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Solar electric tricycle development and research

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Abstract. Due to the fact that the world's energy resources are declining, various alternative energy sources are being sought. One such source of energy is solar energy. However, due to the large size of solar photovoltaic panels, solar energy is not widely used in mobile vehicles. In some electric automobiles, solar energy is used as an additional energy source, yet usually the sun is not able to provide more than 15–20% of the energy needed for their propulsion. There are some experimental design solutions for water vessels that are propelled by solar energy only. A recumbent electric tricycle was designed, constructed and tested within the present research. The recumbent electric tricycle used a 330 W solar battery, which was designed as a tricycle roof. During the tests with the solar battery, the electric tricycle reached a maximum speed of 32 km h^{-1}. On a sunny day in May under the conditions in Latvia, a distance of 50.20 km was experimentally covered without battery recharging, compared with a distance of 17.14 km covered without the use of a solar battery. By skilfully operating the solar electric tricycle and limiting the speed to 20 km h^{-1} on a sunny day, the expected distance covered could be unlimited. The acceleration and braking parameters of the solar electric tricycle were identified by using a scientific radar Stalker ATS.

Key words: acceleration, distance, range, solar tricycle, solar energy.

INTRODUCTION

There are many known solutions for internal combustion engines that use fossil fuels. In recent years, however, there has been a trend towards the development of vehicle propulsion technologies relying less on fossil fuels or replacing them with other forms of energy such as electrical energy. In the last decade, the use of electric automobiles has become more widespread, and now almost every auto manufacturer supplies electric or hybrid automobiles. Electric drive technology significantly reduces harmful emissions at the place of exploitation of the vehicles; however, the total emission balance depends on the way electricity is produced from renewable or fossil energy sources. The introduction of electric automobiles can reduce CO_2, C_nH_m, NO_x, CO and other exhaust components of internal combustion engines. The main advantages of using electric drive are the quiet emission-free operation, yet the disadvantages are the relatively long charging time and the high price.

When introducing electric automobiles, scientists have also considered using alternative energy sources to charge the electric automobiles, e. g. solar and wind power. The first experimental solar charging station in Latvia, designed to charge electric automobile batteries, was opened in 2011. After successfully testing the solar station, experiments were done on the use of a solar battery in slow-moving vehicles for shopping, placing the solar battery on the roof of the electric automobile for shopping. On a sunny day, such an electric automobile can travel at a speed of 7 km h^{-1}, and a 180 W solar battery provides a practically unlimited operating time on a sunny summer day (Berjoza & Misjuro, 2014). However, the vehicles of this design reach a low speed, which limits their use.

Solar energy is widely used in water vessels. Design solutions have been found both for the development of water vessels for scientific research purposes and for commercial uses. The requirements and operational characteristics for water vessels (maximum speed, weights of engine and batteries, area occupied by solar panels and their weight) are usually not as high as for automobiles. Therefore, solar-powered commercial and experimental boats are found in latitudes closer to the equator. The solar energy available is enough to propel such boats (Kurjakov et al., 2012; Nobrega & Rossling 2012; Mahmud et al., 2014; Kurniawan, 2016; Rodrigues et al., 2016; Sunaryo & Ramadhani, 2018). In some countries, e.g. the Netherlands, solar boat races involving several student teams are held. (Sutherlanda et al., 2017).

It is difficult for ground vehicles, i. e. electric automobiles, to create a sufficiently powerful solar battery for propelling them well. With the current technologies, it is difficult to achieve it because even the most modern solar cells have only a 24% efficiency factor. By fully covering the entire useful surface of an electric automobile with solar panels, it is usually possible to generate no more than 1,500 W of electricity, which is not enough to reach high speeds. Even a small electric automobile needs a 1.5 kW power supply to ensure smooth propulsion at a speed of 50 km h^{-1}. The solar batteries of this capacity could not be placed on an electric vehicle. Accordingly, in modern solar electric automobiles, solar energy is usually used as a partial energy source to increase the distance covered by the traditional electric automobiles. In 2016, Toyota tested the solar hybrid car Prius, which aimed to generate 1,000 W of energy from solar panels located throughout the car's horizontal body. The best solar cells are expected to have an efficiency factor of up to 34%. Solar panels not only charge the electric car batteries in stationary conditions but also increase the driving range by 45 km (Future car; Casey, 2019; Bellini, 2020). Some prototypes of solar energy use have also been developed by the automobile manufacturer Tesla.

