INVESTIGATION OF ELECTRIC BICYCLE ACCELERATION CHARACTERISTICS

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Abstract. This article deals with five different electric bicycle (power from 0.2 to 1.0 kW) acceleration characteristic studies testing them on real road conditions. The measurements were carried out using the scientific radar *Stalker ATS* on two various flat and straight 300 m long asphalt road sections with fully charged batteries under different test modes depending on the electric bicycle type. The investigation results show that the maximum speed and run-up dynamics of electric bicycles are mainly determined by electromotor power, but they are also affected by the weight of the bike, the gear ratio from the motor to the wheels and other parameters. If the electric bicycle has several gears, the character of acceleration in the first seconds is similar, only the maximum achievable speed for each gear differs. Pedalling at the beginning of the run improves the acceleration of the bike, but not the maximum attainable speed.

Keywords: electric vehicle, electric bicycle, acceleration run, scientific radar.

Introduction

During the last few decades negative environmental impact of the gasoline and diesel fuelled vehicles has led to renewed interest in an electric transportation infrastructure. Electric vehicles (EVs) are vehicles that are equipped with electric motors for propulsion.

The main types of electric vehicles are: rechargeable battery vehicles, hybrid vehicles, and electric vehicles that can be refuelled using fuel cells. Rechargeable battery vehicles can also be divided into several different categories. For example, there are electric bicycles or e-bikes, the low speed vehicles that form a class of vehicles with maximum speeds up to 40 km·h^{-1}, and conventional road vehicles using rechargeable batteries [1; 2].

The main barriers to the large scale deployment of EVs are:

- high cost of the vehicle, batteries and service;
- limited driving range on a single charge;
- very little or no public charging infrastructure available;
- limited number of EVs currently on roads and hence limited data and experience regarding their performance [3].

Electric bicycles are probably the most popular type of rechargeable battery vehicles. It is estimated that there are approximately 150 million e-bike users in China and nearly 1 million electric bicycles are sold in Europe each year starting from 2010. China is also the country where the most of researches concerning electric bicycle evolution, as well as the common e-bike user gender, age, income level and daily habits are carried out [4; 5].

There are many different electric bicycle manufacturers and types, with a very wide range of power methods: hub motors in the front or back wheels, and drives on the pedal cranks are the most common variations. In most European and North American countries it is becoming a standard regulation that these bikes must be of the "pedal-assist" type. This means that they cannot be powered by the electric motor alone. However, the regulatory situation is very changeable and depends also on local regulations [1].

A significant electric vehicle exploitation parameter is the dynamic behaviour that allows to judge about the following features:

- electric vehicle fitness for road or walkway traffic;
- identification of the most cost-effective driving speed to ensure maximum mileage per charge;
- ability to safely perform dynamic manoeuvres [6].

The purpose of this study is to compare the different power electric bicycle run-up dynamics, performing measurements in different modes depending on the electric bicycle type, for example, using different gears, with or without a passenger, with or without the assistance of pedals.

Materials and methods

Five different electric bicycles were used during this investigation. They are named accordingly EB1, EB2, ..., EB5, adding the nominal motor power (See Table 1).

Table 1

Main technical parameters of electric bicycles

No.	Conventional name of electric bicycle in experiments	Nominal motor power, W	Bicycle weight with batteries, kg	Bicycle weight with batteries and a driver, kg	Power-to-weight factor, $W \cdot kg^{-1}$
1.	EB1-1000	1000	39.5	121.5	8.23
2.	EB2-500	500	68.5	150.5	3.32
		500	68.5	230.5*	2.17*
3.	EB3-250	250	31.0	113.0	2.21
4.	EB4-200	200	35.8	117.8	1.70
5.	EB5-200	200	37.5	119.5	1.67

* *– electric bicycle EB2-500 was tested also with a passenger*

The acceleration intensity of electric bicycles was determined using the scientific radar *Stalker ATS* on different calendar days and on two various flat and straight 300 m long asphalt road sections with an average rolling resistance coefficient from 0.018 to 0.020. The road surface during the experiments was dry, ambient temperature +15 ± 2 ºC, wind speed did not exceed 2.5 $m \cdot s^{-1}$. Before the experiments a full charge of batteries was performed under laboratory conditions and the electric bicycles were transported to the experiment site by a van.

