Initial bench tests of a parallel hybrid system of a scooter

B Zagól and W Grzegożek

Cracow University of Technology
Al. Jana Pawla II 37, 31-864 Krakow, Poland

E-mail: witek@mech.pk.edu.pl; bartoszzagol@gmail.com

Abstract. The article presents initial bench tests of a vehicle with a parallel hybrid drive and with an internal combustion engine. During the research, special attention was paid to the impact of regulator's rollers masses in CVT on acceleration of a hybrid vehicle and powered by an internal combustion engine. The differences in the CVT transmission ratio values are presented, at which the electric motor is disconnected during acceleration of the hybrid vehicle.

1. Introduction

Growing technological progress contributes to continuous increase in the number of vehicles on roads around the world. The growing number of cars and scooters causes irreversible changes in the natural environment. For this reason, standards in the European Union witch regulate the permissible emission of carbon oxides (NOx), hydrocarbons (HC) and particulates (PM) for new vehicles sold within its borders have been introduced. Many cities in Europe (i.e. Berlin, Brussels, Stuttgart) banned vehicles witch do not meet the required emission standards from entering. To reduce the emission of exhaust gases, alternative solutions have been sought. Energy savings for small two-wheeled vehicles [1] such as scooters and motorcycles with small capacities were compared. It was found that two-wheeled city vehicles (scooters) are a very good solution for commuting in urban agglomeration. Nowadays, the introduction of hybrid solutions to these vehicles is also increasingly considered. Hybrid solutions are intended to allow these vehicles to move in zero emission zones by using part of the electric drive system. At the same time, hybrid vehicles, provide sufficient range to reach city centers from suburbs of the urban agglomeration using the internal combustion engine of the drivetrain. In hybrid scooters and motorcycles, it is necessary to consider the electric motor with an internal combustion engine working together which are usually connected via road. There is a number of papers about hybrid vehicles containing results of theoretical research on control systems for electric motors and internal combustion engines in order to ensure primarily reduced fuel consumption [2,3]. There is also a small number of publications regarding road tests of this type of vehicles [4,5,6]. Bench tests of this type of vehicles are also rare [7]. Bench tests ensure repeatability of load and ambient conditions. Unfortunately, in case of parallel hybrids in which drive systems are connect by the road, they require special construction of test stands. This article contains a description of such a test stand and the results of research on the prototype hybrid scooter. Obtained results indicate that in order to achieve optimal fuel consumption, it is necessary to develop a special CVT transmission control system.

2. Stand for testing hybrid vehicles

The test stand should allow parallel loading of both combustion and electric drive systems. Considering that the simplest hybrids are constructed by mounting an electric motor in the front wheel of the vehicle and that the propulsion systems are connected via the road, the test stand should provide the possibility of burden for such a hybrid drive. Attention should also be paid to the construction of the stand so that the scope of research should also apply to dynamic tests. The simplest way to ensure that the correct load is applied during dynamic test is to implement an inertial mass in the form of a flywheel.

