Three-Wheeler Electric Energy Saving Vehicle
Prototype and Experimental Energy Intensive Research

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Abstract
The three-wheeled vehicle construction and ready prototype are described. The vehicle is equipped with two energy recovery systems: one based on lithium-ion battery and electrical engine while the other one is applied with the spring mechanisms to accumulate energy. Both systems are combined together by an energy managing system based on a microcontroller. The construction serves as a testing and developing platform for energy save and recovery systems. At the end of the paper conveyed studies involving the vehicle range and efficiency are described and discussed.

Keywords: energy-saving vehicle, vehicle efficiency, energy accumulation and recovery, strain energy accumulation.

1 Introduction

Green energy and energy saving in transport industry are popular topics and actual problems at the same time. Increase of number of cars in cities and on motorways and permanent traffic jams require new ideas and technical solutions to deal with the increasing air pollution. Therefore, there is a wide range of available technologies aiming at reduction of used energy by road vehicles. The problem which arises is the following: how to combine different solutions in order to create one efficient construction. The main aim of this paper is to describe the construction of a prototype vehicle which employs different mechanisms of energy saving. It also serves as a testing platform for collaboration of used systems and is susceptible of modifications and further development.

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One of the most obvious ways for minimization of energy consumption by the vehicles is their weight reduction. Therefore, there is a wide range of new materials that can be used in vehicles manufacturing (Obst et al., 2016). This trend along with new optimization methods in design is already developed in modern cars and power-trains industry (Raugei et al., 2015; Kumar, 2016; Das et al., 2016). The use of such materials as modern steel, aluminum, titanium, or magnesium intensive, glass fiber, carbon fiber, plastic components and other material composites instead of mild steel allow to reduce 10-70% of the vehicle mass (Raugei et al., 2015; Das et al., 2016). Along with new materials the new design methods are developed. Non classical materials like plastic materials, pure and mixed, require new mathematical models of the material. For example, it can be useful to apply strain energy methods for modeling mechanical properties of such materials (Obst et al., 2016; Wegner, 2009). Strain energy based methods used in mechanical materials properties description give possibilities to prepare useful designing tools for engineers. Energy based methods can be applicable in static loads, thermal, dynamic and multiaxial loads. These ones can be useful also in the area of the loaded parts life estimation (Lagoda and Ogonowski, 2007; Lagoda, 2008).

The other way for the environment pollution reduction is changing the source of power for the vehicles. For the last several years there was growing interest in electric and hybrid (combustion and electric engines combined together) powered vehicles. Such solutions require advanced control (Taghavipour et al., 2015; Chung and Hung, 2015; Lan et al., 2016) and energy storage (Luo et al., 2015) systems. Both structures have huge influence on performance and efficiency of the vehicle (Chung and Hung, 2015). Therefore, careful design and implementation of the modeled systems with the use of such tools as e.g. Matlab Simulink is of importance (Yi et al., 2016). As far as the energy accumulators are concerned, there are many different factors influencing their efficiency and lifetime, and ways of the accumulators implementation - for example the influence of temperature on the conventional batteries efficiency and design of the dedicated cooling system for these batteries (Smith et al., 2016), application of solid oxide electrolysis cells for storing electric energy which dynamically changes over time (Luo et al., 2015) or thermal energy recovery by means of heat pipes (Lan et al., 2016; Putra et al., 2016; Rosiński, 2008). There are also other ways of improving efficiency of electrically powered vehicle like for example wheels slip control system which reduces energy consumption during sudden accelerations (Nam et al., 2015).

New guidelines and law restrictions for environment-friendly vehicles (Lajunen and Lipman, 2016) support projects which develop and implement mentioned technologies in city transport, e.g. electrically powered city buses (Corazza et al., 2016; Mahmoud et al., 2016) or personal vehicles (Ishak et al., 2016). There are also papers that widely describe and summarise the knowledge about different types of energy management systems for various models of vehicles and ways those systems could be optimised (Zhang et al., 2015).
The main goal of this paper is to introduce a project which integrates two different energy recovery systems: one based on battery and the other one based on mechanical accumulator. As a basis the three-wheeled construction was chosen with an electric engine as a drive. Details of the frame and the engine are described in Subsections 2.1 and 2.2, respectively. Subsections 2.3 and 2.4 are devoted for battery selection process and the steering system construction. At the end of Section 2 the energy recovery system is described which consists of the electric engine and a string mechanism combined together by means of the microcontroller. In Section 3 conveyed studies are depicted and discussed.

