Modeling and Simulation of Performance and Range of Electric Sweeper and Fuel Cell Sweeper

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Abstract
In the last decade, major progress in alternative propulsion technologies for vehicles has been made. In these terms, batteries are widely used as an alternative source of energy. However, the concept of a fuel cell propulsion system has also been attracting greater attention. In this paper, electric sweeper and fuel cell sweeper are modeled in order to determine their performance, that is their longitudinal dynamics. Maximum speed and acceleration are determined, as well as required traction force to overcome all resistance forces and achieve the required speed. Furthermore, the change of power of the electric motor, its torque and angular speed are calculated for a given test method defined by EN 15429-2:2012 standard. These dynamic characteristics could be useful for a simple analysis of the characteristics of a vehicle with a new or modified design. Additionally, the model that defines the longitudinal dynamics has been expanded to determine the working range. A validation test of the mathematical model has been conducted.

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I. INTRODUCTION

In order to reduce fossil fuel consumption and the emission of greenhouse gases, vehicles and mobile machines powered by alternative energy sources have been developed. Assuming that the energy used for the production of batteries and hydrogen comes from clean energy sources (solar, hydropower, or nuclear) these technologies are the only ones that have zero emissions and are essential for a clean and efficient urban traffic system.

Recently, the field of alternative energy sources has become attractive to scientific researchers, as well as to the world's largest manufacturers in the automotive industry. In order to show the performance of battery propulsion systems, C. Abagnale et al. [1] design the simplest vehicle, a motor-powered electric bicycle. A.K.M. Mohiuddin et al. [2] design a prototype fuel cell vehicle and experimentally determine the output power of the electric motor using a controlled variation of the input parameters. This research is useful in choosing the most influential input parameters that must be considered when modeling a fuel cell vehicle. Yasuhiro Nonobe [3] explains the development process of a fuel cell vehicle. He describes the full development process of Toyota Mirai, where the goal is designing a vehicle with the highest efficiency. A basic design tool for developing a new or upgraded version of an existing model of vehicle or machine is a mathematical model which allows characteristics to be determined even before a prototype is produced. As an illustration, Vu Trieu Minh et al. [4] mathematically modeled a new improved hybrid vehicle design with a parallel configuration designed by Daimler Chrysler. The torque-angular speed characteristic of an electric motor can be determined using the research from F. Adegbohun et al. [5]. They perform modeling and simulation of a vehicle propulsion system using WOT (Wide Open Throttle) testing and further validation with experimentally obtained data. The greatest challenge in designing a new electric or fuel cell vehicle is predicting and extending its range as much as possible. Chiara Fiori et al. [6] develop a model which determines the energy consumption of an electric vehicle. Simulations have been performed to compare the performance and range of electric vehicles of the world's largest manufacturers: BMW, Tesla, Nissan. Jenn-Jiang Hwang et al. [7] define a mathematical model for determining the energy consumption of a hybrid vehicle that uses a fuel cell system as the basic propulsion system and an auxiliary electric lithium-ion battery. C. Bingham et al. [8] use a different approach in determining the energy consumption of batteries and vehicle range. In this research, the influence of the selected test method, which is used as an input in the simulation, on the vehicle range of the vehicle is studied. The test methods are selected so that they represent conditions for urban traffic and open road traffic. Similar to previously stated vehicles, sweepers can also be powered by alternative energy sources. Comparison between conventional propulsion systems of sweepers and battery-powered sweepers is shown in the following papers: Jordan M. [9] compares the performance of a sweeper driven by an internal combustion engine and an electric sweeper based on experimentally collected data under the same experimental conditions. Rene Budich et al. [10] simulate a sweeper whose internal combustion engine is replaced by an electric motor, in order to determine its dynamic characteristics. Rene Budich et al. [10] complements the research of Jordan M. [9] and analytically proves it.