Stand description

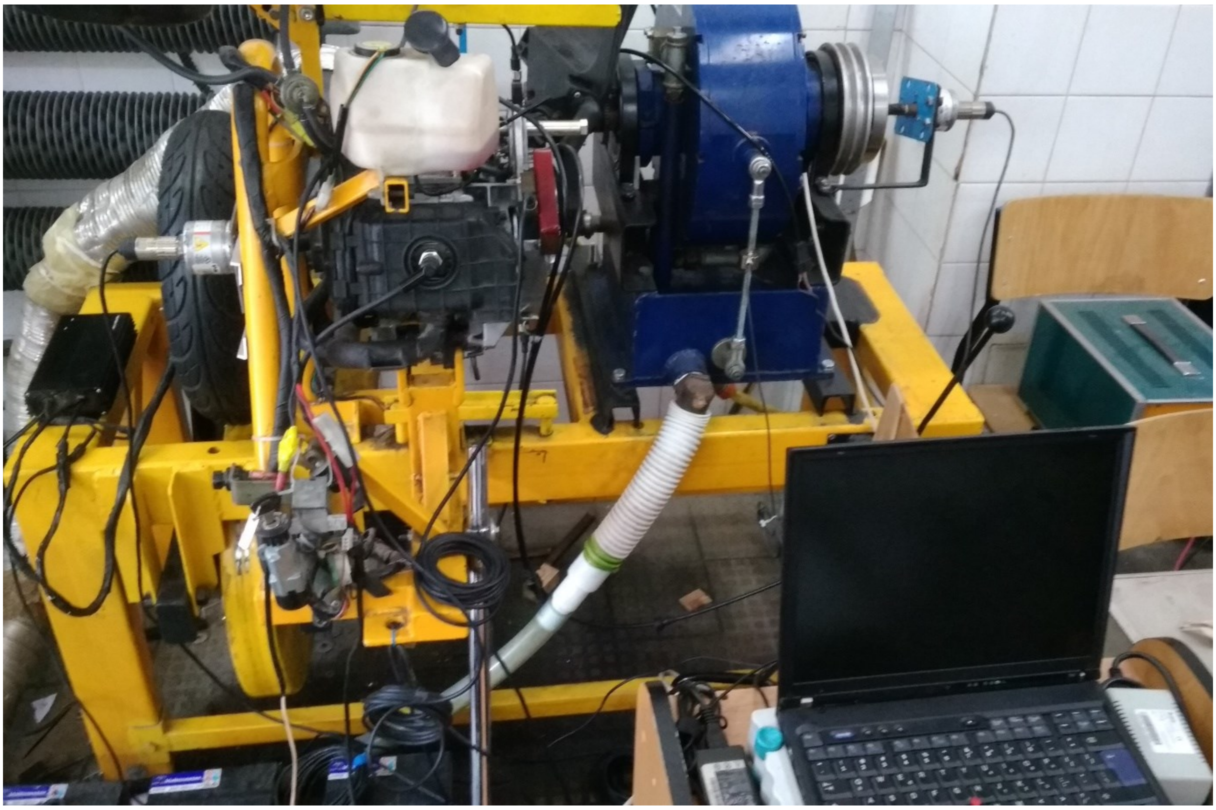

Figure 1. Picture of the test stand for hybrid vehicles

The stand consists of a complete scooter drive system, an eddy current brake, a scooter front wheel with an electric motor, a flywheel constituting a dynamic load and measuring systems. The complete internal combustion engine drive system is connected by means of a drive shaft one side with an eddy current brake on the other side via a belt transmission with a flywheel. This part of the stand enables the measurements of both quasi-static and dynamic losses of the combustion drive system. A rubber wheel is mounted on the surface one the outer flywheel integrated with the electric motor, preloaded by screw tension force. This part of the test stand, after disconnecting the CVT belt transmission, allows testing of the electric drive system. The inclusion of the CVT transmission allows experimental testing of the hybrid system. Resistance of motion such as air resistance and rolling resistance is provided by the eddy current brake. The load resulting from inertia forces is provided by the flywheel. The size of the moment of inertia of the flywheel was chosen so as to be equivalent to the mass of the scooter with the driver of around 200 kg.

