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Analysis of an employment of a gear ratio rate in CVT control system

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Abstract. Continuously variable transmissions(CVTs) potentially ensure the selection of such a gear ratio that scooter fuel consumption can reach minimum value. Traditionally these CVT gearboxes are mechanically controlled, causing a gear ratio to be an engine revs function. This solution does not ensure optimum gear ratio. In this paper the solution for fuel optimal control problem is presented. The results obtained during brake stand research of scooter powertrains show the significant values of brake specific fuel consumption for the velocity that is maximum for a scooter according to highway code. With the introduction of CVT gearbox in which the selection of gear ratio can be controlled according to the worked out strategy the solution for fuel consumption problem is possible. Electromechanical actuators ensure the selection of a gear ratio independently of engine revs. Such type of construction solution makes working out the suitable control strategy that ensures decreasing of scooter fuel consumption possible. Presented strategies do not use precise optimization techniques. The CVT efficiency has a strong influence on transient operation. In the paper the control strategy owing to which fuel consumption decreases by over 40% is presented. The strategy was worked out on the basis of fuel consumption map for a defined scooter exploitation model. The possibilities of realization of the worked out strategy were tested on the brake test stand.

1. Introduction

Continuously variable transmission (CVT) is more and more often used in automotive application. Its large transmission ratio coverage enables the engine to operate at more economic operating points. For every power level in internal combustion engine, there is one speed torque combination which achieves optimal fuel efficiency. Using continuously variable range of transmission ratio a line connecting these operating points can be followed for high drive unit efficiency. In spite of this, the use of CVTs in the automobile industry has remained marginal. Two-wheeler and snowmobile are major sections of automotive industry using CVTs. In this application a rubber dry belt is commonly used. Dry belts are usually used because a high friction coefficient is created between a belt and pulleys so that clamping force can be much smaller than it is in lubricated variants. Unfortunately, the problem which appears in non-lubricated belt pulley contact points results from the lack of cooling of this contact, which causes limits of the torque capacity of this type of variator. But these types of CVTs can be small and light and ideal for application in small motorbikes and scooters only. Moreover, hydraulic control of the CVTs axial thrust that is most often used is not indispensable and that is why hydraulic losses are eliminated. Despite these advantages CVTs are perceived as the most inefficient transmission system. It is the result of the application of mechanically controlled variators. Centrifugal rollers and torque cams are widely used in rubber belt CVTs as the mechanical actuators [2]. The performance of CVT depends on the characteristics of these actuators. Using mechanical actuators it is impossible to shift the transmission ratio in such a way as to make speed-torque combination point remain on an engine optimal operating line [1].

2. Optimal Operation Line

Optimal operation line (OOL) tracking is the most fuel economical way to operate the drive line. The OOL can be calculated from engine map by minimizing the fuel consumption for a set of output power values. A large number of different control strategies exist. The most popular approaches are *speed envelope*, *single track* and *off the beaten track*. A simple approach for transient ratio shift control is to maintain the engine on the "quasi-static" pick efficiency curve which corresponds to the assumption that any arbitrary speed torque combination can be realized instantaneously. This approach is called *single track strategy* (fig. 1*)*. This strategy does not use precise optimization techniques but relies on heuristic arguments. Since the vehicle performance of the single track strategy is limited Pfiffner and all [6] have proposed another approach called *off the beaten track* strategy. Driver can select two modes: the economy and the performance modes. These two trajectories represent different driver selectable modes and they are presented in figure 2.

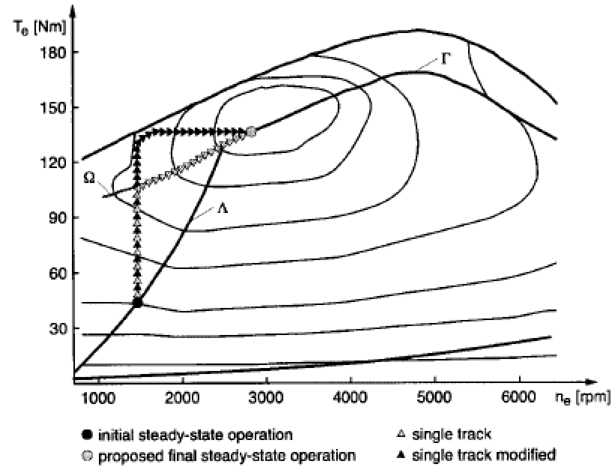

Figure 1. System trajectories of the single track and single track modified strategy. The maximum gear ratio stationary driving resistance curve Λ, the peak efficiency curve for quasi static operation Ω and the peak efficiency curve for stationary operation Γ [6].