A question that constantly arises is which technology is the future of alternative propulsion systems. In order to propose an answer, concerning their performance and energy consumption, this paper analyses propulsion systems of two sweepers, one powered by electric batteries and the other powered by a fuel cell system, concerning their performance and energy consumption. Apart from the energy source which powers both sweepers, everything else is identical, i.e. both sweepers have identical mass and design. More precisely, the modeling of longitudinal dynamics and work range of the two sweepers is shown in this paper.

II. METHODOLOGY

The methodology of modeling the longitudinal dynamics and work range of the two sweepers is shown in fig. 1. The first step in modeling the performance of a vehicle or a sweeper is defining the relation for the required tractive effort [11]. This relation enables determining the maximal acceleration of the sweeper, its traction force, and power supplied at the wheels at each second of the test cycle. It is important to be emphasized that the change of each parameter during one test cycle is determined at time intervals of 1 second. Once parameters that define the tractive effort of the sweeper are defined, the change of power of the traction electric motor, its angular speed, and torque at each second of the test cycle are easily calculated.

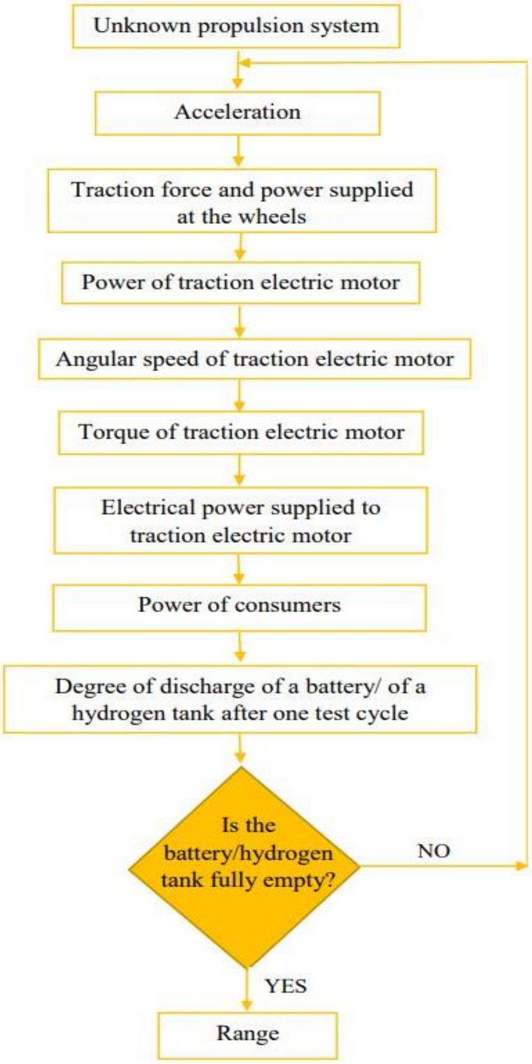

Figure 1. Algorithm of activities

If the model which defines the longitudinal dynamics of a sweeper is slightly expanded, the obtained dynamic parameters could further be used to determine features of a sweeper with a new or changed design of a component. In this case study, they are used for determining its work range, which is an extremely important feature of vehicles and sweepers with propulsion systems on alternative energy sources.

Thus, electrical power supplied to the traction electric motor and other power consumers is determined. Traction electric motor is not the only power consumer. Additional consumers of a sweeper include a fan that extracts air from the collection hopper and enables the transport of collected debris to the hopper, a hydraulic pump that moves the brushes, and auxiliary devices. In order to predict the working range, the energy consumption of the sweeper is calculated for each second of the test cycle. The test cycle is repeated until the battery is flat or the hydrogen tank is empty.

At the same time, the output result for the working range of the sweeper is used as a validation method for its modeling. Results from the simulation are compared to obtained data from an experiment performed under the same work conditions as the ones during the simulation.

III. MODELING AND SIMULATION

Following the algorithm of activities (fig.1), the modeling of both sweepers concerning their performance and working range is shown in detail in this section.

