

electric bicycle; energy efficiency; energy consumption

**Ivan EVTIMOV\***, **Rosen IVANOV**, **Gergana STANEVA**, **Georgi KADIKYANOV**

University of Ruse, Department Engines and Vehicles

8, Studentska st., 7017 Ruse, Bulgaria

\*Corresponding author. E-mail: [ievtimov@uni-ruse.bg](mailto:ievtimov@uni-ruse.bg)

## A STUDY ON ELECTRIC BICYCLE ENERGY EFFICIENCY

**Summary.** The paper presents a construction of an experimental electric bicycle for evaluation of the energy efficiency. The bicycle is equipped with onboard computer which can store the information about motion and energy consumption. The result concerning power, energy consumption, recharging during brake process, etc. are given. Energy consumption for 3 typical city routes is studied.

## ИССЛЕДОВАНИЕ ЭНЕРГОЭФФЕКТИВНОСТИ ЭЛЕКТРИЧЕСКОГО ВЕЛОСИПЕДА

**Аннотация.** В статье представлена конструкция экспериментального электрического велосипеда для оценки энергетической эффективности. Велосипед оснащен бортовым компьютером, который может хранить информацию о движении и потреблении энергии. Приведены результаты по вопросам мощности, потребления энергии, подзарядки во время процесса торможения и т.д. Изучено потребление энергии для 3 типичных городских маршрутов.

### 1. INTRODUCTION

Moving in urban areas is connected with big intensity, often braking and starting and continuous working of the engines in idle mode. The increased fuel consumption leads to increased level of the air pollutions.

The governments in different countries apply different measures for stimulation the use of environmentally cleaner vehicles [1, 3, 5, 7] and production of electric energy by renewable energy sources [1, 3, 6].

Many European and Asian countries encourage the usage of bicycles and special attention is paid to the bicycle moving infrastructure [3, 4, 7]. One special category of the vehicle is the electric bicycle. They combine some advantages both from the classic bicycle and the electromobile [1] such as less costs for self-movement, typical for the two-wheeled vehicles, possibility for electric operation or help for climbing etc. In the bigger part of the existing ones there is a possibility provided for generating of energy by charging of the battery during braking or descending.

The aim of the present work is to study the energy efficiency of the electric bicycle and the possibilities for re-generating of energy in a medium town.

## 2. DISCRIPTION OF THE EXPERIMENTAL ELECTRIC BICYCLE

For the purposes of the research, a team from the Ruse University has worked out an experimental electric bicycle [2] based on a Bulgarian bicycle and electric elements. The general structure of the electric bicycle is shown on fig. 1.

The electric bicycle is operated by BLDC electric motor 5 with a nominal power of 500W, built-in the front wheel. It is operated by lithium ion battery 3. The battery has a working tension of 36V, capacity 9Ah and a weight of 3,5kg. The battery contains 324Wh electric energy. The total weight of the electric bicycle is 24,4kg.

The parts for operating and control are assembled on the handlebar (fig. 2, 3, 4). The controller 4 optimizes the working regimes of the electric motor and the regime of regenerative braking.

The autopilot 1 (fig. 4) provides a constant speed of the electric bicycle thus giving a possibility to free the right hand from the speed regulation lever 2 (fig. 3). The regenerative stopping is operated by a separate button 2 (fig. 4) aiming to eliminate the eventual switch on of the mechanical brake system.



Fig. 1. General view of the electric bicycle: 1 – frame; 2 – back wheel with a chain mechanism; 3 – battery; 4 – controller; 5 – electric motor; 6 – handlebar

Рис. 1. Общий вид электрического велосипеда: 1 – рама; 2 – заднее колесо с цепным механизмом; 3 – аккумулятор; 4 – контроллер; 5 – электромотор; 6 – руль



Fig. 2. General view of the electric bicycle handlebar: 1 – board computer; 2 – right handle; 3 – left handle

Рис. 2. Общий вид руля электрического велосипеда: 1 – бортовой компьютер; 2 – правая рукоятка; 3 – левая рукоятка