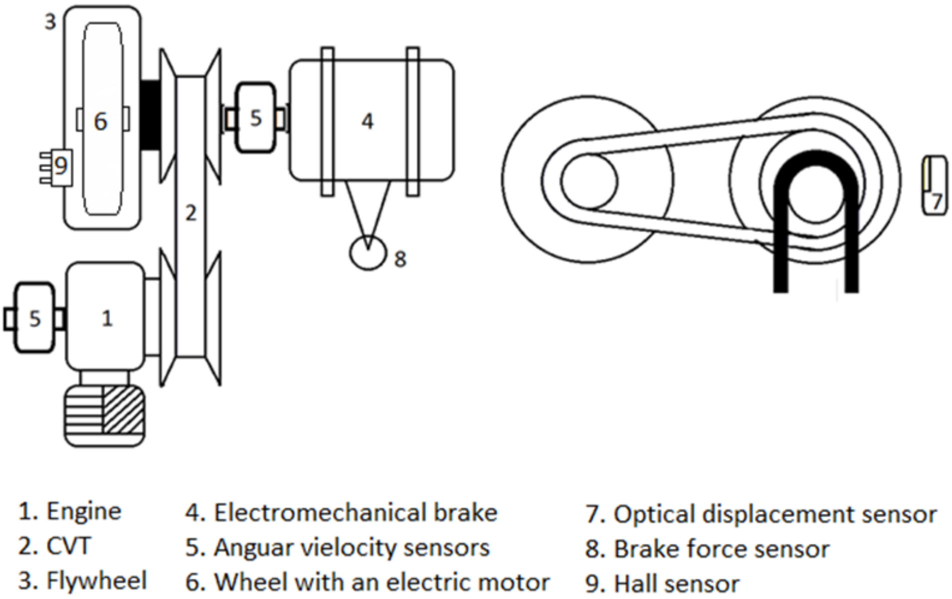

Figure 2. Scheme of the test stand

3. Studies of drive systems

The scope of the tests included acceleration of the drive system for three different driveway modes. The measured values were: rotational speed of the internal combustion engine, the electric motor, the flywheel, the CVT transmission gear wheel, and the CVT gear ratio change. The tests were carried out by 0/1 throttle opening.

Stand acceleration of the scooter

The torque of the internal combustion engine obtained on the drive shaft is transferred from the drive shaft through the CVT transmission and the main transmission reaches the rear wheel hub which is connected to the flywheel. The speeds of the scooter driven by the internal combustion engine was determined from the following:

$$V_e = \omega_r * \ r_r = \frac{\omega_e * r_r}{i_{CVT} * i_{mt} * i_{bt}}$$

where:
$\boldsymbol{V_e}$ – wheel speed obtained by the internal combustion engine,
ω_r – angular speed of the wheel as driven by the internal combustion engine,
$\boldsymbol{r_r}$ – rear wheel radius,
$\boldsymbol{\omega_e}$ – angular speed of the internal combustion engine,
$\boldsymbol{i_{CVT}}$ – ratio of the continuously variable transmission,
$\boldsymbol{i_{mt}}$ – gear ratio of the main transmission,
$\boldsymbol{i_{bt}}$ – gear ratio of the belt transmission.

The speed of the vehicle driven by the electric motor was determined from the following:

$$V_{el} = \omega_f * \ r_f$$

where:
V_{el} – speed of the wheel obtained by the electric motor,
ω_f – angular speed of the wheel with an electric motor,
r_f – front wheel radius.

