Model of a prototype vehicle powered by a hybrid hydrogen system

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Abstract. The paper presents a physical mathematical model of the movement of a prototype vehicle equipped with an electric drive system powered by two sources of hydrogen fuel cell and supercapacitors. The model is based on the analysis of the forces acting on the vehicle during motion, taking into account both resistance to motion and propulsion. The model also considers the flow of electrical energy from two sources: a hydrogen fuel cell and supercapacitors, taking into account energy buffering. The aim of the model was to develop a tool to analyse fuel consumption at different control strategies of energy flow in a vehicle. The paper also presents the results of model identification for the Hydros prototype vehicle developed at Lublin University of Technology for the Shell Eco Marathon competition. Model validation was performed for a selected run during the 2019 London competition. High agreement of the model with the results of the actual vehicle was obtained.

1. Introduction
Automotive is one of the largest global industries by revenue. It is mainly used in global transport. For many years, significant changes have been observed in the automotive market, aimed at reducing the emissions of toxic gases into the Earth's atmosphere. The introduction of increasingly stringent emission standards and growing public awareness are causing significant changes in the automotive market. For decades, the dominant powertrain in the automotive industry was the internal combustion engine (ICE), but today it is increasingly being replaced by an electric drive [1-2]. In 2017, the 100000 new electric vehicles (EV) sold mark was crossed for the first time. According to the Bloomberg agency, the sales of electric cars will increase significantly in the coming years (Figure 1) [3].

BEV (Battery Electric Vehicles) are powered by an electric motor and take their energy from a storage device, which is usually a battery. The drive range of a BEV depends on the capacity of its energy storage device. Currently, the main factor blocking the further development of BEVs is the energy storage. Currently, the lithium-ion batteries are mostly used in fully electric vehicles. These have a considerable energy density of 0.889 (MJ/kg) (Figure 2). However, this is significantly less compared to the conventional propulsion systems, for which the energy density is 43 to 46 MJ/kg (for petrol and diesel). Of course, it is always possible to improve the amount of electricity storage by increasing the number of cells. Unfortunately, this results in an increase in the total weight of the vehicle and thus in the energy consumption over a given distance. Vehicle weight and battery energy are two main parameters which are difficult to balance. Moreover, when analysing the batteries of
electric vehicles, it is worth noting that they are the basic component of the vehicle purchase cost. An additional limitation is the limited number of battery charging cycles. This means that a battery can only be recharged a limited number of times, much less than the total lifetime of the vehicle. This necessitates their replacement during the life of the vehicle [4-6].

![The Rise of Electric Cars](image1.png)

**Figure 1.** Forecast of the volume of sales of electric cars for the following years [3].

![Energy-density](image2.png)

**Figure 2.** Comparison of the energy density of energy sources used in transport [5].

Other solutions are therefore being sought to exploit the advantages of electric propulsion but with significantly reduced problems with battery packs. One solution is to use renewable fuels such as hydrogen.

Hydrogen is the most abundant gas in the universe. Furthermore, its calorific value is very high: 120 MJ/kg (Figure 2). Hydrogen, like electricity, is considered an energy carrier rather than an energy source because, as a gas (H₂), it does not occur naturally on Earth. Unfortunately, due to its very low density, it is necessary to store hydrogen under high compression (up to 700 bar) or in liquefied form to ensure an adequate energy density. In liquid form, hydrogen has an energy density of about 120
(MJ/kg), which is about 130 times better than that of lithium-ion batteries (Figure 2). Hydrogen itself, as an energy carrier, can be used to power fuel cells, which are a fairly new technology in the field of electricity generation. The advantage of this approach is the high efficiency in converting the chemical energy directly into the electrical energy used in electric propulsion systems [7-8].

The hydrogen fuel cell system has a very high energy density, mainly due to the characteristics of the hydrogen fuel, and is capable of delivering high power for long periods. However, the system has a poor response to dynamic changes, due to the need for compression to supply air to the fuel cell cathode. It is therefore recommended to introduce an additional energy buffer element to smooth out the variation in energy demand from the fuel cell [9-11]. In addition, the introduction of such a buffer allows the capture of the energy recovered from braking. Therefore, a combination of fuel cells with supercapacitors is used very often [13-14].