A. Modeling of performance

Firstly, as explained in section II, a relation for determining tractive effort of the sweeper is written [12]:

$$F_{te} = F_{rr} + F_{ad} + F_{hc} + F_{a} \qquad [N] \qquad (1)$$

F_{te} – tractive force [N]
F_{err} – rolling resistance force [N]
F_{te} – aerodynamic drag force [N]
F_{a} – acceleration force [N]

For a sweeper with mass m [kg], which moves on a horizontal flat surface, with a speed v [m/s] and air density of 1.25 kg/m^3, expression (1) can be written as:

$$F_{te} = \mu_{rr} \cdot m \cdot g + 0.625 \cdot A \cdot C_d \cdot v^2 + m \cdot a + I_{EM} \cdot \frac{G^2}{\eta_g \cdot r^2} \cdot a$$

(2)

μ_{rr} – coefficient of rolling resistance
A –frontal area of the sweeper [mm^2]
C_d – drag coefficient
a - acceleration [m/s^2]
I_{EM} – moment of inertia of the rotor of the el. motor [kg·m^2]
G – gear ratio
r – effective radius of a tire [m]
η_g – gear system efficiency

Also, this expression is relevant:

$$F_{te} = \frac{G}{r} \cdot T \qquad [N] \qquad (3)$$

T – torque of the traction electric motor [Nm]

Left sides of expressions (2) and (3) are equal:

$$\frac{G}{r} \cdot T = \mu_{rr} \cdot m \cdot g + 0.625 \cdot A \cdot C_d \cdot v^2 + m \cdot a + I_{EM} \cdot \frac{G^2}{\eta_g \cdot r^2} \cdot a \quad (4)$$

Essential technical specifications of the sweepers for their modeling are given in Table I. Torque of the electric motor is not a constant parameter. On the contrary, it depends on the angular speed of the electric motor. This relation is expressed with the torque-speed curve of the electric motor, which for AC electric motors follows two different functions.

Generally, the torque-speed characteristic is defined by a linear function. Using the technical specifications concerning the electric motor of the sweepers, which is completely identical for both sweepers, the torque-speed linear function can be expressed as:

$$T = 134 - 0.035 \cdot \omega \qquad (5)$$

Table I. Technical specifications of sweepers

Parameter	**Electric sweeper and Fuel cell sweeper**
gross mass [kg]	2325
frontal area [mm^2]	2.188
no-load angular velocity of electric motor [rpm]	4300
peak voltage of electric motor [V]	80
resistance of electric motor [Ω]	0.010
max. torque of electric motor [Nm]	80
tire radius [m]	0.27
gear ratio	18:1
max. power of electric motor [kW]	12

The traction electric motor is AC. The torque-speed curve for AC electric motors follows two different relations, fig 2. The angular speed, or critical angular speed [13], can be found in the intersection of the function expressed in (5) and the function:

$$T = T_{\max} \qquad (6)$$

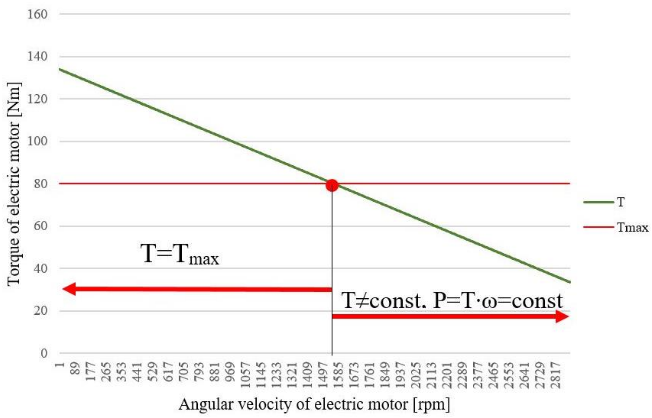

Figure 2. Torque-speed curve

Consequently, the following can be stated:

- for $\omega<\omega_c$, $T=T_{max}$;
- for $\omega>\omega_c$, torque of the electric motor changes so that the power of electric motor remains constant.