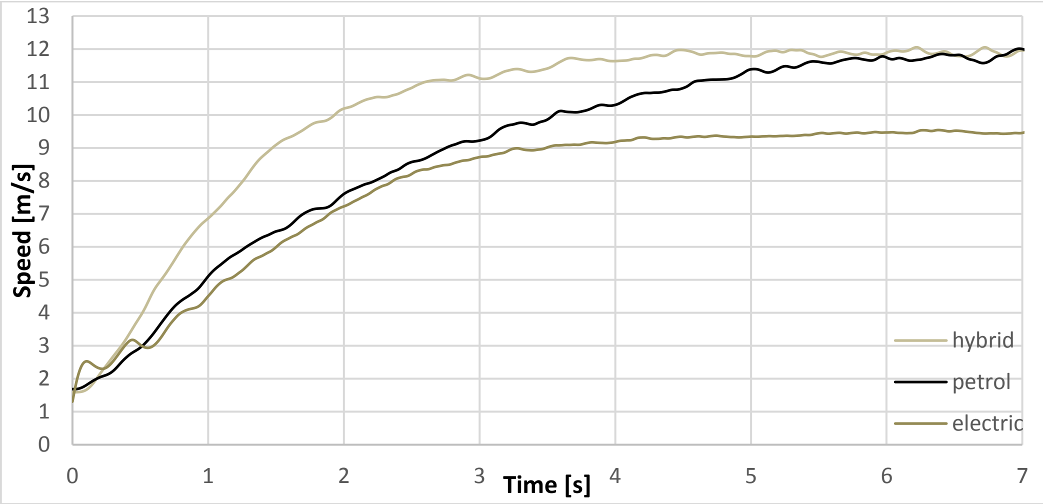

Figure 3. The acceleration of the vehicle with electric, diesel and hybrid drive

Due to the limitation of the rotational speed of the electric motor, further analyses will be for acceleration process to the vehicle's linear speed of approx. 9 m/s. This is the speed obtained by the vehicle powered with the electric drive. In case of an internal combustion engine, the acceleration is strictly dependent on the gear ratio changes in the CVT transmission. The standard characteristic of the transmission is shown in Figure 4.

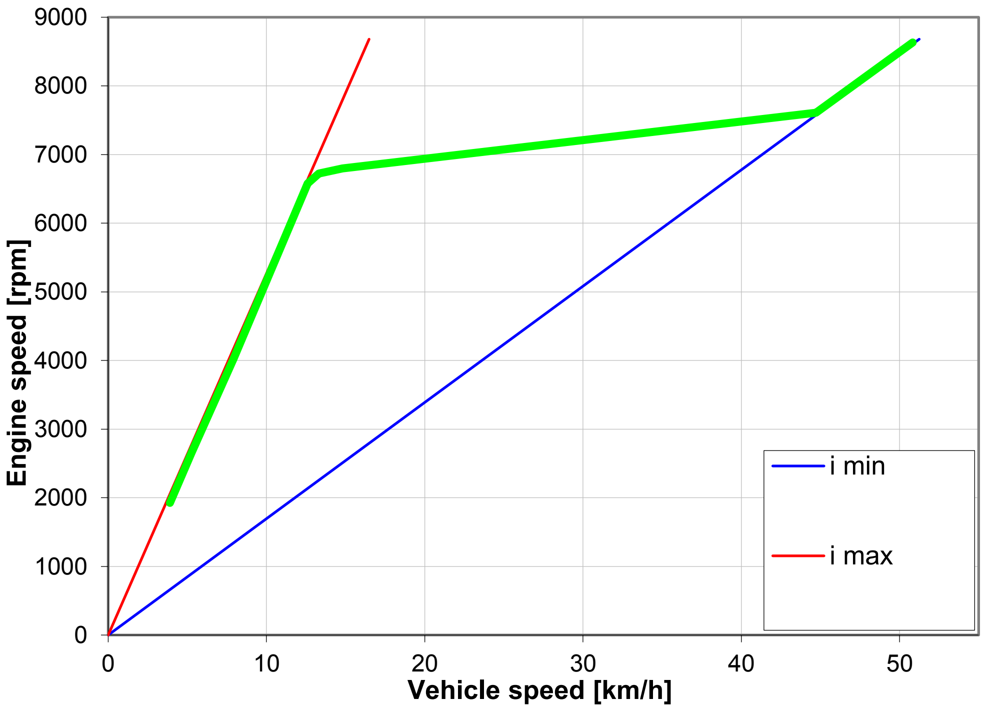

Figure 4. The standard CVT characteristic

By increasing the mass of rollers in the centrifugal regulator of the CVT transmission, changes in the characteristics of the transmission can be obtained. Taking into account the combination of the two propulsion sources, tests of acceleration of the vehicle for various masses of regulator rollers were carried out. In order to analyze the common drive, gear change in the CVT transmission as a function of time was made (Figure 5). Tests carried out with the standard rollers showed that the electric motor reaches its maximum speed at the total ratio of the drivetrain system, of approx. i_c = 15,15. During simulations with the 7.5 g rollers, the total gear ratio was approx. i_c = 14,6. When using 9 g rollers, the electric motor stopped supporting the hybrid system at a total ratio of approx. i_c = 13,75. The mass difference between 6 g and 9g rollers is about 33.3% and despite such a huge difference in masses, the differences in the CVT transmission ratio at which the electric motor is disconnected are small.