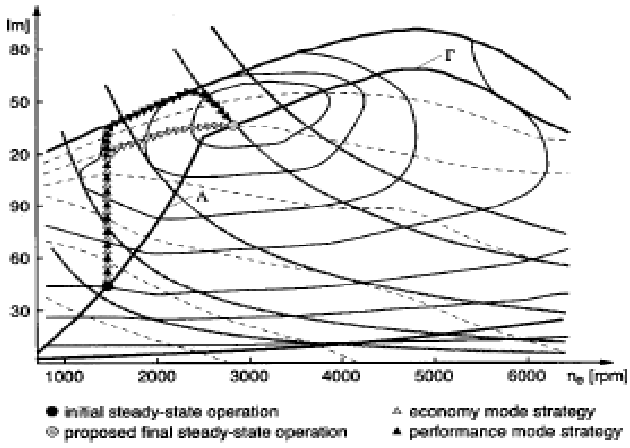

Figure 2. Engine map trajectories of the two modes *off beaten track* strategy on an accelerator step [6].

In many cases the actual engine torque is not controlled along the "quasi static" peak efficiency curve Ω but is brought directly to the final steady-state operation point. Due to this the dynamics of the vehicle increases and so is the fuel consumption.

Presented strategies do not use precise optimization techniques. The CVT efficiency has a strong influence on transient operation. Unfortunately, there are a lot of times when the demand power level is higher than engine's capability. Then engine operates at the maximum torque line until the demand power is reached. When hard acceleration is commanded, engine speed flares and corresponding torque is consumed and vehicle acceleration decreases. Due to this CVT vehicles have poor drivability. Drivability [8] is a subjective assessment and hard to measure. Figure 3 shows four objective parameters which have obvious relations with CVT drivability assessment. In figure 3 t_0 is the moment when throttle was opened. The acceleration decreased at first reached its minimum value a $_{min}$ and began to rise. The four objective parameters related to drivability assessment were: acceleration delay $\Delta t_1=t_1-t_0$, duration of acceleration $\Delta t_2=t_2-t_0$, acceleration reduction $\Delta G=a_0-a_{min}$ and peak value of acceleration G_{max}. If the values of Δt_1, Δt_2, ΔG are very small and G_{max} is high the assessment of drivability is good. These parameters are strongly related to gear ratio rate.

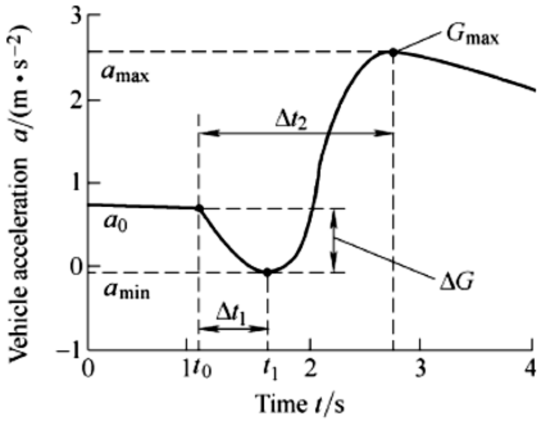

Figure 3. Objective parameters for drivability evaluation [8].

The CVT vehicles drivability is the result of gear ratio rate. It is impossible to improve the drivability under conventional control because gear shift rate depends directly on throttle position and outer resistance torque. The electromechanical actuator should be employed. It is necessary to have the CVT vehicle drive line characteristic to define the control algorithm for such actuator.