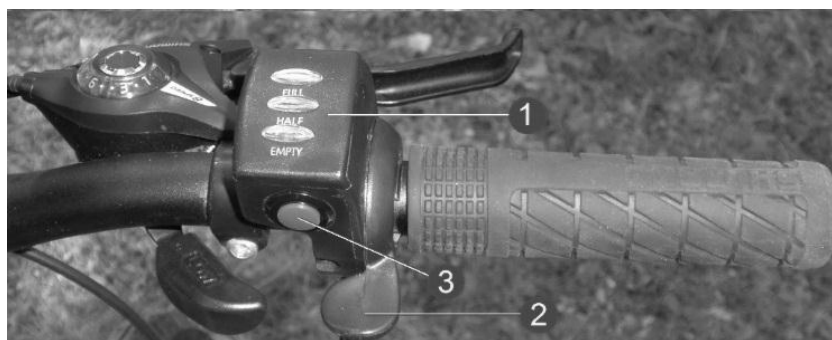


Fig. 3. Operating elements on the right handle: 1 – an indicator for the discharge of the battery; 2 – lever for speed regulation; 3 – a button for switching on/of the electric supply

Рис. 3. Органы управления на правой рукоятке: 1 – индикатор разрядки аккумулятора; 2 – рычаг для регулировки скорости; 3 – кнопка переключения вкл/выкл электропитания



Fig. 4. Operating elements on the left handle: 1 – cruise control; 2 – the button for regenerative stopping

Рис. 4. Органы управления на левой рукоятке: 1 – круиз-контроль; 2 – кнопка для регенеративного торможения

During braking and descending the electric motor works in a generative regime and charges the battery.

The board computer can register and show on a display the following parameters (fig. 5):

- the tension in V and the used capacity in Ah of the battery, the power in W of the electric motor and the speed of movement in km/h (fig. 5a);
- the tension of the battery, the power of the electric motor the speed of movement and the running distance in km (fig. 5b);
- the tension of the battery, the power and the current of the electric motor in A and the used capacity of the battery (fig. 5c);
- the total used energy from battery in Wh and the used energy per 1km in Wh/km (fig. 5d);
- the minimum and maximum current in the electric motor and the minimum tension of the battery (fig. 5e);
- the maximum and average speed of movement in km/h and the total time for movement in hrs, m and s (fig. 5f);
- the total number of charges, the total used capacity of the battery and the total running distance (fig. 5g).