The scientific radar main technical parameters [7]:

- measurement speed range: 1 – 480 $km \cdot h^{-1}$;
- accuracy: ± 1.069 $km \cdot h^{-1}$;
- target acquisition time: 0.01 s;
- maximal measurement range: 1.82 km;
- weight: 1.45 kg;
- RS-232 communication system.

The *Stalker ATS* software program saves the speed data, assigns the time information, and then calculates the distance and acceleration rates for each data sample. These data are then saved as a file on the computer hard drive in *.RAD* format with speed, acceleration, and distance fixation step after every 0.03 seconds (See Fig. 1).

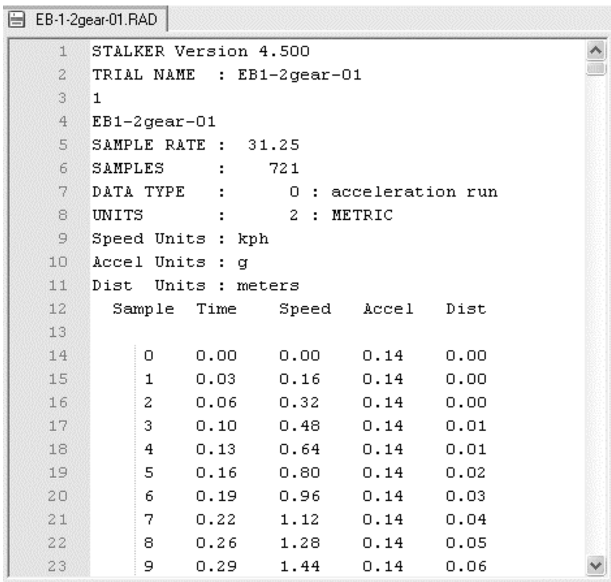

Fig. 1. **Example of electric bicycle acceleration measurement data storing**

Starting the experiment the radar was placed straight behind the e-bike (See Fig. 2). Two operators have participated in the experiment. One worked with the radar, which is connected to a portable computer, the second rode the bicycle.

Fig. 2. **Electric bicycle acceleration measurement using scientific radar *Stalker ATS***

After the radar operator commands, the bicycle driver started sharp run-up, holding the accelerator throttle in maximum position all the way. The experiment was performed from 0 km·h^{-1} until maximum speed was achieved. After the test the bicycle returned to the starting position and the next experiment repetition was carried out.

Each experiment was repeated at least 5 times on each test day. If during the test a car or any other vehicle appeared on the road and disturbed the radar measurements, the experiment was repeated. If already in the radar *Stalker ATS* software distortion of curves was seen, these repetitions also were discarded. An example of discarded repetition is shown in Fig. 3.