Supercapacitors are characterised by high efficiency, simple circuit system, long life and safety of use. The high power density of supercapacitors (10 kW/kg) (Figure 3.) enables them to charge and discharge quickly, which is ideal when a sudden surge of power is required. Supercapacitors can operate for more than 15 years, while batteries are capable of operating for about 5 years [11-12]. The main disadvantage of supercapacitors is their low energy density, which is less than 10 Wh/kg (compared to lithium-ion (Li-on) batteries, the energy density of which is 150 ÷ 180 Wh/kg) [15-16].

![Figure 3. Comparison of energy density and power of different electrochemical energy storage methods [15].](image)

A power system based on fuel cells and supercapacitors requires an appropriate selection of components and control strategies to enable the use of their advantages to achieve the desired effect: minimising fuel consumption. This can be achieved at the level of real-world experimental or modelling work. This paper presents a modelling approach. The paper focuses on the development of a vehicle model and its identification as a tool to optimise the powertrain design.

2. Research object
Hydros (Figure 4) is a prototype hydrogen powered vehicle, designed and built by members of the Student Scientific Group of Aerospace Propulsion Systems at the Department of Thermodynamics, Fluid Mechanics and Aerospace Propulsion Systems of the Faculty of Mechanical Engineering of Lublin University of Technology. It was created with the Shell Eco-marathon cyclical competition in mind. The basic technical data of the vehicle are presented in Table 1. The Hydros monocoque is made of carbon fibre reinforced with aluminium profiles at the points bearing the highest loads. The vehicle is based on a 2+1 design, i.e. two steering front wheels and one driving rear wheel.
Figure 4. Hydros vehicle.

| Parameter                  | Value             |
|---------------------------|-------------------|
| Length                    | 2920 mm           |
| Height                    | 625 mm            |
| Width                     | 680 mm            |
| Wheelbase                 | 1600 mm           |
| Front track width         | 820 mm            |
| Unladen weight (without driver) | 37 kg            |
| Total weight (with driver) | 75 kg             |
| Coefficient of resistance Cx | 0.1               |
| Motor power               | 260 W             |
| Cell power                | 300 W             |
| Number of cells           | 60                |
| Hydrogen pressure         | 0.45-0.55 bar     |
| Maximum speed             | 50km/h            |
| Braking distance          | 15m               |
| Installation voltage      | 24v               |
| Type of drive             | Hydrogen          |
| Hydrogen uptake           | 2.9 ln/min        |
| Reported range            | 100 km            |
| Planned range             | 250 km            |
| Recorded energy consumption | 270 km/kWh       |
| Planned energy consumption | 700 km/kWh        |

A schematic of the propulsion system is shown in Figure 5. The vehicle is driven by a Maxon EC 90 flat 260 W motor and is controlled by a dedicated controller. The electrical power for the system comes from two sources: a Horizon H300 PEM hydrogen cell and a supercapacitor pack: 16 Quik connect type units of 500 F capacity connected in series. The fuel cell is supplied from the hydrogen system consisting of the tank with compressed hydrogen at the pressure of ca. 200 bar, pressure regulator and the shut-off valve which is the safety element of the vehicle. The cell is controlled by a controller developed by the constructors of the vehicle. The drive from the engine is transmitted to the wheel by means of a chain transmission with the gear ratio 156/34. A single-row roller chain 04B-1 is used.
3. **Vehicle model**

The developed vehicle model is based on the power balance of the resistance to motion $N_{res}$ and vehicle drive power $N_{prop}$ at the drive wheel. The model was based on the work of [17-20].

\[ N_{res} = N_{prop} \]  \hspace{1cm} (3.1)

The model assumes that the power of resistance to motion is the product of the drag forces acting on the vehicle and its progressive velocity. The drag force is the sum of the forces resulting from the rolling resistance ($F_t$), lift ($F_w$), air ($F_p$), inertia ($F_b$) and turning ($F_{sk}$).

\[ N_{res} = F_{res} \cdot v \]  \hspace{1cm} (3.2)

Where: $v$ – vehicle speed in m/s

\[ F_{res} = F_t + F_w + F_p + F_b + F_{sk} \]  \hspace{1cm} (3.3)

Where:

- $F_t$ – rolling resistance force:
  \[ F_t = f_t \cdot G \cdot \cos \alpha \]  \hspace{1cm} (3.4)

Where:

- $f_t$ – rolling resistance coefficient;
- $G$ – vehicle weight with driver;
- $\alpha$ – track elevation angle.
The value of rolling resistance coefficient was taken from the work [1] as:

\[
f_t = 0.0125 + 0.0085 \left( \frac{V}{100} \right)^{2.5}
\]  