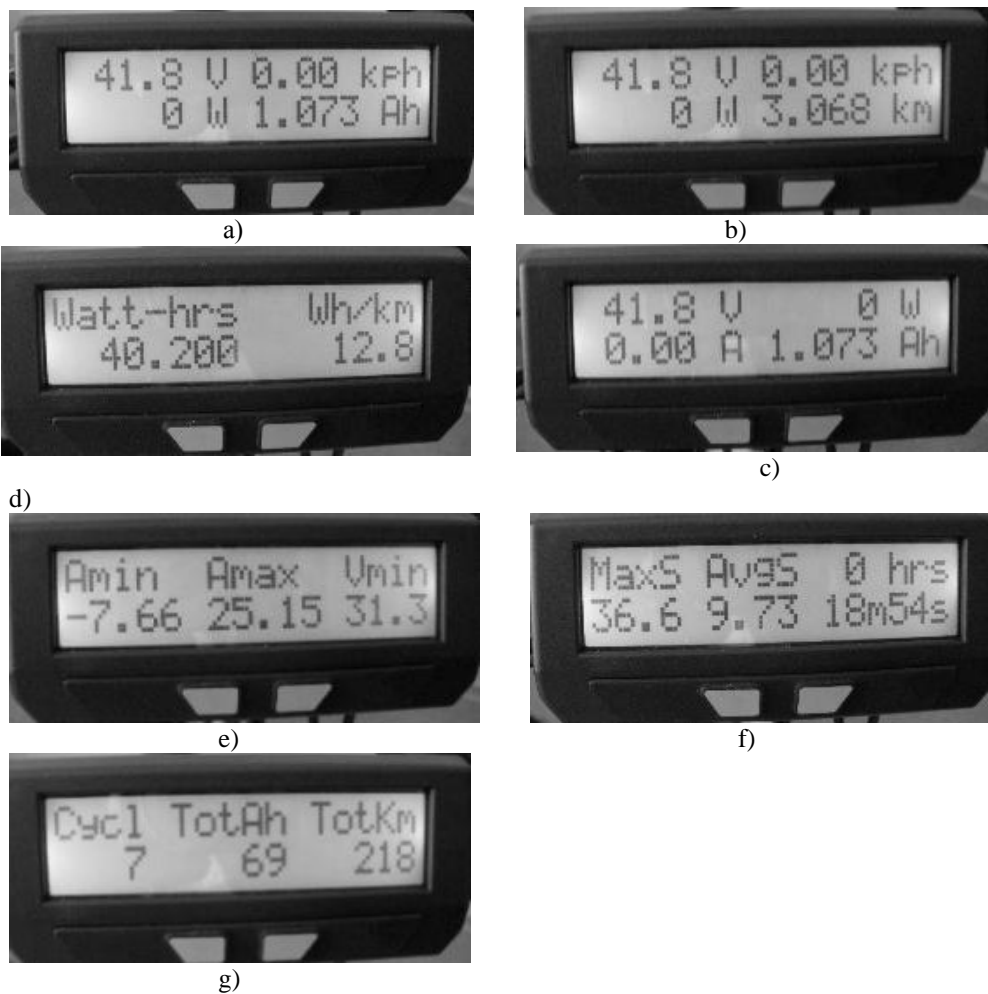


Fig. 5. Registered parameters from the board computer

Рис. 5. Регистрируемые параметры при помощи бортового компьютера

### 3. RESULTS AND ANALYSIS

#### 3.1. Studying the energy consumption

The energy consumption of the electric bicycle has been studied during different working regimes.

There have been made experiments on a horizontal road in two directions with a five time repeating at a constant speeds from 5 to 30km/h. The total weight of the electric bicycle and the cyclist 99,4 kg.

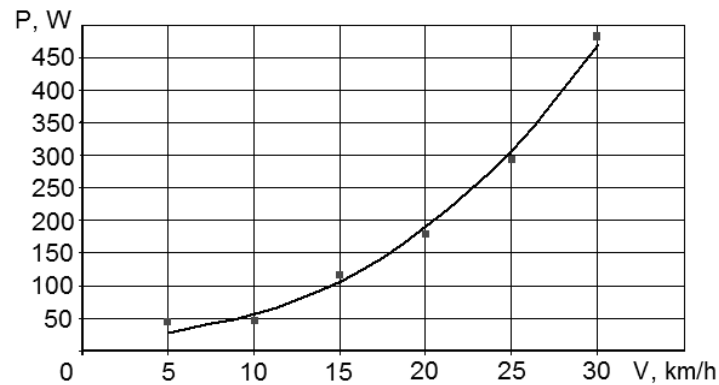
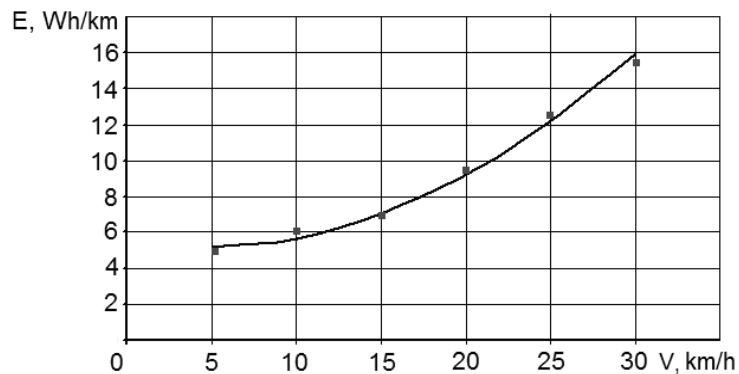
The power  $P$  from the electric motor at different speed  $V$  of the electric bicycle is shown at fig. 6.