The value of critical angular speed is 1573 rpm, or expressed as a critical linear moving speed of sweeper the value is 2.47 m/s. As a result, expression (4) will differ for the moving speed of the sweeper under the critical speed and above it. Therefore, two differential equations are defined:

- if v<2.47 m/s

$$\frac{dv}{dt} = 2.06 - 0.0004 \cdot v^2 \qquad (7)$$

- if v≥2.47 m/s

$$\frac{dv}{dt} = \frac{4.86}{v} - 0.104 - 0.0004 \cdot v^2 \qquad (8)$$

Differential equations (7) and (8) are identical for both sweepers because all of the constants expressed in (4) are identical (Table I). (7) and (8) are numerically solved in MATLAB. Acceleration and tractive force (using expression 4) of the sweeper are calculated. Using the next expression:

$$P_{te} = F_{te} \cdot v \qquad [\text{W}] \qquad (9)$$

supplied power to the wheels is calculated.

Next, power given out by traction electric motor is calculated:

$$P_{EM\_out} = \frac{P_{te}}{\eta_g} \qquad [\text{W}] \qquad (10)$$

Angular speed of electric traction motor is:

$$\omega = G \cdot \frac{v}{r} \qquad [\text{rad/s}] \qquad (11)$$

Torque of the electric traction motor can be expressed as:

$$T = \frac{P_{EM\_out}}{\omega} \qquad [\text{Nm}] \qquad (12)$$

Previously stated parameters which define the performance of the sweepers are calculated at each second of the used test cycle. Standard EN 15429-2:2012 proposes the test method [14] shown in fig.3.

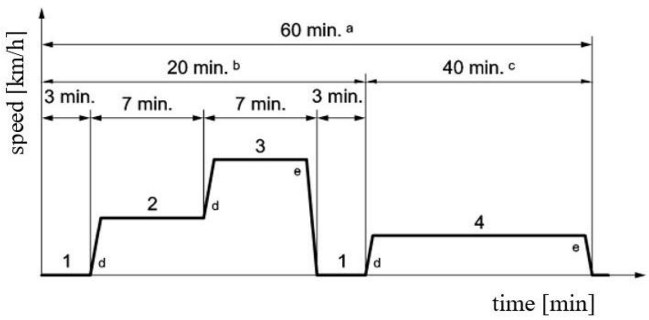

Figure 3. Test method for sweepers EN 15429-2:2012

1- propulsion prime mover at idle speed

2 – maximum travel speed not exceeding 16 km/h

3 – maximum travel speed not exceeding 40 km/h

4 – 50% of maximum work speed, not exceeding 6 km/h

a – duration of one test cycle

b – travel mode sub-test

c – work mode sub-test

d – accelerate

e – brake.

B. Range modeling

Traction electric motor is not the only power consumer. Additional consumers of a sweeper include a fan, a hydraulic pump that moves the brushes, and auxiliary devices. Before modeling of the range is started, one has to be familiar with the energy flow of the sweepers, fig.4.

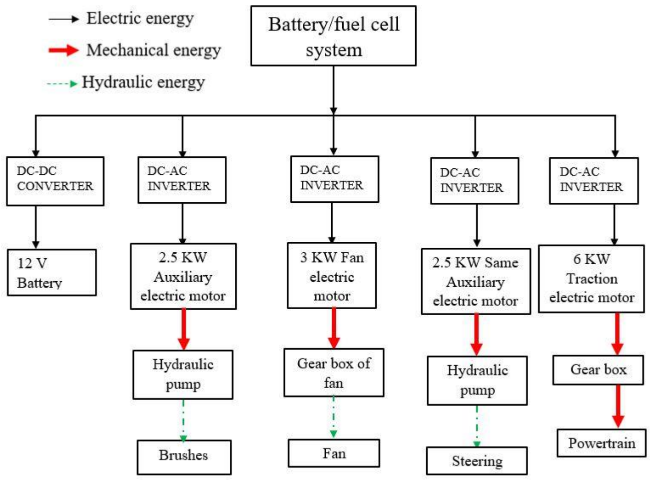

Figure 4. Scheme of energy flow of sweepers

For the stage of range modeling, the scheme shown in fig.4 could be simplified as shown in fig 5.