Where:
\[ V \] – vehicle speed in km/h.
\[ F_w \] – contribution resistance force:
\[
F_w = \tan \alpha \cdot G
\]  
\[ F_p \] – drag force:
\[
F_p = c_x \cdot A \cdot q
\]  
\[ q \] – dynamic air pressure in N/m².
\[
q = \frac{\rho \cdot v^2}{2}
\]  
\[ \rho \] – air density;
\[ b \] – barometric pressure in hPa;
\[ T \] – air temperature in K.
\[ F_b \] – force of inertia of vehicle motion:
\[
F_b = a \cdot \frac{2l_{kt}}{(r_t r_d)} + I_{kz} \cdot \frac{i_p}{\eta_p (r_t r_d)} \cdot a + I_{kn} \cdot \frac{a}{(r_t r_d)} + m \cdot a
\]  
\[ a \] – acceleration of the vehicle in m/s²;
\[ m \] – mass of the vehicle including the driver in kg;
\[ I_{kt} \] – moment of inertia of the rolling wheel kg·m²;
\[ r_t \] – rolling radius of the wheel in m;
\[ r_d \] – dynamic radius of the wheel in m;
\[ I_{kz} \] – moment of inertia of the large gear wheel in kg·m²;
\[ i_p \] – gear ratio; \( \eta_p \) – gear efficiency equal to 0.95;
\[ I_{kn} \] – moment of inertia of the driving wheel in kg·m².
\[ F_{sk} \] – steering resistance force:
\[
F_{sk} = f_{sk} \cdot G
\]  
\[ f_{sk} = 6 \times 10^{-6} \frac{V^4}{R^2}
\]  
Where: \( f_{sk} \) – coefficient of turning resistance, \( R \) – turning radius of the wheel in m.

The drive power \( N_{prop} \) is derived from the action of an electric motor driving the rear wheel of the vehicle through a chain transmission. The value of this power was taken as:

\[
N_{prop} = \frac{M_{prop} \eta_{prop}}{9.55}
\]
Where:
\( M_{prop} \) – drive wheel torque;
\( n_{prop} \) – wheel speed.

\[
n_{prop} = \frac{60 \cdot v}{\pi d}
\]  
(3.14)

Where:
\( d \) – outer diameter of the drive wheel.
The drive torque on the attack wheel can be determined as:

\[
M_{prop} = \eta_p \frac{M_m}{i_p}
\]  
(3.15)

Where:
\( M_m \) – driving torque of the electric motor;
\( \eta_p \) – efficiency of the chain transmission;
\( i_p \) – gear ratio of the chain transmission.

The electrical power consumed by the engine results from the energy balance of the power system. The analysed power system has two power sources: a fuel cell and supercapacitors, as well as two consumer systems: the electric motor and accessory systems. In the model, it should also be taken into account that the supercapacitors are a buffer of energy at changes in the load of the engine and can be both a power source and a receiver of energy. The balance can therefore be written as:

\[
N_{m_{el}} = N_{FC} + N_{SC} - N_{aux}
\]  
(3.16)

\( N_{FC} \) – electrical power produced by a fuel cell;
\( N_{SC} \) – electrical power generated/stored by supercapacitors;
\( N_{aux} \) – power consumed by the accessory devices (such as engine controller...).
The drive power calculated earlier is equal to the product of the electrical power generated by the power system, the efficiency of the motor controller, and the overload efficiency of the electric motor.

\[
N_m = N_{m_{el}} \cdot \eta_m \cdot \eta_{cont}
\]  
(3.17)

Where:
\( \eta_m \) – motor efficiency;
\( \eta_{cont} \) – controller efficiency.

According to the electrical power balance (equation 3.16), the sum of the power consumed by the motor and the power consumed by the auxiliary equipment was equal to the power extracted from the system of cooperating sources: the fuel cell and the supercapacitors. It should also be noted that it is necessary to take into account the charging and discharging of the supercapacitor package. In the case of supercapacitors, the direction of energy flow depends on the voltage difference between the cell and the supercapacitors. If the voltage of the cell is higher, the capacitors are charged, and if it is lower, they are discharged (giving energy to the drive system). By analysing the time derivative of the voltage across the supercapacitors, it is possible to determine the direction of current flow and thus identify the charging and discharging process of the pack. Due to the different charging and discharging behaviour of the capacitors, the power and efficiency of the process were calculated for these cycles separately.