The energy consumption  $E$  per 1km at different constant speeds  $V$  is shown at fig. 7.

#### 3.2. Study on the regenerative braking of the electric bicycle

At serial production of the electric bicycles and the sets on the market, the regenerating braking is achieved by the levers for activation of the front and the back brake. At the first starting of the lever only the regenerating braking is switched on and after that depending on the power of pressing of the lever is achieved the desired brake delay, accordingly from the two braking systems – the electric and the mechanical.

Due to the fact that the mechanical braking system has a separate operation (the braking system of each wheel is operated by a separate lever) it is possible for the realization of the following ways for using the braking systems:

Fig. 6. Dependence of the used motor power  $P$  by the speed  $V$ Рис. 6. Зависимость используемой мощности двигателя  $P$  от скорости  $V$ Fig. 7. Dependence of the energy consumption  $E$  by the speed  $V$ Рис. 7. Зависимость потребления энергии  $E$  от скорости  $V$ 

1. Regenerative braking through starting of one of the levers for operating of the braking mechanisms of the wheels (fig. 8).

- regenerative braking and switched on braking mechanism of the front wheel;
- regenerative braking and switched on braking mechanism of the back wheel;

2. Regenerative braking and switched on braking mechanism of both wheels (fig. 9).

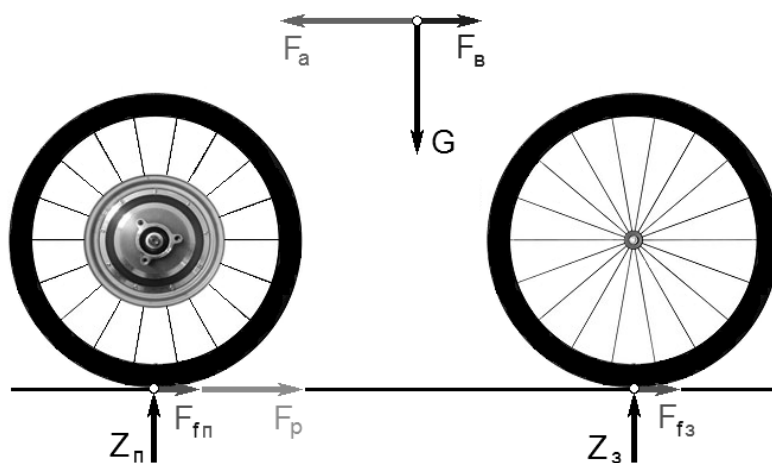


Fig. 8. Forces balance during regenerative braking and without braking for one wheel

Рис. 8. Баланс сил в течение регенеративного торможения и без торможения на одном колесе

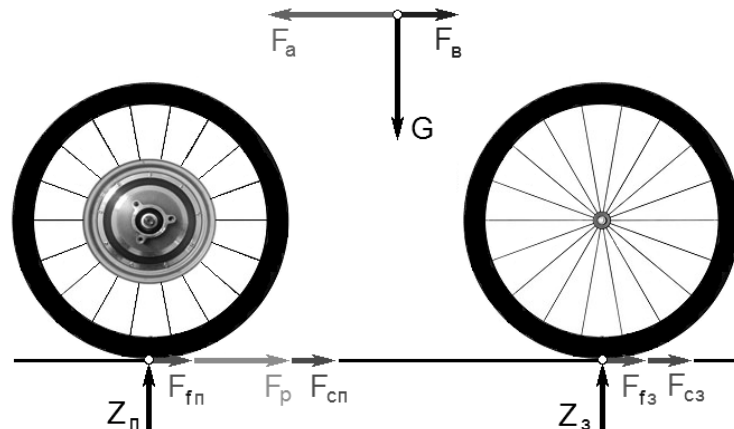


Fig. 9. Forces balance during regenerative braking and switched on braking mechanisms of both wheels