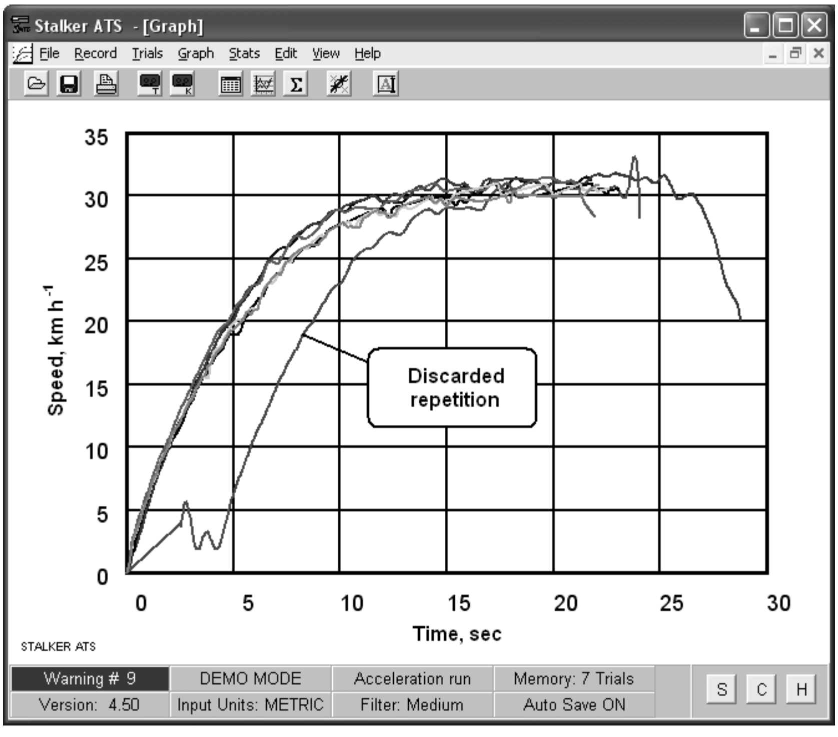

Fig. 3. **Raw radar data and example of discarded repetition**

From all repetitions in each test mode three to six were selected with the closest data, i.e., with the highest correlation between experimental series data points. Average values were calculated from at least 3 repetitions if correlation between the series data points was at least 0.995, i.e., above 99.5 %. After that the curves $v = f(t)$ and $s = f(t)$ were constructed.

The experiments with electric bicycles EB1-1000, EB3-250 and EB5-200 were carried out performing simple run-up, i.e., only holding the accelerator throttle in maximum position all the way. The bicycle EB4-200 additionally was tested using pedal assistance – half a turn starting acceleration. EB2-500 electric bicycle run-up studies were performed using 3 different gears or driving modes and additionally, accelerating on the 3rd gear, also with a passenger.

Results and discussion

Acceleration characteristics, testing all bicycles, are shown in Fig. 4-6. As the maximum speeds and acceleration times of the electric bicycles were different, the two different points were chosen for comparison – the time and distance until the bicycles reach the speed of 15 km h^{-1}, and the achieved speed and travelled distance during 15 seconds acceleration.

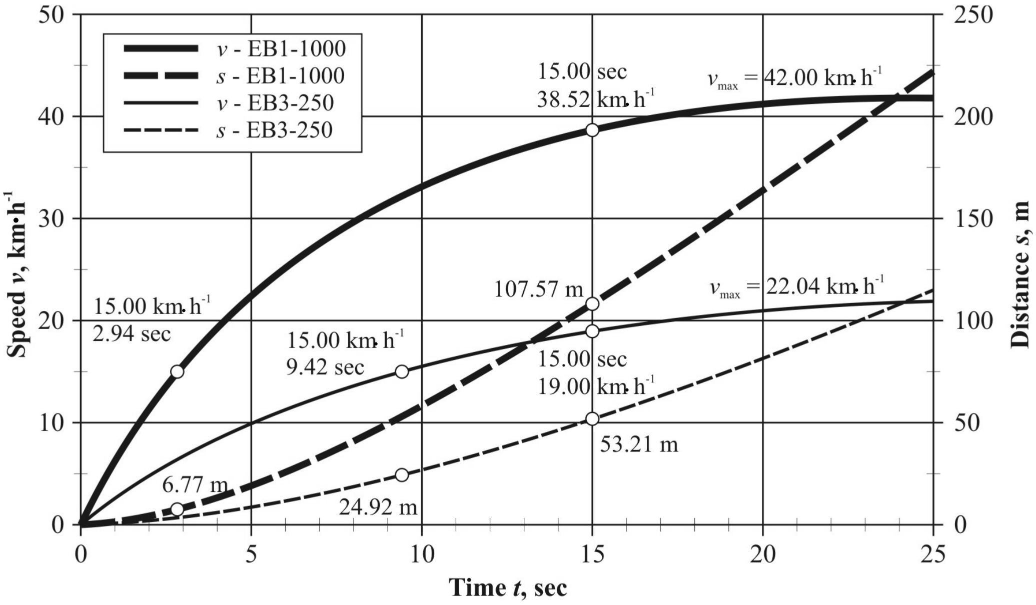

Fig. 4. **Acceleration characteristics testing EB1-1000 and EB3-250 electric bicycles**

