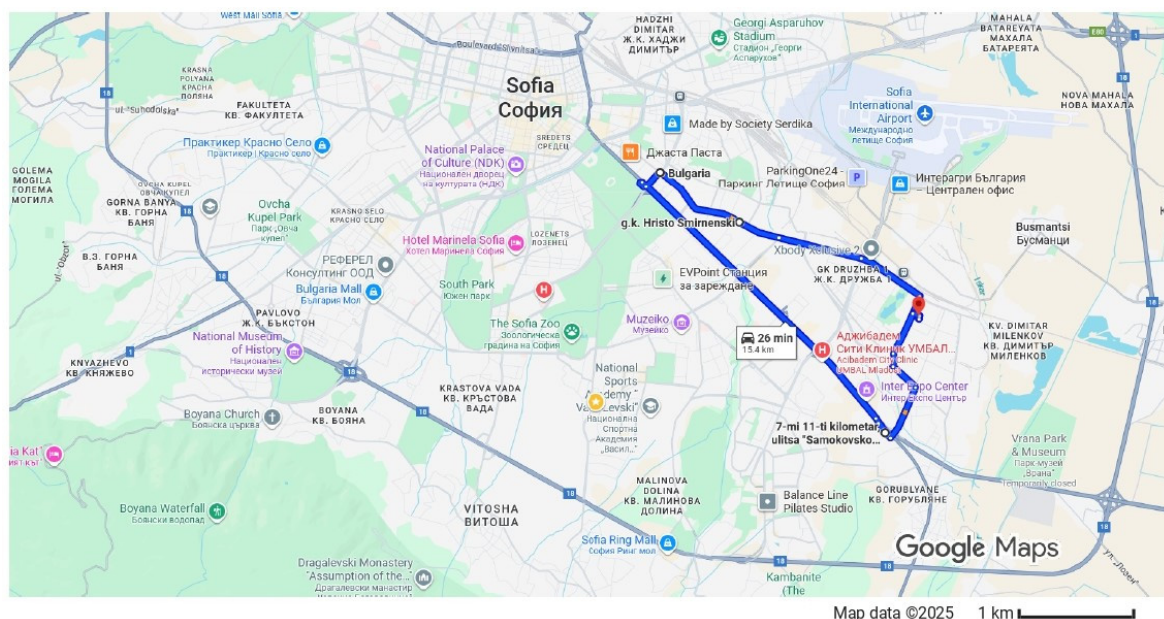


Figure 1: Map of the urban route traveled



Figure 2: Velocity change as a function of time

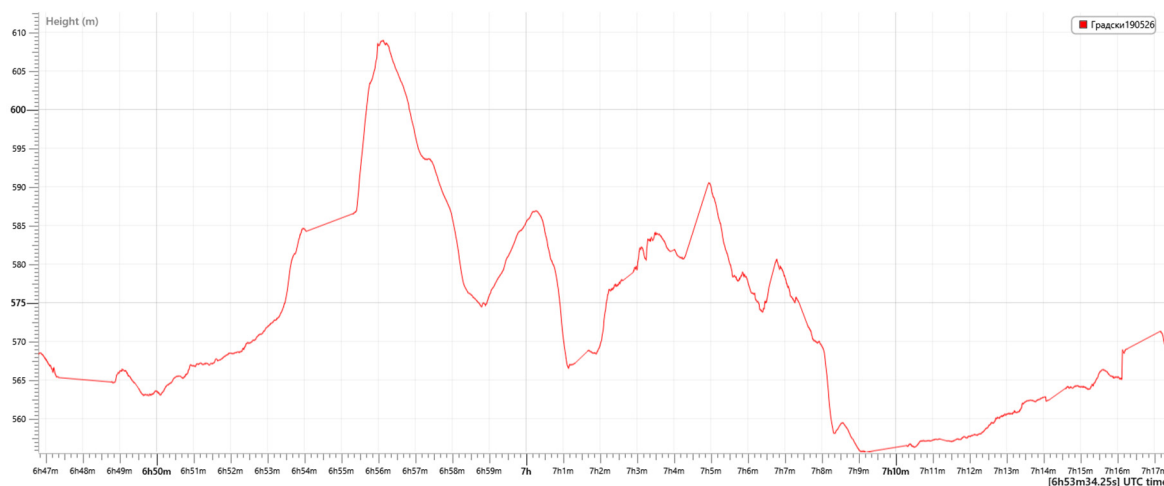


Figure 3: Overcome elevation changes as a function of time

After driving the mixed route, the measurement data shows an average consumption of 0.8 km/100km of hydrogen. For the specific trip, this is 0.246 kg of hydrogen, which is equivalent to 8.178 kW/h.