The angle of sunlight falling on the ground can significantly affect the efficiency of non-adjustable angle photovoltaic panels, which makes solar electric automobiles more suitable for operation in countries closer to the equator. To popularize solar energy uses, Australia holds international car races for student-designed solar electric cars that travel 3,022 km, crossing Australia from north to south. The average speed of such cars specially designed for the race exceeds 80 km h^{-1}.

The prototypes of solar-propelled vehicles are studied by scientists from various countries. During a sunny day, solar electric vehicles have no driving range restrictions and dependence on charging infrastructure. Hydrogen fuel cells could also be used as an additional source of energy. The efficiency of a solar electric vehicle could be affected by several road infrastructure factors, e. g. trees, the height of buildings and other elements that obscure sunlight. In their research studies, scientists have developed an optimal route planning model, which takes into account both electric vehicle operating parameters and environmental parameters. The accuracy of the model was tested on a slow-moving electric automobile at a campus. The electric automobile used a 270 W solar battery placed on its roof solar and a 2.2 kW electric motor. The experiments were done at a 41.75-degree latitude. The experiments were carried out both in sunny conditions when the solar battery power supply reached 180–210 W and in cloudy conditions when the solar battery power supply was only 60 W.

In the countries where bicycles are popular, e. g. the Netherlands (almost 1 million bicycles are exploited), it has been found that the use of solar energy can significantly reduce CO_2 emissions from energy production, as almost a quarter of the bicycles were electric ones. The prototypes of solar electric bicycles were also developed, with a small-capacity solar battery (66–72 W) mounted on the front wheel. The solar battery charged the bicycle when it was not ridden. An experiment involving 79 individuals working at two universities was carried out, in which 5 test bicycles were used; the average distance covered was 10.3 km, while the largest distance covered was 56 km (a total of 327 experimental rides were made), and the average speed was 17.3 km h^{-1} (Apostolou et al., 2018).

The total surface area of a car that could be covered with solar panels is quite large. For a middle-class car, the area of the bonnet is about 1.6 m^2, the total area of the right and left doors is about 3.4 m^2, the area of the roof is about 2 m^2, the area of the boot lid is about 0.6 m^2. If solar panels are installed on all the mentioned places, there might be a problem with energy flow management because in a particular position of the car, the solar panels are exposed to different, even very different intensities of solar radiation and also generate very different energy amounts (Kim et al., 2014). In order for an electric car equipped with solar photovoltaic panels to operate in several modes, e. g. solar electric car mode in combination with battery mode, charging mode during the day and night and regenerative braking mode, the development of a complex control algorithm with a superboost converter is required (Kumar et al., 2019). In most modern electric cars, the prototypes of which use photovoltaic panels experimentally, the panels can provide only a part of the energy required for their propulsion. Therefore, scientists propose to employ mathematical models for optimizing the energy flow, which manage the flow in different operating modes of the electric car and also while stopping at a charging station (Hu et al., 2016).

There are available many research studies on the use of solar energy to charge electric automobiles, which reduces CO_2 emissions. No additional energy transmission is required at such charging stations. Simulations were performed for Italy, the Netherlands, Norway, Brazil and Australia (Longo et al., 2015; Rodriguez et al., 2019).

With the emergence of technologies for the use of solar panels on automobile roofs, it is also necessary to consider the standardization of these technological devices. Testing electric vehicle solar panels should include an alternating voltage tests, a temperature change test, a temperature-humidity change test, a dew test, a vibration test, an impact test, a water jet-moisture insulation test, a salt water test, a dust and oil resistance test to determine solar panel readiness for real operating conditions in vehicles (Araki et al., 2018).