The energy consumption of the sweeper is calculated at each second of the test cycle (3). Consequently, energy consumption at each second is identical to the power consumption of the sweeper (13).

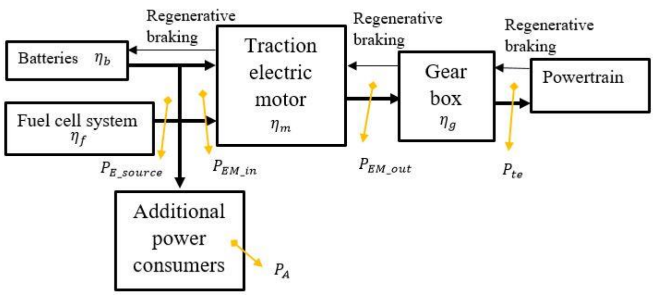

Figure 5. Simplified scheme of energy flow of sweepers

Energy consumption for 1 s = $P_{te} = F_{te} \cdot v$ (13)

The efficiency of all subsystems powered by the energy source has to be calculated. Additionally, the efficiency of the energy source itself (batteries or fuel cell system) must be taken into consideration.

The efficiency of the electric motor and its control unit can be calculated as:

$$\eta_m = \frac{T \cdot \omega}{T \cdot \omega + k_c \cdot T^2 + k_i \cdot \omega + k_i \cdot \omega^3 + C_{EM}} \quad (14)$$

k_c – Cooper losses coefficient for electric motor

k_i – Iron losses coefficient for electric motor

k_w – Windage losses coefficient for electric motor

C_{EM} – constant losses of electric motor.

According to the values of technical specifications of both sweepers (Table I) recommended value for the coefficient of efficiency of the gearbox is 0.98 [5]. For electric motor with characteristics shown in Table I, values are taken from the research of F.Adegbohun et al. [6]. Once mechanical power given out by traction electric motor and its coefficient of efficiency are calculated using (10) using (14), electrical power supplied to the electric motor can be calculated:

$$P_{EM\_in} = \eta_m \cdot P_{EM\_out} \quad \text{[W]} \qquad (15)$$

Finally, electrical power from the energy source (batteries or fuel cell system) needed to power all consumers can be calculated:

$$P_{E\_source} = P_{EM\_in} + P_A \quad \text{[W]} \qquad (16)$$

P_A – power of additional consumers: electric motor for fan and auxiliary electric motor.

It must be emphasized that electric vehicles have regenerative braking. In this case, coefficients of efficiency η_g and η_m have reciprocal values to the one calculated using expressions (10) and (15). The coefficient of regenerative braking is 0.5 [18].

C. Modeling of lithium-ion batteries

Modeling of the batteries is in order. The electrical sweeper is powered by lithium-ion batteries. The model shows the change of open circuit voltage for lithium-ion batteries. Open circuit voltage does not have a constant value. On the contrary, it depends on the battery charge or its degree of discharge, number of battery cells, and work temperature. The function which defines this relationship is a polynomial function whose coefficients and highest degree vary depending on the battery type. Polynomial function for lithium-ion batteries [6]:

$$E_{OC} = NoCells \cdot (4.2 - 17.9 \cdot DoD^7 + 28.4 \cdot DoD^6 + 7.42 \cdot DoD^5 - 35.7 \cdot DoD^4 + 22.2 \cdot DoD^3 - 4.3 \cdot DoD^2 - 0.75 \cdot DoD) \qquad (17)$$

DoD – degree of discharge of the battery

In order to determine open circuit voltage for each new test cycle, firstly battery capacity is calculated, using the Peukert model [16], after each second of the (n+1)-th test cycle:

$$C_{n+1} = C_n + \frac{\Delta t \cdot I}{3600} \quad \text{[Ah]} \qquad (18)$$

I – current [A]

Δt – time interval [s]

where,

$$I = \frac{E - \sqrt{E^2 - 4RP_{E\_source}}}{2R} \quad \text{[A]} \qquad (19)$$

E – nominal battery voltage [V]

R – battery resistance [Ω].