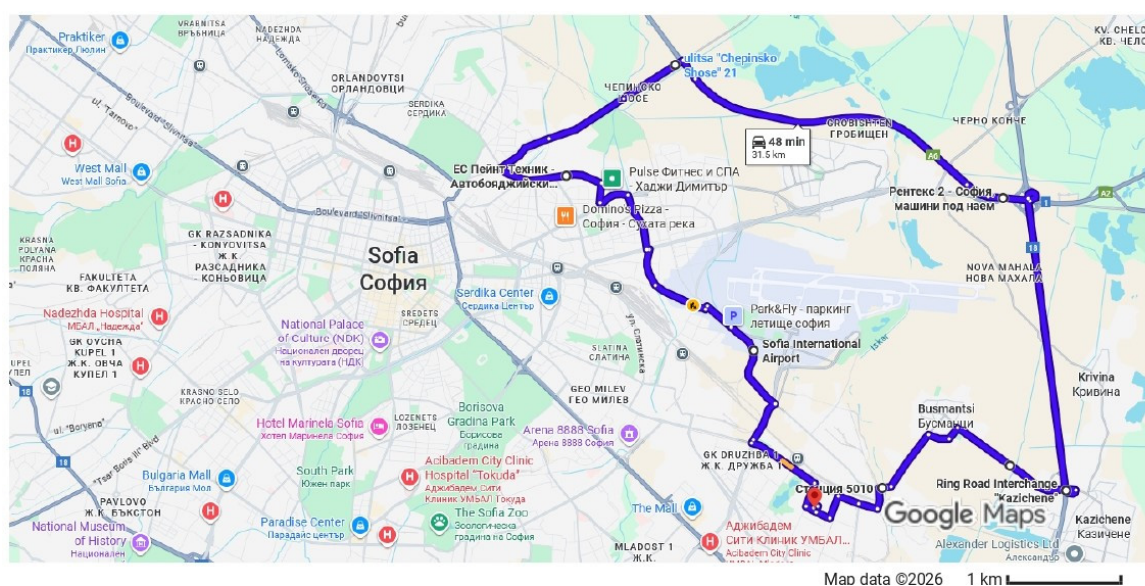


Figure 4: Map of the mixed route traveled

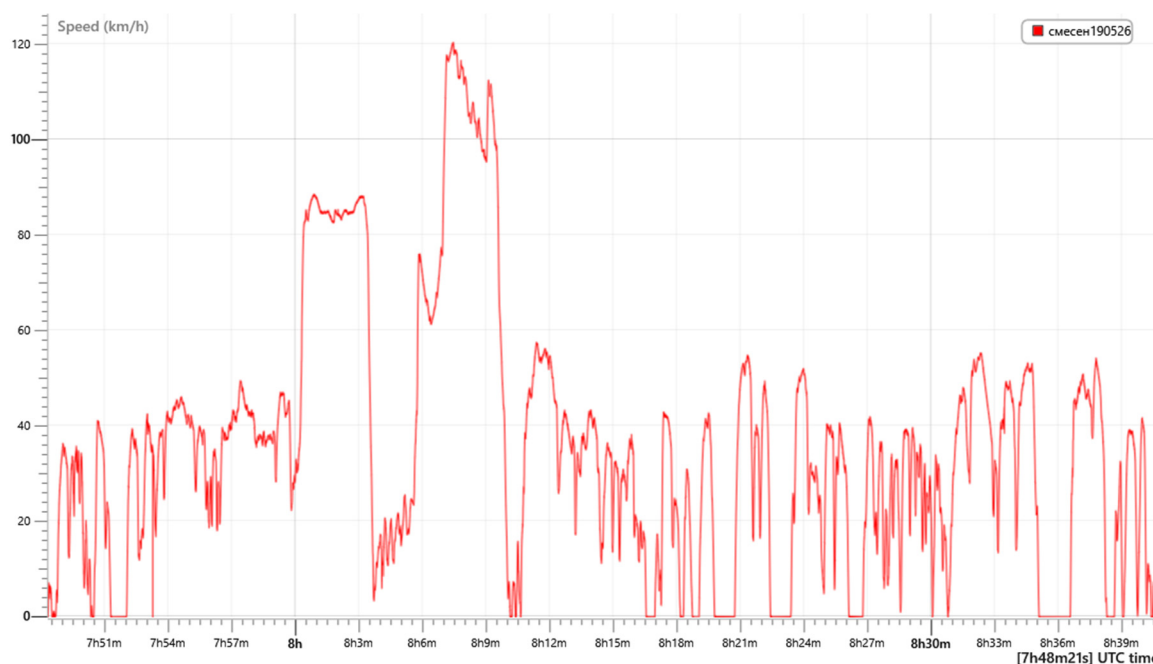


Figure 5: Speed variation on a mixed route

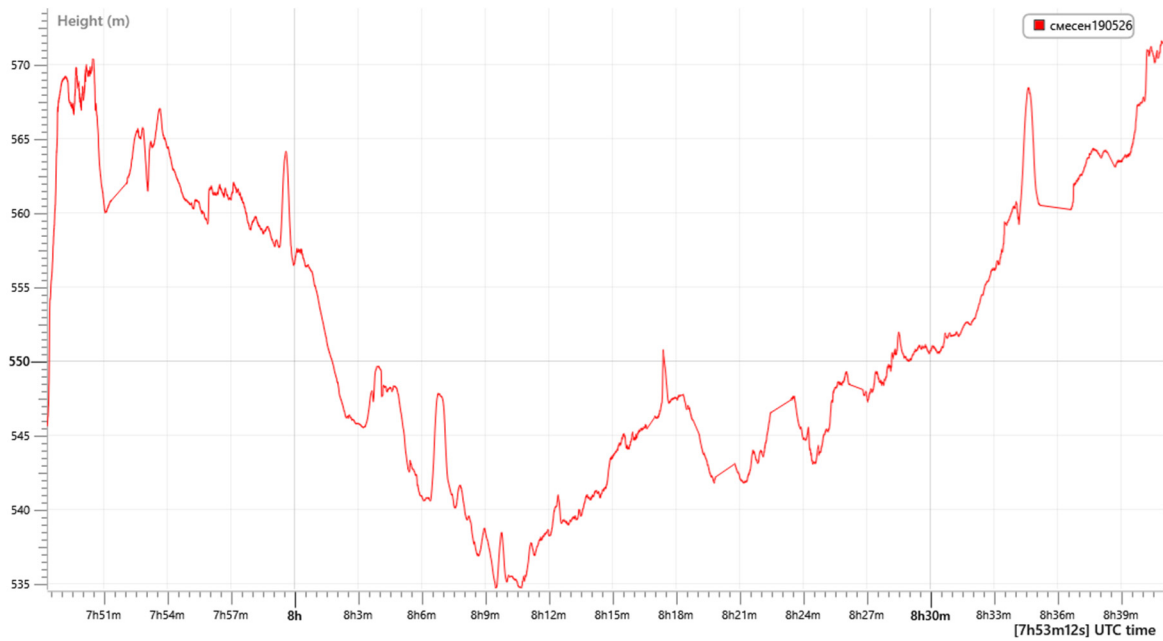


Figure 6: Variation of elevation gain over time for a mixed route

During the study, data was obtained on average fuel consumption and kilometers traveled.

By the formula:

$$C_{H_2} = \frac{m_{H_2}}{s} \cdot 100 \quad (1)$$

$C_{H_2}$  - average hydrogen consumption [kg/100km]

$m_{H_2}$  - hydrogen consumed [kg]

$s$  - distance traveled [km] [11]

From which it follows that:

$$m_{H_2} = \frac{C_{H_2} \cdot s}{100} \quad (2)$$

The energy used for a specific trip is determined by the formula:

$$E = m_{H_2} \cdot LHV_{H_2} \quad (3)$$

$E$  - energy used [kWh]

$m_{H_2}$  - hydrogen mass [kg]

$LHV_{H_2}$  - lower calorific value of hydrogen (assumed to be 33.3 kWh/kg) [12]

$$e = \frac{E}{s} \quad (4)$$

$e$  - energy intensity [kWh/km]

$E$  - energy used [kWh]

$s$  - distance traveled [km] [13]

Table 2: Comparison of hydrogen consumption in urban and mixed routes

| Route | Average hydrogen consumption | Travelled distance | Hydrogen consumption (2) | Energy intensity (4) | Consumed energy (3) | Maximal distance travelled with this consumption |
|-------|------------------------------|--------------------|--------------------------|----------------------|---------------------|--------------------------------------------------|
|       | kg/100km                     | km                 | kg                       | kWh/km               | kW/h                | km                                               |
| City  | 0.90                         | 14.866             | 0.133794                 | 0.2997               | 4.4553402           | 696.67                                           |
| Mixed | 0.80                         | 30.7               | 0.2456                   | 0.2664               | 8.17848             | 783.75                                           |