2 Vehicle design

The following constraints for the design were established:

- minimisation of the vehicle mass,
- minimisation of the wheels rotation resistance,
- minimisation of the friction force in bearings,
- highly efficient drive,
- energy recovery from braking.

In order to achieve all goals the three-wheel, pipe construction will be used as a frame. Wheels have maximised diameter and minimised width for reduction of the rotation resistance while preserving the good traction features. Electric drive seems a natural candidate for such vehicle, since it does not require gearbox and can serve as energy generator while braking. Those constraints are the main decision factors for choosing the components described in details in the consecutive subsections.

2.1 The frame

In the work (Niegoda, 2001) there were described four variants of the optimized frame for mass reduction which are also compatible with the chosen type of the three-wheel construction of the vehicle.

Firstly, the model of the construction of the frame was made in the Autocad Inventor program. The original construction was modified in the following way: for easier implementation of the project all parts were made from round, standard profiles which have the same thickness of the wall on the whole length of the profile. The front beam was modified in a way that improves the rigidity of the frontal part of the vehicle (see Fig. 1). Additionally, the dimensions of the frame were slightly changed in order to lower the load center. The used material was aluminum 6060 T6 temper.
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Fig. 1. The frame for the vehicle.

The static analysis was made for the load equal to 10 [kN] placed as shown in Fig. 1 with the dynamic stress factor equal to 5 and the safety factor equal to 2. The yield point for chosen aluminum is 160 [MPa]. The maximal Huber-Mises reduced stress noted were below the 160 [MPa] (see Fig. 2) and the maximal displacement was equal to 4 [mm].

Fig. 2. The Huber-Mises reduced stress pattern in the loaded frame.

Another static analysis was conveyed to test the rigidity and endurance for torsion. There were two forces: the first one was placed in the middle of the frame and was equal to 1 [kN], while the second one was placed where the left wheel is attached and equal to 940 [N] (the other end of the frame was fixed). The maximal displacement in such setting was 21.3 [mm] (see Fig. 3).
2.2 Drive selection

The construction with a BLDC engine placed in the rear wheel was chosen. The advantages of such solution are the following: easy structure for engine mounting which include lack of need for the additional place for it and straightforward control of the engine. The power of the engine was calculated on the basis of the following criteria:

- mass of the vehicle with the driver (70 kg): $m_p = 110 \text{ [kg]}$,
- track friction factor: $f_{t0} = 0.013$,
- maximal velocity of the vehicle: $v_m = 13.89 \text{ [m/s]}$,
- the factor of additional drag for smooth asphalt surface which relates to the velocity of the vehicle: $A = 5 \cdot 10^{-5}$,
the vehicle acceleration: \( a_m = 5 \text{ [m/s}^2\text{]} \),

- engine efficiency: \( \eta_s = 0.83 \).

The overall resisting force for the vehicle which has velocity equal to 13.89 [m/s]

\[
F_n = m_p \cdot g \cdot f_0 \cdot (1 + A \cdot v_m^2) = 14.168 \text{[N]} \tag{1}
\]

The inertial force of the vehicle which is accelerating 5 [m/s²]

\[
F_b = m_p \cdot a = 660 \text{[N]} \tag{2}
\]

There is no gearing, therefore the power measured on the wheel is equal to the power of the engine:

\[
P_k = P_s = (F_n + F_b) \cdot v_m = 936.3 \text{[W]} \tag{3}
\]

The engine which meets all the requirements Magic Pie 5 with the characteristic shown in Table 1.

**Table 1.** Chosen characteristics of the engine Magic Pie 5.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal power</td>
<td>1000 [W]</td>
</tr>
<tr>
<td>Peak power</td>
<td>1248 [W]</td>
</tr>
<tr>
<td>Maximal current</td>
<td>26 [A]</td>
</tr>
<tr>
<td>Main supply voltage</td>
<td>48 [V]</td>
</tr>
<tr>
<td>Efficiency</td>
<td>83 [%]</td>
</tr>
<tr>
<td>Weight</td>
<td>8.5 [kg]</td>
</tr>
</tbody>
</table>

### 2.3 Battery selection

The battery for the vehicle is selected with accordance to the engine (see previous subsection) and the assumption that the vehicle minimal range is 30 [km]. In order to make the calculations easier additional assumptions were made: the vehicle moves with the uniform motion and the velocity is equal to 35 [km/h] on a flat ground. The rest of the factors are the following:

- \( v = 35 \text{ [km/h]} = 9.722 \text{ [m/s]} \),
- supply voltage: \( U_{ak} = 48 \text{ [V]} \),
- the range of the vehicle: \( S = 30 \text{ [km]} \).
The overall resisting force for the vehicle which has velocity equal to 13.89 [m/s]

\[ F_n = m_p \cdot g \cdot f_t \cdot (1 + A \cdot v^2) = 14.095[N] \]  

(4)

Power needed to overcome the resisting force

\[ P_k = F_n \cdot v = 137.031[W] \]  

(5)

Power of the battery taking the efficiency of the engine is under consideration

\[ P_{ak} = \frac{P_k}{\eta_s} = 165.097[W] \]  

(6)

Current intensity for the battery

\[ I_{ak} = \frac{P_{ak}}{U_{ak}} = 3.44[A] \]  

(7)

Time of the vehicle in motion

\[ t = \frac{S}{v} = 0.857[h] \]  

(8)

The minimal capacity of the battery

\[ Q_{ak} = t \cdot I_{ak} = 2.948[Ah] \]  

(9)

In order to cover the effect of acceleration and possible roughness of the road the safety factor \( n = 2.5 \) was assumed

\[ Q_{akk} = n \cdot Q_{ak} = 7.37[Ah] \]  

(10)

On the basis of the calculations and engine characteristic the lithium-iron-phosphorus (LiFePO4) battery was chosen with the capacity equal to 10 [Ah] - dedicated battery for the Magic Pie electrical engine was applied. The characteristic of the battery is shown in the Table 2.

**Table 2. Battery technical data.**

<table>
<thead>
<tr>
<th>Voltage</th>
<th>48 [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>10 [Ah]</td>
</tr>
<tr>
<td>Weight</td>
<td>5.5 [kg]</td>
</tr>
<tr>
<td>Maximal current load (maximal current peak)</td>
<td>30 [A] (50 [A])</td>
</tr>
<tr>
<td>Maximal charging voltage</td>
<td>58.4 [V]</td>
</tr>
<tr>
<td>Work temperature</td>
<td>20-55 [°C] (discharging); 0-45 [°C] (charging)</td>
</tr>
<tr>
<td>Lifetime</td>
<td>&gt; 2000 charging cycles</td>
</tr>
<tr>
<td>Dimensions</td>
<td>361 x 149 x 83 [mm]</td>
</tr>
</tbody>
</table>
2.4 Steering system construction and geometry

Steering system does not include gearing in order to reduce the weight of the vehicle. Therefore, the maximal angle of the steering wheel is equal to 160°. The minimal diameter of the steering wheel is calculated with the assumption that the driver is able to act on the steering wheel with the force equal to 20 [N]. Other factors needed for calculations:

- width of the tyre: \( B = 30 \) [mm],
- distance between the middle of the tyre and the axle of the front-wheel spindle: \( e = 50 \) [mm],
- friction factor between tyre and road: \( \mu = 0.8 \),
- steering knuckle arm: \( r_s = 0.012 \) [m],
- steering arm: \( r_k = 0.008 \) [m],
- force on the steering wheel: \( F_{cz} = 20 \) [N].

Additionally, the assumption is made that the mass of the vehicle with the driver is distributed equally among the wheels:

\[
G = \frac{(2 \cdot m_p \cdot g)}{3} = 719.4\,[N] \tag{11}
\]

The moment needed to turn the front wheels is calculated as in [14]

\[
M_s = \frac{(0.05 \cdot G \cdot B \cdot \mu)}{((1 + e/B) \cdot 200 \cdot 0.7)} = 2.312\,[Nm] \tag{12}
\]

The force on the steering knuckle arm

\[
F_s = \frac{M_s}{(2 \cdot r_s)} = 96.348\,[N] \tag{13}
\]

Moment on the steering wheel

\[
M_k = 2 \cdot F_s \cdot r_k = 1.542\,[Nm] \tag{14}
\]

The minimal radius of the steering wheel

\[
r_{kier} = \frac{M_k}{(2 \cdot F_{cz})} = 0.039\,[m] \tag{15}
\]

In order to make wheels self-return to the initial straight position the advanced angle for the steering knuckle arm was applied (it is equal to 5° and can be regulated by the shift of the screws which fix the steering knuckle to the frame). Such solution may cause tilting the wheels while turning, therefore the wheels are fixed in the position presented in Fig. 4 (the frontal view). In this case there is no excessive wearing of the tyres because the width of the tyre is very small.
2.5 Energy recovery system

The Magic Pie engine already enables recovery of energy while handling. The sensor in the handbrake on the steering wheel measures the position of the handling lever - if the handbrake is used, but with the lever displacement is "small", only engine handling is used (with the energy recovery), otherwise the disc brakes are launched. However, the energy recovery system in the electrical engine works efficiently only if the vehicle velocity is greater than 15 [km/h].