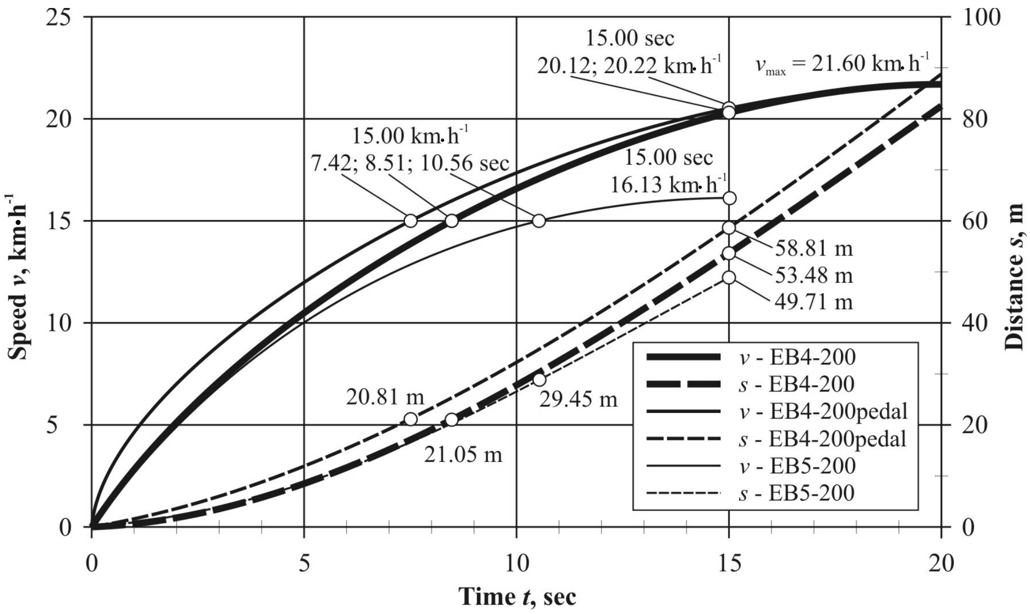

Fig. 5. **Acceleration characteristics testing EB4-200 and EB5-200 electric bicycles**

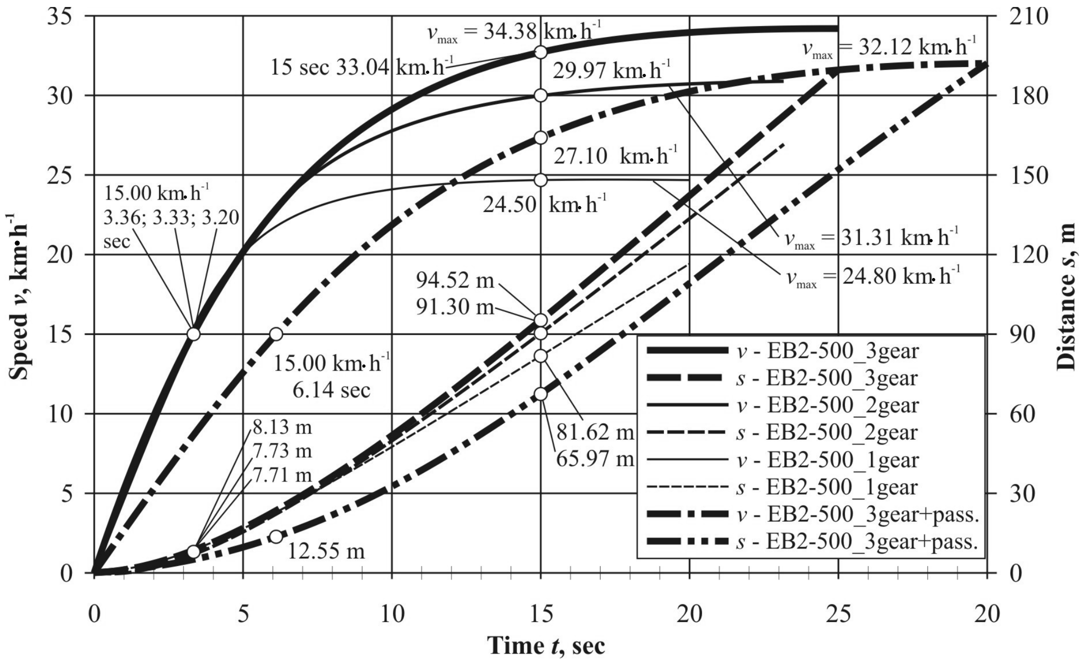

Fig. 6. **Acceleration characteristics testing EB2-500 electric bicycle**

All the above-mentioned test mode results are summarized in Table 2.