At latitudes greater than 55 degrees, the use of solar energy to propel mobile vehicles might be constrained, especially the use of solar energy for full propulsion. Therefore, a solar electric tricycle prototype was developed to experimentally identify the possibility of using solar energy in latitudes exceeding 55. The aim of the research is to develop a workable, environment-friendly solar electric tricycle, which could operate autonomously, and to experimentally identify its key operating characteristics.

MATERIALS AND METHODS

Research object and experimental equipment

For the experimental examination of solar energy used in mobile vehicles, a three-wheeled recumbent tricycle was constructed, which was the main object of the present research. For the electric tricycle conversion, a standard set of components was used, which included a rear-wheel drive electric motor, front and rear brake levers with built-in switches, an accelerator handle, a controller and a control panel with a speedometer and an odometer. Two 20-inch front wheels and a 26-inch rear wheel were used to construct it (Fig. 1).

The tricycle is equipped with 3 lead gel batteries with a capacity of 12 Ah each. The batteries are connected in series, providing a nominal voltage of 36 V. The front and rear lamps with a nominal voltage of 6 V are used for lighting; the voltage is provided by a voltage converter 36 to 6 V. The frame of the tricycle was made of 33.7×3.2 and 21.3×2 round tubes, as well as 20×20×2 square tubes. The key technical parameters of the electric tricycle are summarized in Table 1. Laser cutting technology was used to make the components made of sheet steel.

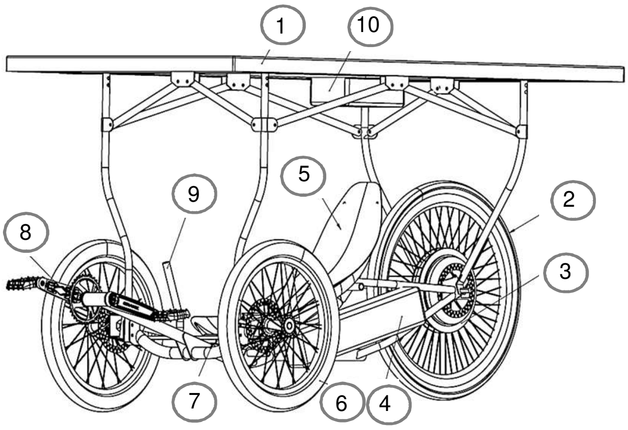

Figure 1. Solar energy-powered recumbent tricycle: 1 – solar panel; 2 – rear wheel; 3 – electric motor; 4 – battery box; 5 – seat; 6 – front wheel; 7 – electric tricycle controller; 8 – pedals; 9 – steering handle; 10 – solar controller.

The solar battery frame was designed to be easily removed from the tricycle, and the frame was designed to be disassembled for easy storage. The electronics related to the solar control were mounted on the solar battery frame. The solar electric tricycle was equipped with a battery Canadian Solar Mono Cs1h-330MS and a controller Epever MPPT.

A Stalker ATS scientific radar was used to measure the acceleration and braking parameters. The key technical characteristics of the radar are as follows:

- accuracy ± 0.1 km h^{-1};
- speed range 1–480 km h^{-1};
- data logging frequency 0.03 s;
- range up to 2,500 m;
- weight 1.45 kg.

Table 1. Key technical parameters of the recumbent tricycle

No.	Parameter	Value and measurement unit
1.	Nominal system voltage	36 V
2.	Batteries	3×12 V, 12 Ah
3.	Brushless DC motor nominal power	500 W
4.	Motor power limitation for road traffic	250 W
5.	Motor nominal voltage	36 V
6.	Number of permanent magnets	46
7.	Motor max current	22 A
8.	Solar panel:	
	maximum power;	330 W
	nominal voltage;	36 V
	efficiency factor;	19.86%
	dimensions	1,700×922×35 mm
9.	Battery pack energy capacity	0.38 kWh
10.	Dimensions (length, width, height) mm	1,850×992×1,020 mm
11.	Wheelbase, mm	1,110 mm
12.	Track width, mm	765 mm
13.	Solar electric tricycle weight	79.4 kg
14.	Maximum speed	32 km h^{-1}
15.	Brakes	Cable-operated disc brakes

The data logger Holux GPSport 245 was used to measure the distance covered. The main technical characteristics of the data logger are as follows:

- saves log data and 200,000 waypoints;
- operating temperature: -10 °C to +60 °C;
- lithium-ion battery, 1,050 mAh, 18-hour operating time.