In order to recover the energy when the vehicle travels with the velocity below the 15 [km/h] an additional mechanical energy recovery system was designed. The system is based on two springs which are stretched during the handling when the vehicle velocity is below 15 [km/h].

The work of the two systems combined into one is described in a graph shown in Fig. 6.
Fig. 6. The working scheme of the whole recovery system.

The calculations of the springs. The factors:

- the length of the stretched spring: \( x = 0.2 \) [m],
- the velocity of the vehicle: \( v = 15 \) [km/h] = 4.167 [m/s],
- the mass of the vehicle with the driver: \( m = 110 \) [kg],
- time from the start of the handling to the end (\( v_k = 0 \)): \( t = 2 \) [s],
- wheel radius: \( r = 0.33 \) [m].

From the energy conservation law we get

\[
\frac{(m \cdot v^2)}{2} = \frac{(k_s \cdot x^2)}{2}
\]  
(16)

\[
k_s = \frac{(m \cdot v^2)}{x^2} = 4.774 \cdot 10^4[N/m]
\]  
(17)

The negative acceleration

\[
a_h = \frac{v}{t_h} = 2.083[m/s^2]
\]  
(18)

Braking distance

\[
S_h = \frac{v^2}{(2 \cdot a_h)} = 4.167[m]
\]  
(19)
The amount of wheel turns until the vehicle stops

\[ n = \frac{S_h}{(2 \cdot \pi \cdot r)} = 2.01 \]  \hspace{1cm} (20)

The diameter of the drum for the rope (0.2 [m] length of the rope on approximately 2 turns of the drum) which will be used to stretch the springs

\[ d = \frac{x}{(\pi \cdot n)} = 0.032{\text{[m]}} \]  \hspace{1cm} (21)

The rope tensile force

\[ F_I = k_s \cdot x = 9.549 \cdot 10^3{\text{[N]}} \]  \hspace{1cm} (22)

Momentum on the drum

\[ M_I = \frac{(F_I \cdot d)}{2} = 151.25{\text{[Nm]}} \]  \hspace{1cm} (23)

3 Efficiency research

After the prototype of the vehicle was built a series of measurements was made. The following subsections describe the characteristics that were made.

3.1 Energy consumption for various velocity values

Energy consumption for various velocity values was measured on 400 [m] of straight road section. The vehicle was accelerated to the given velocity and stabilised by means of the speed controller before the start of the road section. The measurement of the used energy was the difference between the initial and final state of the battery indicator (on the starting and ending point of the road section respectively). For every velocity the measurement was made twice - in both directions of the road section. Obtained results are given in Table 3 and Fig. 7. The energy consumption is the mean value from runs in both directions multiplied to represent the energy consumption for 100 [km] drive with a given velocity.

Table 3. Energy consumption for a given velocity value.

<table>
<thead>
<tr>
<th>Velocity [km/h]</th>
<th>Energy consumption for 100 km [Wh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>1547.25</td>
</tr>
<tr>
<td>35</td>
<td>1284.875</td>
</tr>
<tr>
<td>30</td>
<td>1078.375</td>
</tr>
<tr>
<td>25</td>
<td>964.5</td>
</tr>
<tr>
<td>20</td>
<td>735.25</td>
</tr>
<tr>
<td>15</td>
<td>1090.625</td>
</tr>
<tr>
<td>10</td>
<td>1182.625</td>
</tr>
</tbody>
</table>
Obtained results indicate that in order to minimise the power consumption the vehicle should travel with the velocity value equal to 20 [km/h]. On this assumption the maximal range for the vehicle is calculated:

- the battery capacity: $Q_a = 10 \text{ [Ah]}$,
- nominal voltage for the battery: $U_{ak} = 48 \text{ [V]}$,
- energy required to drive 100 [km] (with the constant velocity equal to 20 [km/h]): $E_{100} = 735.25 \text{ [Wh]}$.

The available energy from fully charged battery

$$E_{ak} = Q_a \cdot U_{ak} = 480 \text{ [Wh]} \quad (24)$$

The required energy for 1 [km] drive with the constant velocity equal to 20 [km/h]

$$dE = \frac{E_{100}}{100} = 7.35 \text{ [Wh/km]} \quad (25)$$

The maximal range of the vehicle traveling with constant velocity equal to 20 [km/h]

$$S_m = \frac{E_{ak}}{dE} = 64.865 \text{ [km]} \quad (26)$$

### 3.2 Energy consumption for various acceleration values

The acceleration of the vehicle was divided into 3 intervals: from 10 to 20 [km/h], from 20 to 30 [km/h] and from 30 to 40 [km/h]. For each interval 4 measurements were made. The obtained data is shown in Table 4 and Fig. 8.
### Table 4. Energy consumption for acceleration of the vehicle in each interval.