3. Test stand

Figure 4 shows the test stand. The test stand consists of: engine with CVT gearbox, flywheel, water brake, engine equipment and apparatus for measuring the following variables; engine torque, angular velocity of engine, angular velocity of inner and outer shafts of CVT and fuel consumption [4]. The flywheel is used to simulate the conditions during start of vehicle.

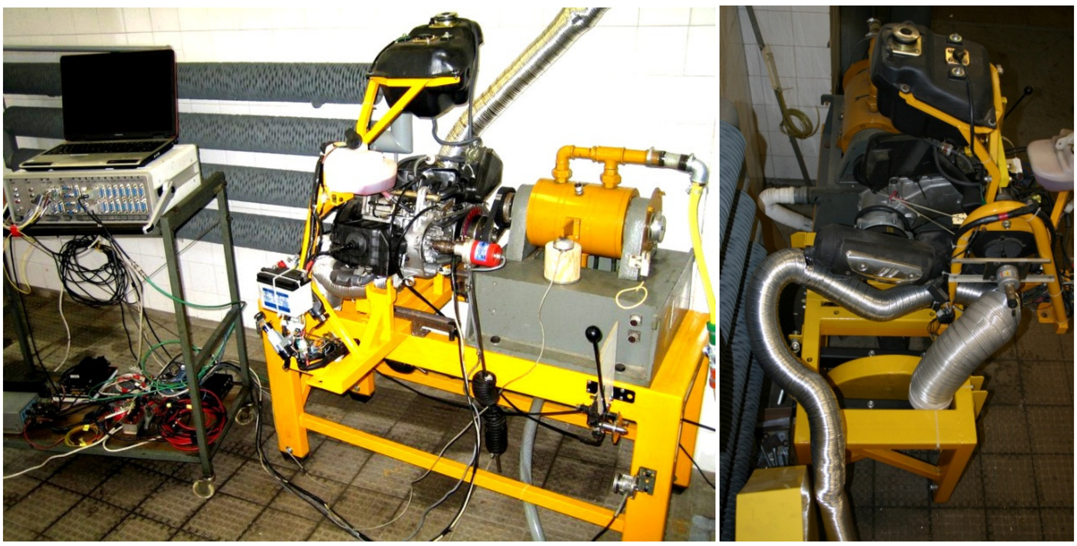

Figure 4. Test stand.

In popular motorbikes and scooters with two stroke engine very often the two minimum of brake specific fuel consumption (BSFC) were appeared. The same situation was noticed for tested engine. Due to this engine it is very difficult to approximate OOL line by using a simple function of engine rpm. From the OOL the optimal engine speed for a given throttle position can be obtained. The real operation line is beyond engine high efficiency area. The real operation line (ROL) is also presented in figure 5 (spotted line). A big difference between these lines can be observed. Maximum scooter velocity is reached by 8500 rev/min of the engine. The BSFC value at this point is very high. This big difference is the consequence of a mechanical governor employed. To ensure the tracking of a OOL the special electromechanical actuator system has to be employed. However, the tracking of OOL influences the scooter drivability due to the lack of its dynamic response. Since drivability is also important for ratio control design, the special strategy should be worked out for a good combination of fuel economy and drivability.

Unfortunately, the change of a gear ratio in order to obtain the scooter maximum velocity at lower rpm can cause noticeable diminishing of scooter performance. Moreover, there is a possibility to increase the range of typical scooter CVT by about 10% only. However, this change is still too small to obtain noticeable improvement of engine –CVT drive system efficiency. The required power of scooter drive system to reach its limited maximum velocity is 30-40% lower than the maximum power of