Finally, the degree of battery discharge can be determined:

$$DoD = \frac{C_{n+1}}{C_{nom}} \qquad (20)$$

C_{nom}- nominal capacity of battery [Ah].

The test cycle continues until the degree of discharge reaches 0.9 [17]. Once DoD reaches a value of 0.9, the calculation loop stops, and the range for the electric sweeper is shown.

D. Modelling of PEMFC system

The only type of fuel cell which can be used for the propulsion of vehicles is the

Proton-exchange membrane fuel cell (PEMFC). Based on the theoretical characteristics of a PEMFC system, the modeling of this system comes down to a relatively simple relation. Fuel consumption only depends on the required power for the consumers and the theoretical potential of the fuel cell. The actual potential of the fuel cell is calculated using its theoretical potential whose value depends on the specific type of used fuel cell. If the sweeper uses pure hydrogen as a fuel for the PEMFC system, hydrogen consumption can be calculated using the following expression [19]:

$$\dot{m} = 1.05 \cdot 10^{-8} \cdot \frac{P}{V_{fc}} \qquad [\text{kg/s}] \qquad (21)$$

P – power consumption [W]
V_{fc} – real potential of fuel cell [V].

Fuel cell efficiency can be expressed:

$$\eta_{fc} = \frac{V_{fc}}{V_t} \qquad (22)$$

V_t – theoretical potential of fuel cell [V].

The value of the theoretical potential of a PEM fuel cell is 1.23V at a working temperature of 25°C and atmospheric pressure [19]. Efficiency for PEMFC has an approximate value of 40%. The test cycle continues until the degree of discharge reaches 0.9 [19]. The calculation loop stops when the hydrogen tank is 90% empty and the range for the hydrogen sweeper is shown.

IV. RESULTS

Results from performance modeling of the sweepers are plotted in fig.6. Curves which show the change of speed of the sweepers are identical at each point. The maximum speed of both sweepers in transit mode is 25.14 km/h, while the maximum speed in work mode is 16.08 km/h.

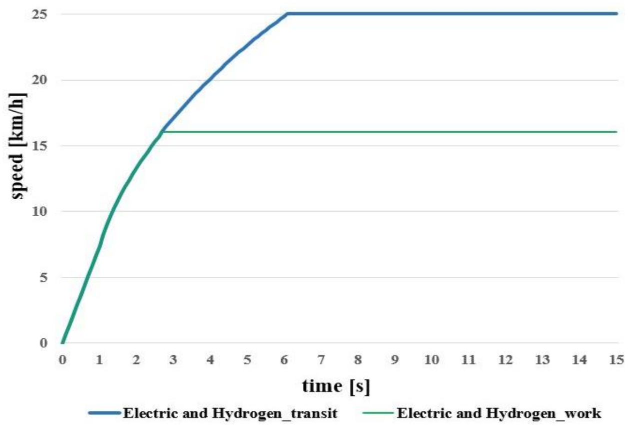

Figure 6. Maximal speed of the sweepers during transit and work mode, WOT (wide open throttle) test

Following the algorithm in fig. 1, once the maximum speed and acceleration of the sweepers have been determined, traction force required to achieve and maintain the required speed at each second of the test cycle can be determined. In this analysis, the test cycle shown in fig. 3 was used. Fig.6 shows the curves of change of traction force of both sweepers, which completely overlap at each second, due to the identical gross mass of both sweepers (table I).