The electricity consumed and the battery charging process was recorded by means of an energy consumption measuring device REV Ritter Gmbh TYP: 9126. The device recorded energy consumption at an increment of 0.01 kWh and the maximum current consumed during the measurements.

Methodology of the experiment

All experiments were performed using an electric drive, without the use of pedals. The range experiment was carried out in two cycles - with and without using a solar battery. The range experiment was carried out in real traffic conditions on tricycle lanes, including areas exposed to sunlight and areas with shade from trees and buildings. The experiment was carried out on a dry asphalt road and a concrete paving block road with an average rolling resistance coefficient of 0.008, the air temperature ranged from +12 °C to +18 °C, the wind speed was less than 3 m s^{-1}. The experiment was done with fully charged batteries. The experimental data were recorded by a data logger Holux GPSport. The experiment was done at a variable speed within a range of 20–28 km h^{-1} according to the road conditions. The experiment without using the solar battery was stopped when the speed of the electric tricycle was less than 15 km h^{-1}. The experiment had 3 replications and was carried out in the period 1–9 May 2020 at a 56.65 - degree latitude. Both cycles of the experiment involved tricycle rides back and forth on a lane route.

The acceleration and braking parameters such as the acceleration time and the acceleration distance were determined on an asphalt road with a rolling resistance coefficient of 0.008 and a coefficient of adhesion of 0.70–0.75 by means of the scientific radar Stalker ATS. Air temperature during the experiment ranged from +15 °C to +17 °C, the wind speed ranged from 1.0 to 3.0 m s^{-1}. The day of the experiment must be sunny and without clouds. The experiment was carried out on 10 May 2020 from 10.30 to 13.00. The experiment was done with fully charged batteries. The road section chosen for the experiment had low traffic intensity, not more than 2–3 automobiles h^{-1}. Two operators participated in the experiment: one controlled the research object, while the other operated the scientific radar, which was connected to a laptop. The acceleration of the tricycle was started 5 m behind the scientific radar until the maximum speed was reached (Fig. 2). The braking of the tricycle was done when the tricycle moved towards and away from the radar, reaching the speed required for braking in a zone of approximately 20–50 m from the radar (Fig. 2) and braking as intensively as possible with all the wheels.

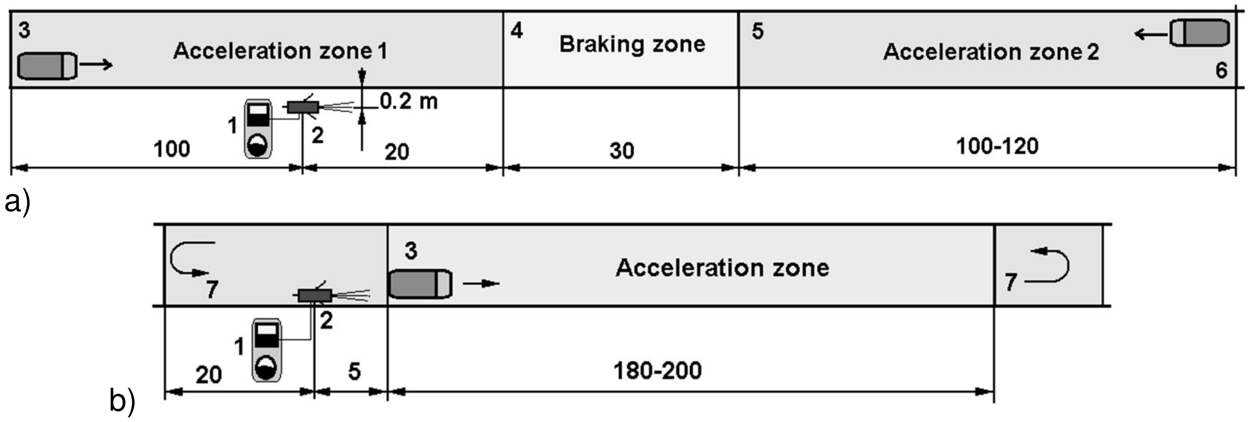

Figure 2. Braking a) and acceleration b) scheme: 1 – radar operator working place; 2 – radar gun; 3, 6 – acceleration start point; 4, 5 – braking start (finish) line; 7 – turning zone.