Рис. 9. Баланс сил в течение регенеративного торможения и включения тормозных механизмов на обоих колесах

At fig. 8 and 9 are indicated the weight  $G$ , the rolling resistance force of the front  $F_{fn}$  and the rear  $F_{f3}$  wheels and the air resistance force  $F_b$  during braking process of the electric bicycle on a horizontal area. The resistance forces  $F_{fn}$ ,  $F_{f3}$  and  $F_b$  are directed against the inertia force  $F_a$  and it is not possible to use the entire kinetic energy of the electric bicycle for generating of electric energy.

At present there are not enough researches for the effectiveness of the regenerative braking of the electric bicycles in urban areas. In [8] it is indicated that depending on the conditions of moving and the slopes of the streets, the regeneration of energy varies from 6 to 14%. The experiments made in city of Ruse during a covered distance of 215 km at some of the routes of public transport a regeneration of 5,5% is obtained.

The full stop only by electric motor, without using the mechanical brake is impossible. At the beginning there is only regenerating braking and after that it is necessary to switch on some of the braking systems to achieve full braking.

There have been experiments made at different initial speed and only regenerative braking has been performed. The results from the studies are presented at fig. 10. Each full braking or speed reduction through the electric motor increases the run of the electric bicycle and the exploitation time of the mechanical brake system.

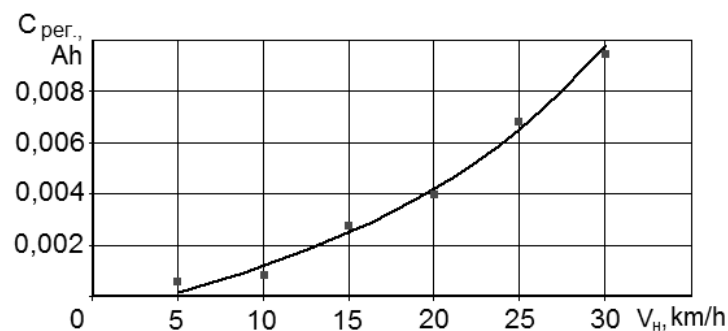


Fig. 10. Dependence of the regenerating capacity in the battery  $C_{пер}$  by the initial speed of braking  $V_s$

Рис. 10. Зависимость емкости регенерации в аккумуляторе  $C_{рег}$  от начальной скорости торможения  $V_s$

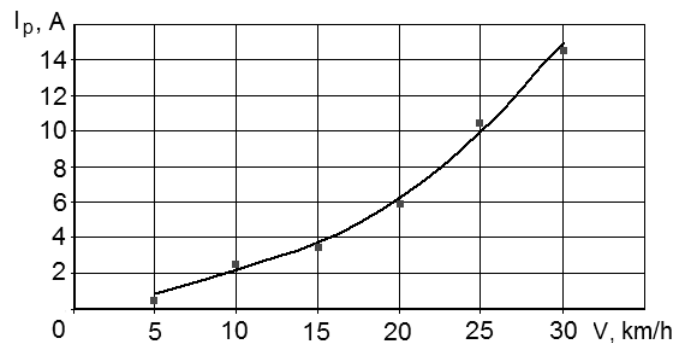


Fig. 11. Dependence of the regenerative current  $I_p$  by the speed of the electric bicycle  $V$   
 Рис. 11. Зависимость тока регенерации  $I_p$  от скорости электрического велосипеда  $V$

It is possible in the infrastructure of the urban area to be realized descending with a speed reduction possibility through the electric motor. With this regard there have been performed experiments of descending at different speed. The results from the experiments are shown at fig. 11. At the different values of constant speed  $V$  is reported the regenerated current  $I_p$  which charges the electric battery.

From this characteristics it is seen that upon descending with speed of 25km/h in a regenerating regime for 60s (the slope is 420 m long) in the battery will be regenerated  $\sim 0,17$ Ah. At 9Ah battery capacity, this regenerated capacity is  $\sim 2\%$ .