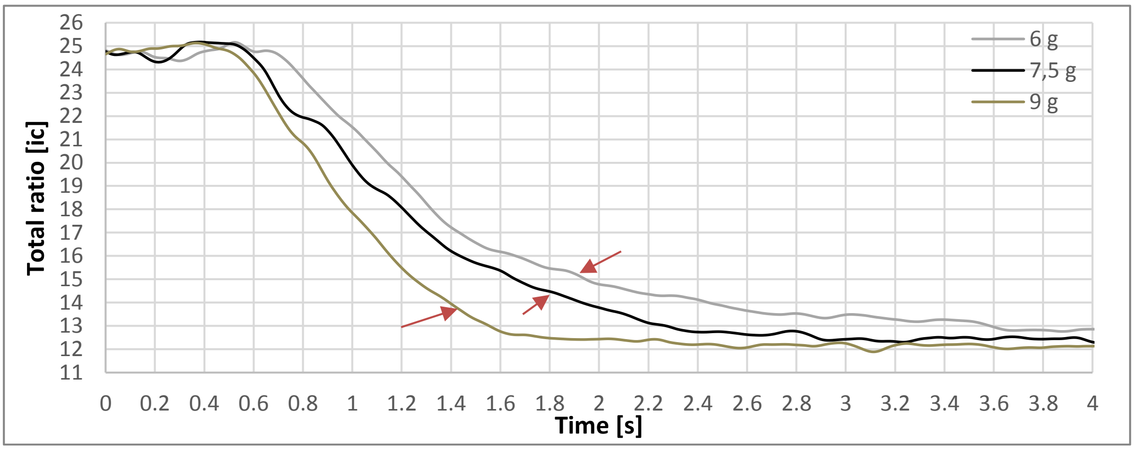

Figure 5. A graph showing the value of the transmission when the electric engine switches off

The acceleration of a vehicle powered by an internal combustion engine and a hybrid system for different values of rollers masses are shown in Figure 6.

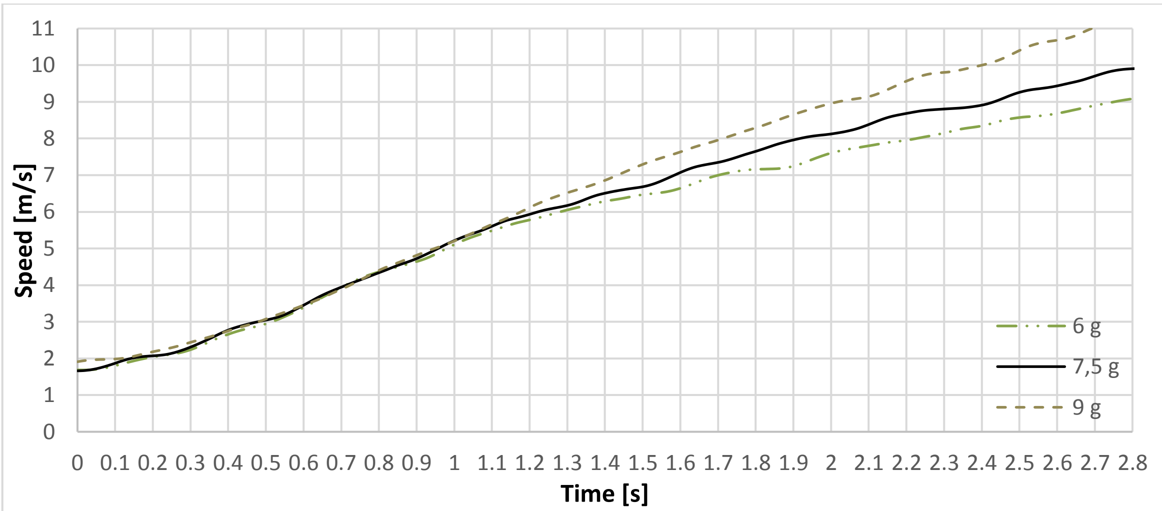

Figure 6. The acceleration of the vehicle powered by the internal combustion engine with the use of three sets of rollers with different weights