Table 2

Summary of acceleration parameters in all test modes

No.	Test bicycle and mode	Test results				
		Maximum speed, km h^{-1}	**Acceleration time from 0 to 15 km h^{-1}, s**	**Acceleration distance from 0 to 15 km h^{-1}, m**	**Speed after 15 sec acceleration, km h^{-1}**	**Distance after 15 sec acceleration, m**
1.	EB1-1000	42.00	2.94	6.77	38.52	107.57
2.	EB2-500 1st gear	24.80	3.20	7.71	24.50	81.62
3.	EB2-500 2nd gear	31.31	3.33	7.73	29.97	91.30
4.	EB2-500 3rd gear	34.38	3.36	8.13	33.04	94.52
5.	EB2-500 3rd gear and passenger	32.12	6.14	12.55	27.10	65.97
6.	EB3-250	22.04	9.42	24.92	19.00	53.21
7.	EB4-200 without pedal assistance	21.60	8.51	21.05	20.12	53.48
8.	EB4-200 with pedal assistance	21.60	7.42	20.81	20.22	58.81
9.	EB5-200	16.13	10.56	29.45	16.13	49.71

Even before starting the tests, it was clear that the electric bicycles with higher motor power will develop higher maximum speed and starting driving will be more dynamic. In general, it was also confirmed in the tests, but there were exceptions. For example, the same motor power electric bicycles EB4-200 and EB5-200 develop a top speed with a 34 % difference. Small cutoff can be described by differences in the bicycle weight, consequently by the power-to-weight factor (See Table 1), but in this case the key factors were different gear ratios of the bicycles from the motor to the wheels (for example, the bicycle EB5-200 was with a smaller tire size), EB5-200 electric motor depreciation and thus lower efficiency. Differences in gear ratios and tire sizes were also the main cause that explains EB3-250 and EB2-500 (running at first gear) similar maximum speeds. At the same time, the highest EB2-500 motor power ensures that the speed of 15 km·h^{-1} was reached about 3 times faster and in a shorter road section, compared to EB3-250.

According to the Latvian law regulations bicycles equipped with an electromotor with a power higher than 250 W or developing greater speed than 25 km·h^{-1}, are classified as mopeds. The experiments show that such a distinction is correct, because the electric bicycles, like the tested E1-1000 and EB2-500 driving on sidewalks (that is allowed for ordinary bicycles) can be dangerous for e-bike drivers themselves and pedestrians, as well as for car drivers when the road intersects with walkways. Bicycles that during 15 seconds can reach speeds up to 30 km·h^{-1}, covering this time almost 100 m distance, may surprise other traffic participants unprepared.

Analyzing the electric bicycle EB2-500 run-up dynamics, it can be concluded that at the first 5 seconds it accelerates equally regardless of the used gear, reaching the speed about 20 km·h^{-1}. The following nature of run-up curves is different because each gear ratio is designed for another maximum speed. Accelerating at the third gear and with 80 kg passenger up to 15 km·h^{-1}, the e-bike speed increase takes 83 % longer time and 54 % longer distance. By increasing the speed, the acceleration difference is not so perceptible, and the maximum speed difference is only 7 %. This leads to the conclusion that also without a passenger a heavier cyclist at start-up will accelerate significantly slower. The EB4-200 test results show that using the pedals assistance as much as half a turn at the beginning of the run-up, the bike is about 15 % more dynamic, but the maximum speed is not affected.

Conclusions

1. The maximum speed and run-up dynamics of electric bicycles are mainly determined by the motor power, but they are also affected by the weight of the bike, the gear ratio from the motor to the wheels and the efficiency coefficient of the motor and transmission.
2. Driving bicycles equipped with an electromotor larger than 250 W along the walkways is undesirable because their high dynamic characteristics may endanger cyclists, pedestrians and car drivers.
3. If the electric bicycle has several gears, the character of acceleration in the first seconds is similar, only the maximum achievable speed for each gear differs.
4. Heavier electric bicycle cyclist has to consider with the reduction of dynamics, particularly in the first movement seconds, or he has to buy a more powerful e-bike.
5. Pedaling at the beginning of the run improves the acceleration of the bike, but not the maximum attainable speed.

Acknowledgements

Funding support for this research is provided by the ERAF Project “Usage of Electric Energy in Motor Vehicles of Physical Persons” (No. 2010/0305/2DP/2.1.1.1.0/10/APIA/VIAA/130).

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