The maximum traction force of the sweepers is 1235.977 N. It is achieved while accelerating to maximum speed in transit mode.

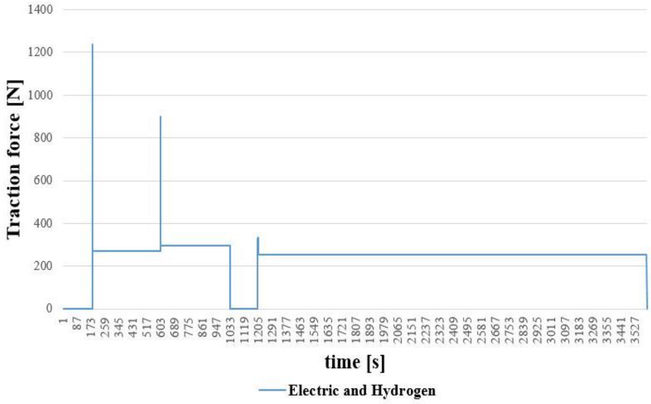

Figure 7. Change of traction force during one test cycle of electric and hydrogen sweeper

Therefore, curves of change of power supplied to the wheels (fig.8) and power of traction electric motor (fig. 9) overlap as well. The maximal value of the power of the electric motor is 6383.761 W. This value is significantly lower than the maximal power of the electric motor of 12 kW (Table I), because, during the test cycle, sweepers move along a horizontal surface.

Fig. 10 and fig.11 contain curves of change of angular speed and torque of traction electric motor, which once again overlap completely for the electric and hydrogen sweeper. The maximal torque of the electromotor is 18.91 Nm, which is a significantly lower value compared to its maximal torque. This is understandable because, during the test cycle, sweepers move along a horizontal surface.

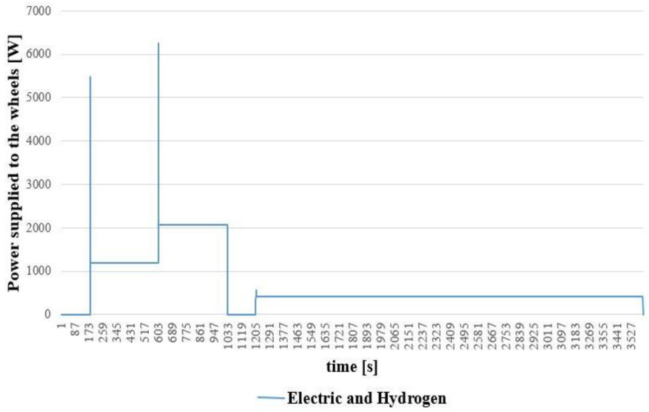

Figure 8. Change of power supplied to the wheels during one test cycle of electric and hydrogen sweeper

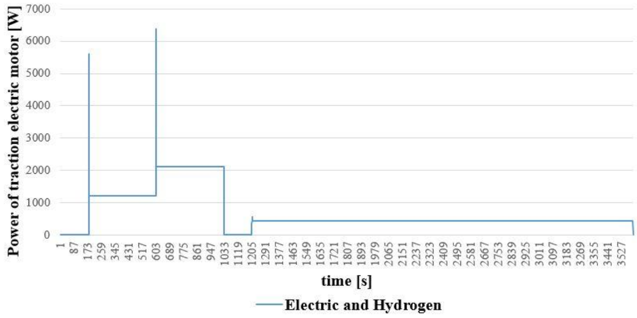

Figure 9. Change of power of electric motor during one test cycle of electric and hydrogen sweeper

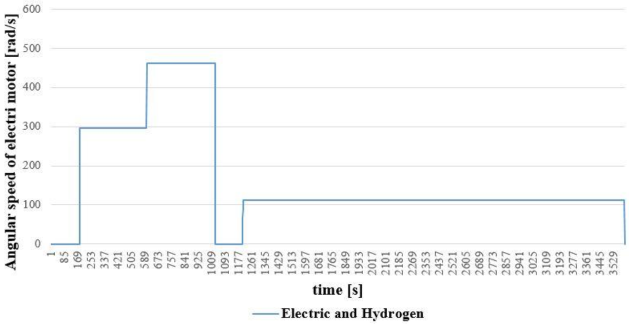

Figure 10. Change of angular speed of electric motor during one test cycle of electric and hydrogen sweeper