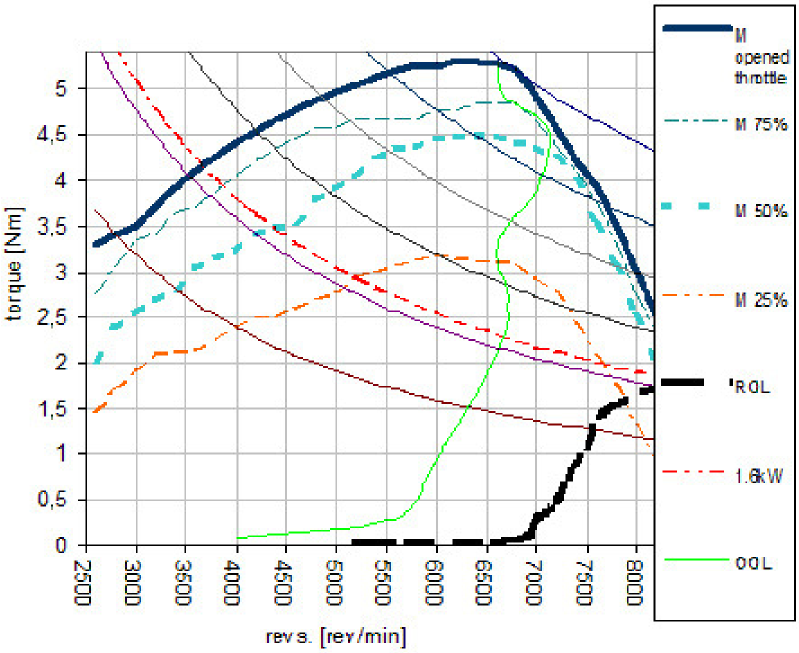

Figure 5. Optimal Operation Line [4].

the employed engine. It allows the designers of a scooter drive system to take into account the possibilities of application of the partly opened throttle for maximum scooter velocity. Introducing electromechanical actuators can improve the drive system efficiency because gear ratio is no longer a function of engine revs. To obtain noticeable decrease of fuel consumption value the change of gear ratio is necessary. The ratio control strategy of CVT should ensure slight lowering of scooter performance together with simultaneous significant lower fuel consumption. The way of the exploitation of such a vehicle is different from the exploitation of other vehicles. These vehicles move usually with wide opened throttle (WOT) from small velocity to maximum velocity. This way of scooter motion requires taking it into consideration when the ratio control strategy of CVT is evaluated. In this case to diminish fuel consumption, the engine revs corresponding to maximum scooter velocity should be lowered to 6800 revs/min.

In order to obtain this value of engine revs the gear ratio should be lowered by about 20%. The value of BSFC is the smallest one at these revs. As the power of an engine at 6800 revs/min exceeds the power calculated from scooter motion resistance the position of engine throttle has to be diminished. In other case the scooter velocity will exceed permitted velocity. The engine work with partly opened throttle will be sufficient. Partly opened throttle causes further lowering of fuel consumption. Employing an electric throttle is essential here.

In order to obtain the value of gear ratio rate under conventional control the test with rapid opened throttle was carried out. The results are shown in figures 6 and 7. The maximum value of gear ratio rate in both direction under conventional control is about 0,7 (1/s).

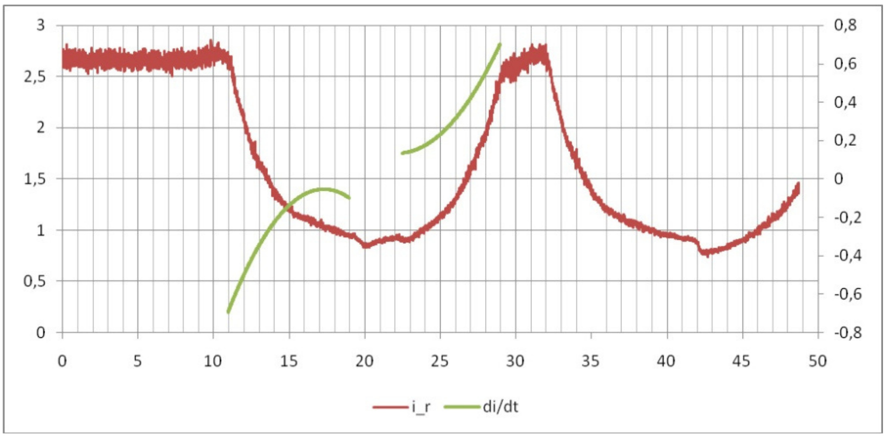

Figure 6. Gear ratio (red line) and gear ratio rate (green line).