The power drawn from supercapacitors during discharge is:

\[
N_{SC} = I_{SC} \cdot U_{SC} \cdot \eta_{SCP}
\]  
(3.18)

Whereby the discharge efficiency \( \eta_{SCP} \) is:

\[
\eta_{SCP} = \frac{U_{SC} - I_{SC} \cdot R_{SC}}{U_{SC}}
\]  
(3.19)
Where the charging efficiency is:

\[ \eta_{SCU} = \frac{u_{SC}}{u_{SC} - I_{SC} R_{SC}} \]  

(3.20)

The current can be determined from the rate of voltage change across the supercapacitors:

\[ I_{SC} = \frac{d}{dt} \frac{u_{SC}}{C_{SC}} \]  

(3.21)

Knowing the values of the power consumed by the engine, auxiliary systems and supercapacitors (power given to or consumed from the system) from the power balance (equation 3.16) the power that the fuel cell generates at any given moment can be determined. According to relation 3.16:

\[ N_{FC} = N_{m,el} + N_{AUX} - N_{SC} \]  

(3.22)

The electrical power produced by the fuel cell is:

\[ N_{FC} = U_{FC} \cdot I_{FC} \]  

(3.23)

Where:

\[ U_{FC} \] – voltage at the fuel cell;

\[ I_{FC} \] – the current produced by the fuel cell.

On the basis of voltage measurements on the cell, the current produced by the cell can therefore be determined.

As it was shown in the paper [21], hourly fuel (hydrogen) consumption in the investigated drive system is linearly dependent on the current drawn from the cell.

\[ Q_n = f(I_{FC}) \]  

(3.24)

Knowing the value of the current it is therefore possible to determine the consumption at a given moment and by integrating over the time of the simulated run the total hydrogen consumption.

\[ Z = \frac{Q_n(t_n - t_{n-1})}{60} \]  

(3.25)

The model thus allows not only tracing the values of power flowing in the drive system, but also determining the instantaneous and total fuel consumption during the entire driving cycle.

4. Model identification and validation

The basic technical data of the vehicle are presented in Chapter 2 of this work. On the basis of these parameters, the basic model parameters were identified – see Table 2.

**Table 2. Basic parameters of the Hydros vehicle model.**

| Parameter                        | Designation | Value  |
|---------------------------------|-------------|--------|
| Unladen weight                  | \( m_e \)   | 37 kg  |
| Total weight                    | \( m_f \)   | 85 kg  |
| Weight                          | G           | 882.9 N|
| Coefficient of resistance       | Cx          | 0.1    |
| Electrical power consumed by auxiliary equipment | \( N_{AUX} \) | 15 W   |

By analysing the design of the propulsion system and the characteristics provided by component manufacturers, the model parameters related to the propulsion system were determined – see Table 3.
Table 3. Basic parameters of the Hydros vehicle powertrain model.

| Parameter                          | Designation | Value                                      |
|------------------------------------|-------------|--------------------------------------------|
| Capacity of supercapacitor set     | $C_{sc}$    | $C_{SC} = \frac{500F}{16} = 31.25F$       |
| Resistance of supercapacitor set   | $R_{sc}$    | $R_{SC} = 16 \cdot 0.0045\Omega = 0.072\Omega$ |
| Motor voltage constant             | $n_{m\text{const}}$ | 41.3 rev/min/V                            |
| Motor current constant             | $M_{m\text{const}}$ | 0.231 Nm/A                                |
| Engine controller efficiency       | $\eta_{\text{cont}}$ | 0.98                                      |

The next parameter identified for the propulsion system model is the engine efficiency. It was determined on the basis of characteristics provided by the manufacturer of the motor (Figure 6).

The highest motor efficiency was assumed at the overload of 0.6. The polynomial functions corresponding to the efficiency curve are presented in Formulas 4.1 ($\text{Load} \leq 0.6$) and 4.2 ($\text{Load} > 0.6$). Therefore, the efficiency can be written as:

$$\eta_m = -113.64 \cdot \text{Load}^5 + 207.96 \cdot \text{Load}^4 - 135 \cdot \text{Load}^3 + 33.214 \cdot \text{Load}^2 - 0.2541 \cdot \text{Load} + 0.1$$ \hspace{1cm} (4.1)

$$\eta_m = 0.5158 \cdot \text{Load}^5 - 3.1064 \cdot \text{Load}^4 + 7.0128 \cdot \text{Load}^3 - 7.5294 \cdot \text{Load}^2 + 3.8364 \cdot \text{Load} + 0.1171$$ \hspace{1cm} (4.2)

Where:

- $\eta_m$ – motor efficiency;
- $\eta_{\text{cont}}$ – controller efficiency;
- $\text{Load}$ – motor overload.

$$\text{Load} = \frac{N_{\text{mmech}}}{N_{\text{mmax}}}$$ \hspace{1cm} (4.3)

Figure 6. Efficiency characteristics of a brushless DC electric motor as a function of load.
Figure 7. Dependence of hydrogen consumption on the power affecting the PEM fuel cell [21].