Each acceleration and braking test was repeated at least 8 times, afterwards selecting 5 measurements yielding the most coherent data. The acceleration tests are performed first with the highest level of battery charge. The tests were repeated at the maximum intensity of solar radiation, which was observed visually.

The braking tests were done when the tricycle moved towards and away from the radar. The braking was started at a speed 2–5 km h^{-1} higher than the initial braking speed required, i. e. 25 km h^{-1}, and continued until the tricycle stopped completely. After the experiment, data processing and a comparative analysis of the data were performed.

The battery charging tests were done after the mileage tests were finished when the batteries were practically discharged. During the charging, a meter measuring the electricity consumed was connected between the charger and the 230 V AC socket. The data were recorded after all the mileage tests. The charging was done indoors, at a room temperature of +18 ± 1 °C.

RESULTS AND DISCUSSION

The solar electric tricycle was operated in two modes - with and without using a solar battery. The data obtained in the mileage tests are summarized in Fig. 3. In both modes, the tests were done according to the driving conditions, thereby trying to move at the maximum speed. If using the solar photovoltaic panel, the average distance covered was 50.20 km. In this experimental regime, the tricycle ride was not stopped when the speed dropped below 15 km h^{-1} as originally planned; however, in the acceleration regime, the solar controller started to limit fast acceleration after turning in the opposite direction. In this way, it was concluded that the batteries were empty. By starting the acceleration of the tricycle very smoothly, even after the batteries were completely discharged, it was possible to continue riding the tricycle at a speed of 20–22 km h^{-1}. The distance covered if using the solar battery was 2.93 times longer than that without using it. It could be hypothetically assumed that at the next stages of the research, the maximum speed to be identified might be in the range of 20–25 km h^{-1}, as at high solar intensity, the battery energy is not consumed to ensure smooth propulsion. If using the solar battery, the maximum speed was 11.5% higher, while the average speed was 22.4% higher.