The acceleration process was limited from a speed about 1.9 m/s to about 9 m/s. The same accelerations were applied to the hybrid system. The change in the masses of the rollers did not cause any significant changes in the accelerations which were:
- 2 s for 9 g rollers
- 2,43 s for 7,5 g rollers
- 2,73 s for 6 g rollers

The significant change in rollers mass in the case of a drive system with an internal combustion engine did not significantly alter the characteristic of the CVT transmission. The rotational range of the internal combustion engine at which the electric drive operating in the hybrid system was switched off, depending on the weight of the rollers, varied from 6300 rpm to 7000 rpm. As can be seen from the fuel consumption map of the engine (Fig. 7), the torque drops significantly above 6800 rpm and it increases the unit fuel consumption. From the fuel consumption map of the internal combustion engine show that the smallest unit fuel consumption and the highest torque is achieved between 6300 rpm and 6800 rpm.

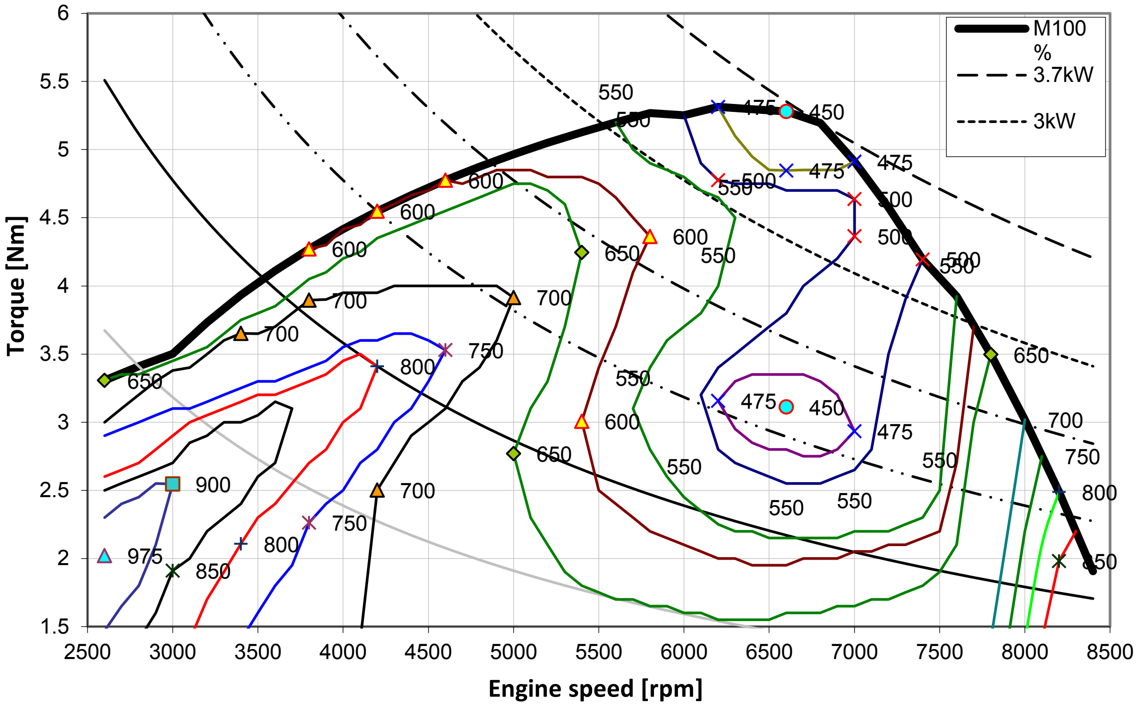

Figure 7. The fuel consumption map of the engine

Considering the fuel consumption map of the engine used, a significant impact on the dynamic characteristic of the vehicle can't be expected. It has been confirmed by the analysis of the speed changes presented in Figure 8. To achieve a significant improvement on the dynamic characteristic of the vehicle or to reduce the fuel consumption of the vehicle a different method of CVT transmission control, independent of engine speed, should be developed.

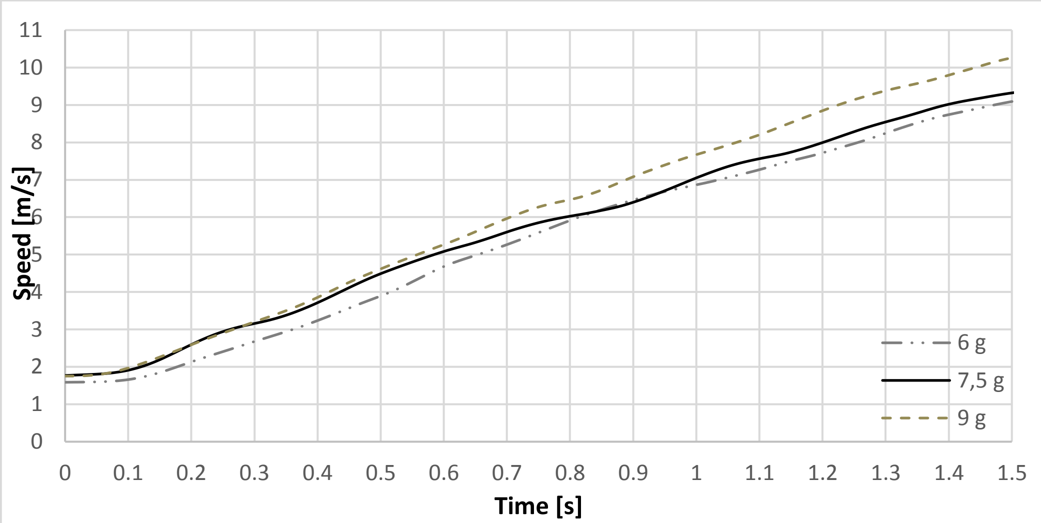

Figure 8. The acceleration course of a hybrid vehicle using three sets of rollers with different weights