For tested powertrain measured maximum gear ratio rate causes the diminishing of engine revs and related with engine torque (fig.7) in small quantity.

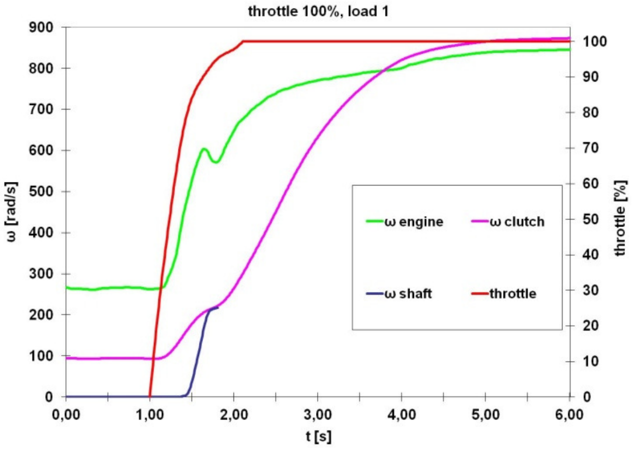

Figure 7. Throttle position (red line), revs of engine (green line), revs of clutch (rose line) revs of outer CVT shaft (blue line) during rapid acceleration.

In accordance with measured results the drivability for tested CVT vehicle is acceptable. In this case the main aim of introducing the electromechanical actuator is to diminishing of a fuel consumption. The test results can be used for limitation of gear ratio rate of electromechanical actuator.

4. System modelling

To improve the fuel consumption of considered vehicle the CVT drive line dynamics must be analysed [5,7]. The drive line is modelled only in its longitudinal behaviour and no drive train elasticities are taken into account. The efficiency of drive line is assumed as equal 1. Figure 8 shows a sketch of this system.

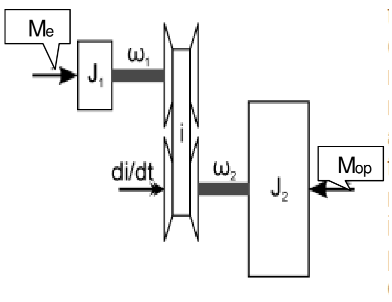

Figure 8. Drive line structure.

The gear ratio of the CVT is defined by:

$$i(t) = \omega_2 / \omega_1 \tag{1}$$

The equations of drive trains motion are as follows:

$$M_e - M_1 = J_1 \frac{d\omega_1}{dt} \tag{2}$$

$$M_2 = i(t) \cdot M_1 \tag{3}$$

$$M_2 = J_2 \frac{d\omega_2}{dt} + M_{op} \tag{4}$$

The resulting drive trains dynamic equation is as follows:

$$\frac{d\omega_1}{dt} = \frac{M_e - M_{op} \cdot i(t) - J_2 \cdot \omega_1 \cdot i(t) \cdot \frac{di}{dt}}{J_1 + J_2 \cdot i^2(t)} \tag{5}$$

where:

J_1 – inertia moment of an engine,
J_2 – equivalent inertia moment of a scooter,
M_e – engine torque,
M_1 – input moment to CVT,
M_2 – output moment out CVT,
M_{op} – resistance moment of motion,
M_R -– resistance moment related to gear ratio rate.

It can be seen from above equation that there is the resistance torque related to gear ratio rate. The torque M_R is the follows:

$$M_R = J_2 \cdot \omega_1 \cdot i(t) \cdot \frac{di}{dt} \tag{6}$$

The principle of control algorithm is that M_R is equal, during gear shifting, to M_e -M_{op} $i(t)$ to obtain the constant engine revs. When engine operates in selected point of its characteristic the decrease of fuel consumption can be obtained.

When in motion, city scooters equipped with small power engines have usually wide opened throttles. The control strategy should take into account the character of the drive which in fact is composed of extreme acceleration, drive with constant speed, breaking and reaccelerating until the maximum velocity is reached. This cycle is repeated several times; in each case the time in which the vehicle velocity is constant is different. Two values that define the run of the cycle are: the angle of opened throttle and the real gear ratio of CVT.