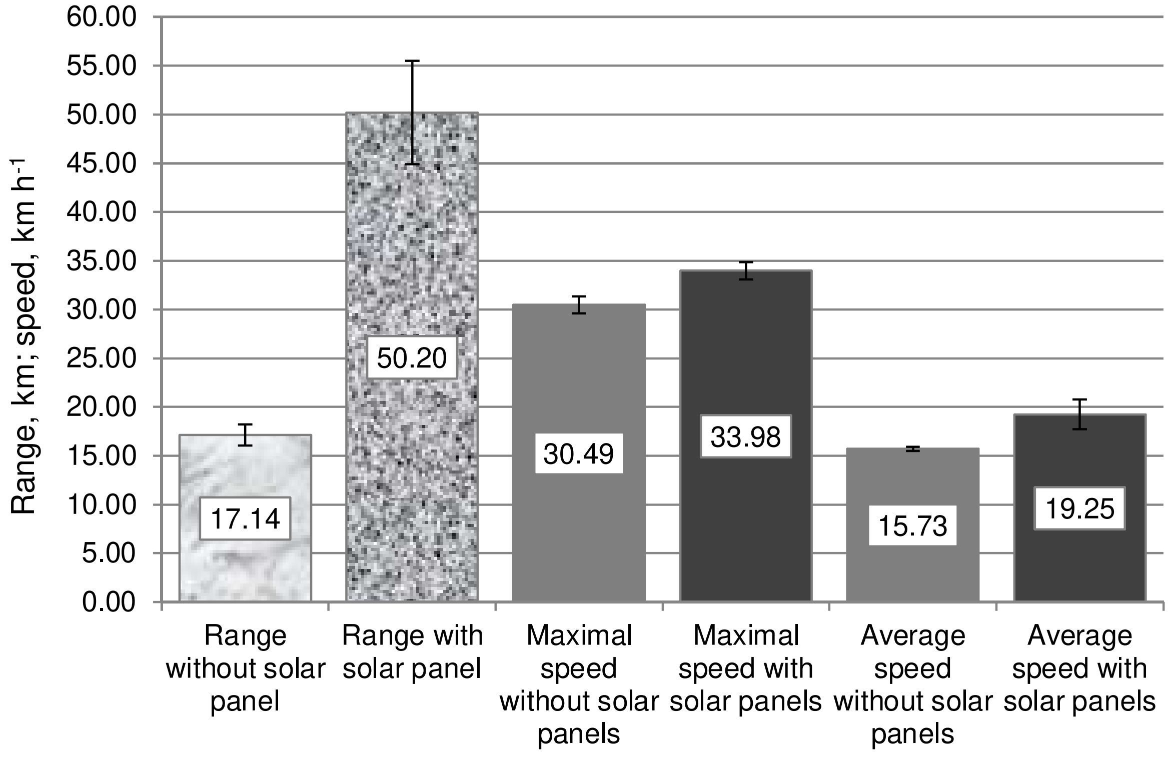

Figure 3. Mileage test results for the solar electric tricycle.

The difference between the average speed and the maximum speed in both experimental cycles could be explained by the fact that the solar panel in combination with charged batteries was able to provide an operating voltage that was higher than the nominal system voltage was, i. e. 36 V. It is also useful to test this visually-read measurement at the next stages of the research by installing data logger equipment for measuring voltage and current changes.

New batteries were used in the experiment. Typically, battery performance and capacity reach nominal parameters after 2–3 charge cycles. For this reason, the distance covered in the first tests (without using the solar panel) with batteries that had several charge cycles could be longer.

The standard error for the mileage test data ranged (chosen confidence level 95%) are from 0.22% to 5.30%.

After each mileage test, the batteries were charged and the charge data were recorded. To prevent the solar panel from charging the battery during the transport of the electric tricycle, the storage batteries were disconnected from the solar panel immediately after each mileage test. The experiment had five replications, which allowed us to determine that the electricity consumed was in the range from 0.38 to 0.41 kW h, with the average energy consumption being 0.394 kW h. The experiment was conducted using a new battery pack; therefore, the first charge cycle required the largest amount of energy.

To determine the acceleration parameters for the solar electric tricycle, the experiment had 7 replications. Speed-time curves were obtained from the average data (Fig. 4).