### 3.3. Studying the energy consumption for typical routes in the conditions of a medium size town

For the study of the energy efficiency of the electric bicycle there have been chosen three typical routes in the town of Ruse (population  $\sim 150\,000$ ) with a different profile but with heavy traffic. They are shown on fig. 12... 14. For their visualization a virtual map [11] has been used.

The three routes were passed by two group experiments. Firstly, at the beginning without the help of the cyclist and starting only by using the electric motor for acceleration. Again the same routes have been passed also with the help of the cyclist though the bicycle pedals only at starting until reaching a speed of 5km/h. All the experiments have been started with fully charged battery. The results are shown on table 1.

There has been an experiment done also for determination of the operating range of the bicycle during day time period with less traffic (Sunday morning). The average results from route 1 showed that with one charge of the battery, the electric bicycle passes a distance of 34,77km in urban conditions, without using the regenerative braking. The maximum achieved speed was 35,4km/h and the average speed - 23,8km/h. For the whole pass of the route, the electric bicycle has used 390,49 Wh of energy and average per km – 11,2Wh/km. For the bicycles designed abroad with working tension of 36V and similar battery capacity of 9-10 Ah, the operating range for 1 charge of battery is approximately 20 – 25 miles or 32 – 40 km [8, 9, 10]. This fact shows a similar energy consumption of the studied bicycle and a good fit of the obtained experimental results for the range in this research and from other authors [8 - 10].

## 4. CONCLUSIONS

From the carried out research and the analyses of the results, the following conclusions could be made:

1. Without regeneration of the energy in urban conditions the range of the electric bicycle is about 35km. Considering the average value of the regenerating energy in a town of Ruse, the run of the electric bicycle could be increased from 5 to 10%. At day time periods with not so heavy traffic, the run of the electric bicycle could be increased with about 11% due to the less number of braking and accelerations.







Fig. 14. Route 3: Railway Station – River Station and back

Рис. 14. Маршрут 3: Вокзал – Речной вокзал и обратно

Table 1

## Results from the trials

Parameters	Routes, passed without help at starting			Routes, passed with help at starting		
	1	2	3	1	2	3
Passed distance S, km	15,03	5,5	4,34	15,77	5,78	4,33
Energy consumption per 1km passed way, Wh/km	12,8	16,4	18,4	12,5	13,4	13,1
Regenerated energy, %	4,5	5,2	9,5	7,7	10,4	10,7
Maximum speed on the route V max, km/h	36,6	35,8	33,1	35,2	39,8	31,6
Average speed on the route Vcp, km/h,	24,5	22,8	18,4	22,4	21,3	20,6
Time for route passing, min, s	36 min, 46 s	15 min, 5 s	14 min, 5 s	42 min, 10 s	16 min, 16 s	12 min, 36 s

- The studies showed that in a town like Ruse, the use of electric bicycle instead of other vehicles by one person could reduce the air pollutions up to 10 times compared to the electromobiles and up to 15 times compared to the conventional cars. Those values concern the air pollutions generated only due to motion and exclude the other parts like pollutions due to production of the car or bicycle, due to disassembling of the old machine etc. The effect of air pollutions reduction could not be so strong because of a parallel replacing a number of conventional bicycles with electric, which will increase pollutions. At the moment it is not possible to predict how significant will be the influence of replacing.
- At speed of 15 to 25km/h the used power of the electric motor is from 100 to 300W and the energy consumption is from 7 to 12Wh/km which is 6 to 23 times less than the energy consumption of the electromobiles produced now.

4. There is a bigger effect from the regeneration of energy on the routes including slopes. For example on the normal route 1 the regeneration is about 5%, but at routes 2 and 3 including slopes the regeneration reaches about 10%.
5. The level of increasing the effectiveness of the regenerative braking depends on the road infrastructure for moving of bicycles and electric bicycles and chosen by the cyclist regimes for speed reduction and braking.

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