As shown in [14], the hourly fuel (hydrogen) consumption of the drive system under study is linearly dependent on the power affecting the fuel cell – see Figure 7. The characteristic can therefore be approximated as:

$$Q_n = 0.4162 \cdot I_{FC} + 0.01$$

Where: $Q_n$ – hydrogen consumption in ln/min.

5. Simulation studies

In order to test the model, calculations were performed for a selected run of the analysed vehicle during the Shell Eco Marathon event in London on 05/07/2019. The analysed run included 11 laps of the track completed in 39 minutes 12.8 seconds. During the run, the position of the vehicle (GPS position) and basic data such as vehicle speed, voltage on the supercapacitors, cell voltage, time and distance travelled were recorded. The uphill resistance force was determined on the basis of the GPM position – see Figure 8. The uphill resistance force was determined on the basis of data obtained from the relative height profile tool of the track on which the vehicle travelled during the run, plotted in Google Earth Pro. The steering resistance force was determined by dividing the track into straight sections, where this force was ignored, and curved sections, where this force was determined based on the curve radius resulting from the track analysis. The parameters used to calculate air density and dynamic pressure were the current atmospheric conditions.

On the basis of the recorded and determined data, the value of the power of resistance to motion $N_{res}$ was calculated and presented in Figure 9. The value of the determined power varies in the range -96.1 W ÷ 212.37 in a cyclic system, consistent with individual laps of the track. The average value is: 83.64 W.

On the basis of the recorded voltages in the system, the value of the power taken/released from the supercapacitors was determined – see Figure 10. The power of the $N_{SC}$ pack varied from -62.55 W to 144.07 W also in the cycling range. It can be seen that during the first phase of driving, the vehicle drew significantly more energy from the supercapacitors. This is due to the power strategy of the system; during the initial acceleration phase, most of the energy comes from the supercapacitors. Later, after the vehicle had accelerated to its average cruising speed, the set of supercapacitors only served as a buffer for momentary accelerations. The average power value is 0.87 W.
Figure 8. Google Earth Pro screenshot and relative height profile view.

Figure 9. The power of resistance to motion occurring during the passage.

Figure 10. Power absorbed and dissipated by supercapacitors during transit.
From the powers obtained in this way it was possible to determine the power drawn from the $N_{FC}$ fuel cells – see Figure 11. The variation in the load on the cell ranged from 0 to 316.44 W in cycles consistent with laps. The average value of the cell load was 85.85 W.

The power thus determined allowed the instantaneous fuel consumption to be determined – see Figure 12. The highest hydrogen consumption was 1.92 ln/min, while the lowest was 0.01 ln/min. As in the case of the previous parameters, a cyclic pattern resulting from the track laps can also be seen here. The average value of consumption was 0.88 ln/min.

By integrating the instantaneous fuel consumption, the total consumption was also determined. For the run under consideration, this was 34.29 ln of hydrogen, giving a result of 455.53 km/m$^3$ on the track. This value was compared with the actual value measured during the run with the flow meter installed on the vehicle: 33.34 ln of hydrogen. The simulation error is therefore 2.85%.

6. Summary
Minimising vehicle fuel consumption requires appropriate optimisation of powertrain systems. This is particularly important in the case of hybrid systems, where the energy comes from two cooperating sources. Proper management of the energy flow in order to use the advantages of individual sources
minimizing their disadvantages is an important factor in achieving the goal, i.e. minimizing energy consumption. As it was shown in the article, the development of a physical model based on the model of vehicle motion allows obtaining a very high compliance with reality. In the case of the analysed run, an error of less than 3% was obtained. This error is the difference between the result obtained from the simulation and the value read from the flow meter after the run. Therefore, the developed model meets the assumptions of the tool describing the operation of the system. It also allows for the determination of load components and detailed energy flows within the system. Thus, it is possible to analyse the phenomena occurring in such a system both under static and dynamic conditions. The model can also form the basis for optimising the energy distribution control system and optimising the vehicle control strategy. Owing to this model, it will be possible to increase the performance of the vehicle and obtain a much better result at competitions.

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