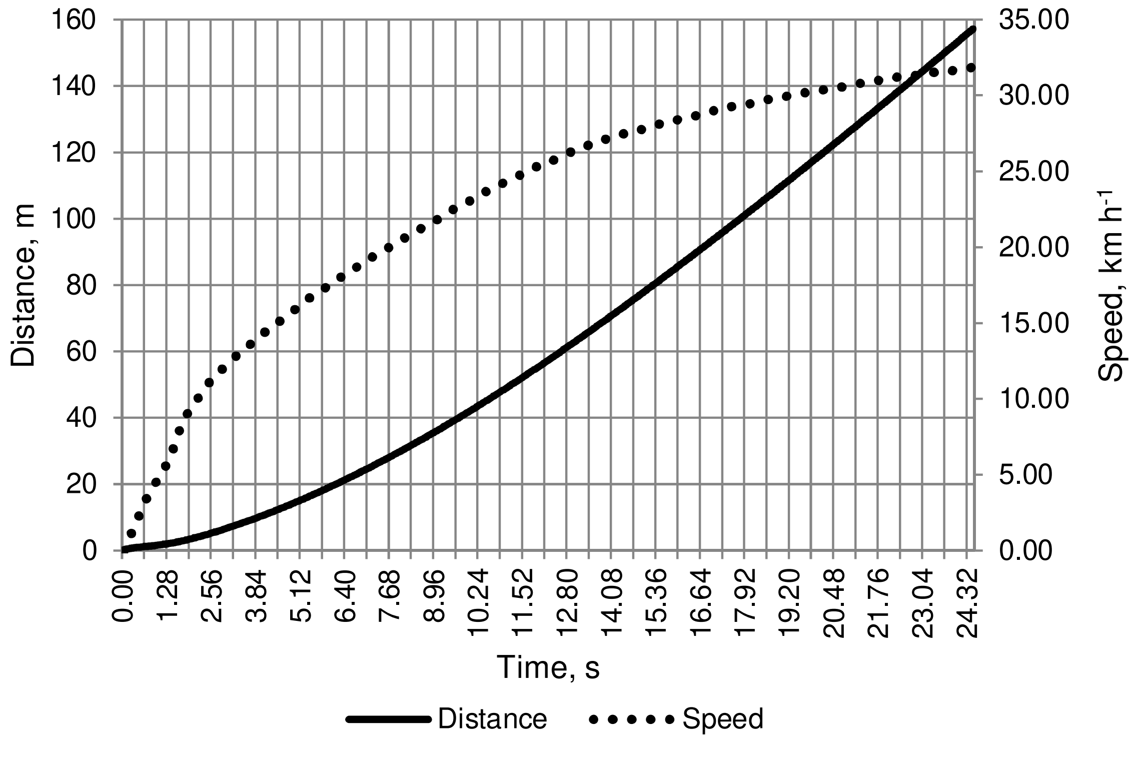

Figure 4. Electric tricycle acceleration speed and distance.

The electric tricycle reached a speed of 10 km h^{-1} fast, in 2.12 s, while 20 km h^{-1} was reached in 7.64 s. The permissible speed for road traffic (electric tricycle category), 25 km h^{-1}, was reached in 11.60 seconds. After reaching this speed, the acceleration was very slow, and the maximum speed of 31.79 km h^{-1} was reached only in 24.48 s. Due to the fact that after reaching the speed of 25 km h^{-1}, the acceleration curve also had a bend point, which indicated additional energy was consumed at higher speeds and the depletion of electricity reserves. Therefore, the cruise speed of 25 km h^{-1} could be considered to be an optimal operating speed for this kind of solar electric tricycles.

An analysis of the acceleration of the tricycle revealed that a speed of 10 km h^{-1} was reached after covering a distance of 4.05 m, while 25 km h^{-1} after 52.90 m. Based on the acceleration characteristics of such a recumbent tricycle, it is recommended to operate it only on tricycle paths or general roads, while sidewalks should be avoided. The maximum speed was reached after covering a relatively long distance of 157.21 m.

The braking of the tricycle was started at a speed of 25 km h^{-1} and finished when it came to a complete stop. In these tests, data were collected from 3 replications. It took 1.99 seconds to stop the solar electric tricycle (Fig. 5). During the braking, the average deceleration was 3.50 m s^{-2}. Taking into account the relatively large weight of the solar electric tricycle used for the experiment, i. e. 155 kg, the braking parameters could be considered to be good.