## 8. EXTRACTS

The conducted research shows that the Hyundai NEXO hydrogen car demonstrates high energy efficiency when operated in real road conditions. The obtained results confirm the possibility of achieving low hydrogen consumption in urban traffic, with the measured values in the conducted tests varying between 0.8 and 0.9 kg/100 km. These differences are a result of dynamic traffic, transient traffic regimes and other factors that are reflected in real traffic conditions in a real environment.

The study shows that the nature of the speed profile has a significant impact on the energy efficiency of the vehicle. With smoother movement and a smaller number of intense accelerations, a decrease in hydrogen consumption is observed, which is associated with more stable operation of the fuel cell and lower instantaneous load on the power system. At the same time, movement at high speeds leads to an increase in energy consumption due to an increase in aerodynamic resistance.

The use of a GPS-based VBOX type measurement system allows for reliable recording of the vehicle's dynamic parameters and detailed analysis of the operating modes. The obtained speed profiles and route data allow for tracking the influence of individual sections of the route on the hydrogen consumption and the overall energy intensity of the vehicle.

Despite the limitations associated with the use of data from the on-board computer and the inability to directly access the internal parameters of the fuel cell, the applied methodology allows obtaining reliable information about the real operational efficiency of the hydrogen vehicle.

The results obtained show that hydrogen fuel cell vehicles have potential for application in sustainable transport, especially when operating in urban and mixed traffic conditions. The present study can serve as a basis for future developments related to expanding the experimental base, conducting long-term tests and comparing different operating modes and types of electric vehicles.

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