The start-on is usually independent of steering systems. The centrifugal clutch is used for the start on. Subsequently, the vehicle is accelerated until the velocity corresponding to engine revs slightly higher than maximum torque is reached. Then the change of a ratio in CVT begins until the minimum ratio is reached. The balance of power on a scooter wheel with power of motion resistance defines vehicle velocity. This balance appears very often in a small scooter when the revs of the engine are much higher than revs of the engine for maximum power. These revs which are much higher are caused by the necessity of achieving the maximum vehicle velocity. The difference between engine revs of maximum torque and maximum power for typical engines which is very small is the reason why engine revs should be much higher than revs of engine maximum power. It is necessary for gaining a wider range of velocity changes. Unfortunately, it results in the increase of vehicle fuel consumption. Moreover, the value of resistance power is on average 40% smaller than the maximum value of power of the engines When an actuator is mechanically steered the ratio value is the function of engine revs and thus its value is defined by a regulator structure. When electromechanical actuator is used simultaneously with electric throttle the characteristics of the engine can be better employed and the fuel consumption can be lowered. The use of electromechanical actuator should ensure the same or at least similar performance as in the traditional version. As lowering fuel consumption requires smaller revs of an engine it is indispensable to lower total gear ratio of a vehicle. In order not to change the drive power too much the vehicle acceleration should be done with possible high value of engine torque. When the rate of the gear ratio change is controlled the whole process of acceleration can be performed with constant engine revs as it

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is shown in revs of engine maximum torque. In such cases, even when total gear ratio is lowered, it should ensure good performance.

The control strategy is as follows: scooter accelerates with CVT low ratio till the engine reach the revs slightly higher than revs of maximum torque. Then the gear ratio starts to change with rate ensures the constant engine revs. When the maximum velocity is reached, the change of a gear ratio will be carried out simultaneously with diminishing the throttle angle to make engine power balance with the resistance power of motion. This control method was implemented in the model described above. The control run simulation is presented in figure 9.

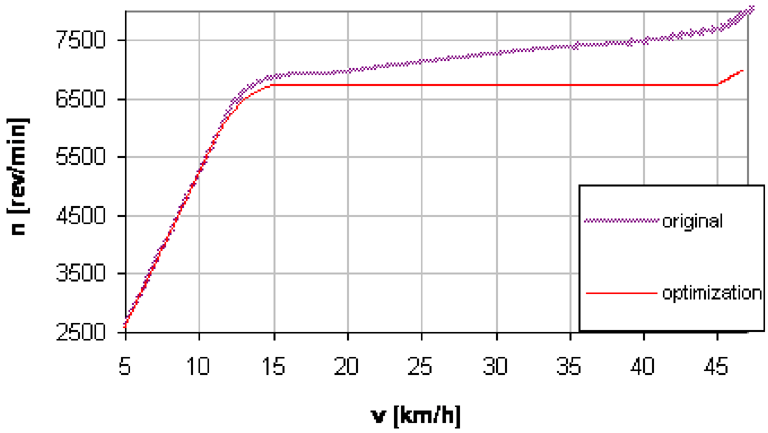

Figure 9. Control strategy.

The results of applying this control method to the mathematical model of drive train are presented in figures10 and11. The characteristics shown in figure 11 present that when the velocity is 45km/h, specific fuel consumption decrease using this control strategy is about 20% when compared with traditional method.

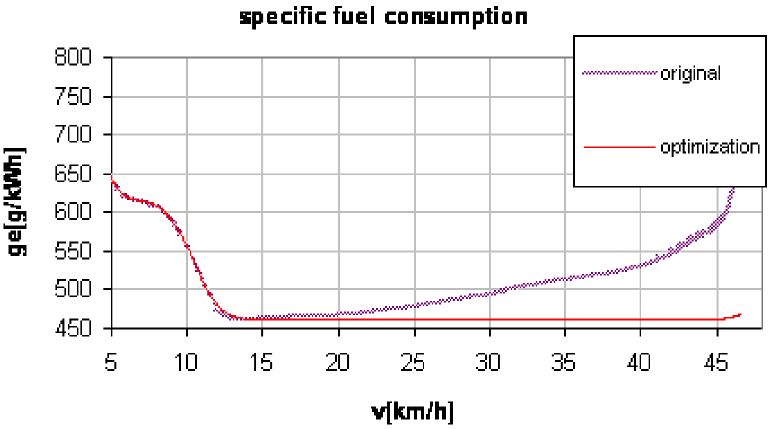

Figure 10. Specific fuel consumption.