<table>
<thead>
<tr>
<th>Interval [km/h]</th>
<th>Distance [m]</th>
<th>Acceleration [m/s²]</th>
<th>Energy consumption [Wh]</th>
<th>Energy consumption calculated on one km [Wh/km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-20</td>
<td>24.28</td>
<td>1.33566</td>
<td>0.47966</td>
<td>19.76</td>
</tr>
<tr>
<td></td>
<td>39.76</td>
<td>0.79748</td>
<td>0.58578</td>
<td>14.73</td>
</tr>
<tr>
<td></td>
<td>24.21</td>
<td>1.47502</td>
<td>0.57451</td>
<td>23.73</td>
</tr>
<tr>
<td></td>
<td>28.65</td>
<td>1.36081</td>
<td>0.53569</td>
<td>18.70</td>
</tr>
<tr>
<td>20-30</td>
<td>95.24</td>
<td>0.74401</td>
<td>1.06205</td>
<td>11.15</td>
</tr>
<tr>
<td></td>
<td>83.58</td>
<td>0.82173</td>
<td>1.06884</td>
<td>12.79</td>
</tr>
<tr>
<td></td>
<td>84.99</td>
<td>0.78739</td>
<td>0.92611</td>
<td>10.90</td>
</tr>
<tr>
<td></td>
<td>100.81</td>
<td>0.60520</td>
<td>0.84669</td>
<td>8.40</td>
</tr>
<tr>
<td>30-40</td>
<td>162.60</td>
<td>0.61075</td>
<td>1.56142</td>
<td>9.60</td>
</tr>
<tr>
<td></td>
<td>148.80</td>
<td>0.65379</td>
<td>1.42500</td>
<td>9.58</td>
</tr>
<tr>
<td></td>
<td>232.36</td>
<td>0.45145</td>
<td>1.47256</td>
<td>6.34</td>
</tr>
<tr>
<td></td>
<td>252.23</td>
<td>0.44127</td>
<td>2.00398</td>
<td>7.95</td>
</tr>
</tbody>
</table>

**Fig. 8.** Energy consumption while vehicle acceleration; lines define polynomial regression for each set of data.
3.3 The run of the vehicle for different types of tires

The maximal run of the vehicle was examined for two types of tires: full tires without the gas chamber and tires which were pumped with the air for three pressures: 4.5, 2.5 and 1.5 bar. The road section for the run started with a slope where the vehicle gained speed by the action of gravity force and the straight section, where the vehicle slowed down because of the friction forces. The results are shown in Fig. 9.

![Fig. 9. The run of the vehicle for different tires.]

3.4 The efficiency of the vehicle moving with different velocities

The theoretical work of the vehicle is expressed by the following equation

\[ W = \left( \frac{m\cdot v^2}{2} \right) + \left( \frac{J \cdot \omega^2}{2} \right) \]  

(27)

where \( J \) is a moment of inertia of a rotating mass. The moment of inertia of the rear wheel was calculated in the following way

\[ J_{kt} = \left( \frac{m_s \cdot r_s^2}{2} \right) + m_o \cdot r_o^2 = 0.4[\text{kg} \cdot \text{m}^2] \]  

(28)

- the engine mass: \( m_s \),
- the tire mass: \( m_o \),
- the engine radius: \( r_s \),
- the tyre radius: \( r_o \).
The real work of the vehicle was calculated by means of the equation:

\[ W = \int P \, dt = \int I \cdot U \, dt \]  

(29)

The results of the two measurements are shown in Fig. 11 along with polynomial regression.

![Fig. 10. The efficiency of the vehicle moving with different velocities and the polynomial regression of the obtained data for two trials.](image)

It should be noted that the measurements were made on the vehicle which was equipped with the full tires (without the gas chamber).

4 Conclusions

The construction and prototype of the energy-saving vehicle was presented in this paper. The vehicle uses electric engine as a drive as well as a part of the energy recovery system. The solution for energy recovery for low velocity of the vehicle uses a string mechanism which is combined with the electrical engine by means of the microcontroller. The prototype of the vehicle was used to convey a series of studies involving energy efficiency of the vehicle, its maximal range and the energy consumption for various velocities and accelerations of the vehicle.
References