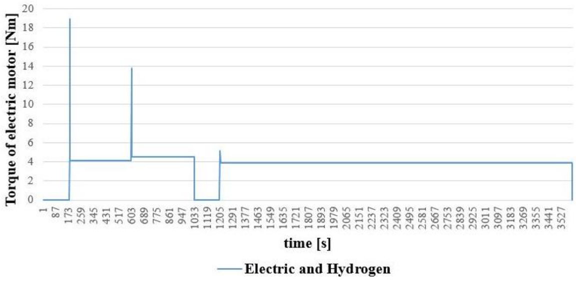

Figure 11. Change of torque of electric motor during one test cycle of electric and hydrogen sweeper

Table II. Results

Parameter	**Electric sweeper**	**FC sweeper**
Max. speed during transit mode [km/h]	25.14	25.14
Max. speed during work mode [km/h]	16.08	16.08
Max. traction force [N]	1235.977	1235.977
Max. power supplied at the wheels [W]	6256.085	6256.085
Max. power given out by traction el. motor [W]	6383.761	6383.761
Max. angular speed of traction el. motor [rpm]	4297.18	4297.18
Max. torque of traction electric motor [Nm]	18.91	18.91
Work range [h]	8.18	13.64

Results from modeling for performance and range modeling of both sweepers are shown in Table II. Parameters which define longitudinal dynamics of the sweepers are completely identical. Only work range values differ.

V. MODEL VALIDATION

Model validation test of the electric sweeper which had been modeled in this paper was conducted. Identical work conditions and test cycles (fig.3) have been used during this test. Power Quality analyzing instrument has been used in order to measure the energy consumption of the electric sweeper during one test cycle. Model METREL PowerQ4Plus has been used. Results have been plotted in fig.12.

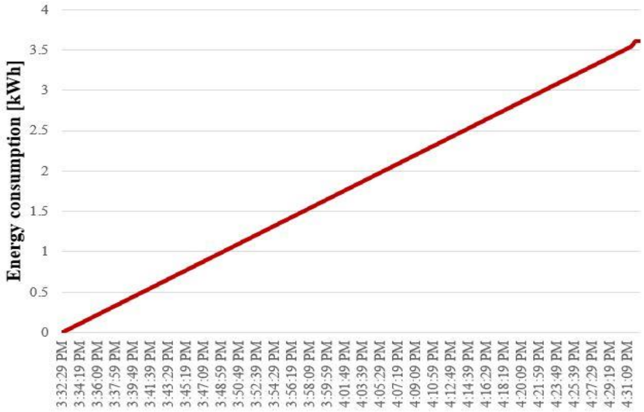

Figure 12. Results from model validation test of electric sweeper

Theoretical battery capacity is 29.5 kWh. Results obtained from the test (Fig. 12), show consumption of 3.614 kWh per cycle, which lasts 1 h. Therefore, the number of working hours of the electric sweeper with a single battery charge is 8.16 h.

CONCLUSION

Conclusions from this study case can be drawn in three directions, concerning:

- longitudinal dynamics parameters: Electric and fuel cell sweeper show identical results from the performance test, as a result of their identical gross mass,
- work range: Fuel cell sweeper has a significantly higher range (1.67 times higher) than the electric one under identical operating conditions and identical test cycle,
- validation test: obtained results from the simulation concerning the working range of the electric sweeper match experimentally obtained results under identical work conditions as those of the simulation.

Based on the analyzed parameters, a conclusion can be drawn that the fuel cell propulsion system has an absolute advantage in performance and range compared to the electric propulsion system.

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