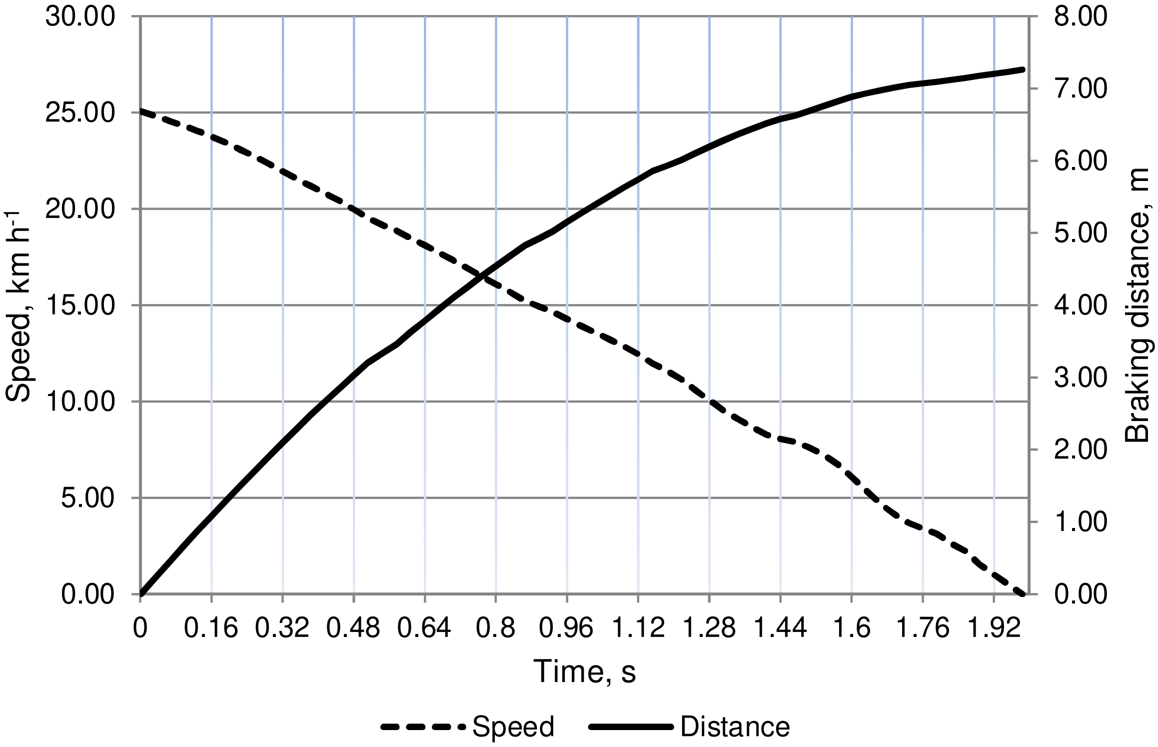

Figure 5. Electric tricycle braking speed and distance.

When braking from a speed of 25 km h^{-1} until the tricycle came to a complete stop, the braking distance was 7.26 meters. When braking from 15 km h^{-1}, the electric tricycle could be stopped in a distance of 2.34 meters, while from 20 km h^{-1}– in 4.23 meters. In terms of braking distance, very good performance was demonstrated by the tricycle. If doing exploitational tests, braking is not recommended with the rear wheel brakes alone, as the wheel might slip under low-adhesion conditions.

The present experiment determined the primary operating parameters of the solar electric tricycle, yet at the next stages of the research, it is planned to carry out experiments using a data logger recording battery charge-discharge parameters and the electricity consumed by the electric motor operated in different modes. It is also intended to determine the maximum speed of a solar electric tricycle at different solar intensities and at different angles of sunlight falling on the ground, with the battery not being discharged.

CONCLUSIONS

1. The developed prototype of a solar electric tricycle proved to be workable in the experiment and could be used for implementing a broader research programme after installing a data logger on it.
2. To charge electric tricycle batteries, 0.394 kW h of electricity is required. Charging the batteries from the mains takes on average 7.2 h. It is also possible to charge the batteries from the solar panel in stationary conditions by using an environmentally friendly kind of energy.
3. In the experiment, the distance covered if using the solar panel was 2.93 times longer than that without using it. The expected distance covered at an optimum speed could be much longer.
4. The characteristics of change in acceleration allows us to conclude that it is not useful to increase the operating speed of the solar electric tricycle above 25 km h^{-1} because, after reaching this speed, the acceleration decreases significantly due to an insufficient power supply.
5. The braking time of the electric tricycle from 25 km h^{-1} was 1.99 seconds, yet the braking distance was 7.26 meters. The mentioned parameters, given the relatively large weight of electric vehicles, could be considered high.
6. It is appropriate to limit the speed to 25 km h^{-1} in order for the vehicle to comply with the category of electric bicycles, as all the other parameters complied with this category.
7. The design defects identified in the primary tests are intended to fix so that the electric tricycle could be used for further research on the use of solar energy in mobile technology at latitudes exceeding 55 degrees.

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