As mentioned above, the maximum torque of the engine used is in the range from 6300 to 7000 rpm and changes very little. As a result, the difference in acceleration of the vehicle to the speed at which the electric motor stops supporting a CVT transmission (9 m/s) at different weights of rollers is also very small. Acceleration times are:
- 1,22 s for 9 g rollers
- 1,4 s for 7,5 g rollers
- 1,45 s for 6 g rollers

The velocity from which the acceleration of the vehicle was analyzed was about 1.9 m/s due to the omission of the centrifugal clutch operation in the tests which in the drive system with the internal combustion engine is necessary for the starting process was correct.

4. Conclusions

Research on this type of hybrid systems requires development of a special test stand. The implementation of preliminary research allowed for a positive assessment of the constructed stand. The possibility of implementing dynamic characteristics is very important from the point of view of the evaluation of drive sources simultaneous work with very different characteristics. The results of the conducted tests indicate improvement of the acceleration ability using a hybrid system. This is due to the commonly used BLDC motors which have a high torque value at a speed of zero. In a traditional CVT transmission, the gear change depends on the rotational speed of the internal combustion engine. These solution prevent utilization of the full potential of an internal combustion engine. The results of the research also indicate the necessity of designing such a control method of the CVT transmission which would fully use the fuel consumption map of the internal combustion engine and thus improve the dynamic properties of the vehicle and reduce fuel consumption.

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