As it was stated before the velocity of these types of vehicles is close to 45km/h, such lowering of specific fuel consumption may be also considered as fuel consumption per hour.

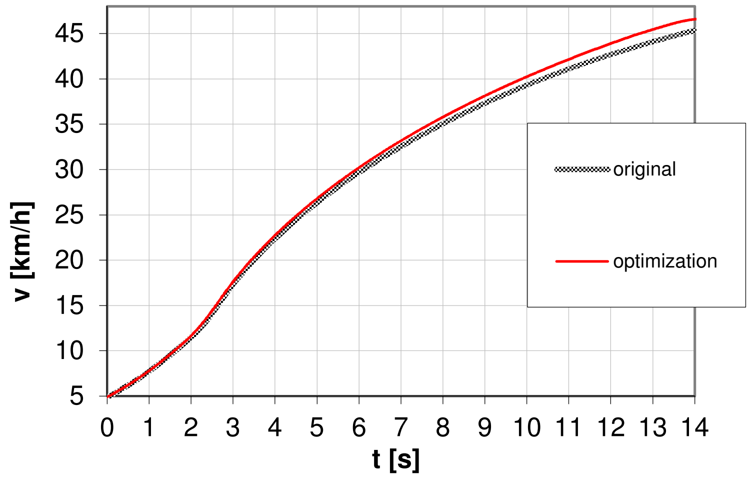

Figure 11. Performance of scooter.

As it can be seen in figure11 the performance of vehicles is almost the same.
Small scooters, motorcycles a and other vehicles of that type are driven in town in a specific way where in which extreme acceleration and braking are dominating. This kind of driving was described as Indian Drive Cycle [3] for Asian (fig. 12) countries, where the number of scooters and motorcycles exceeds 42 million.

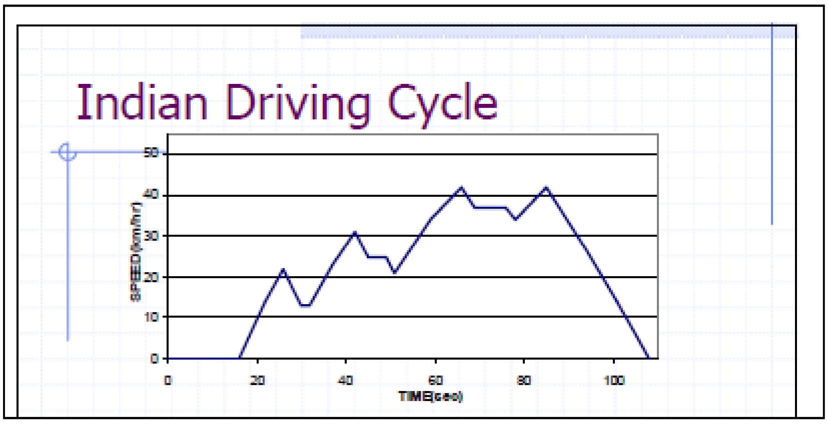

Figure 12. Indian Driving Cycle [3].

5. Theoretical analysis of fuel consumption in accordance with IDC

The mathematical model, which was worked out, was used for the analysis of fuel consumption of the scooter equipped with CVT in accordance with the suggested research procedure. The course of run of the engine torque as well as fuel consumption per hour in revs function were approximated by polynomial. Moreover, additional function courses were created to present the previously described parameters in the function of opening angle of a throttle. In figure13 the run of fuel consumption per hour for different opening angle of a throttle was presented and compared to the runs measured in test stand. These functions were used in motion simulation for the scooter equipped with original as well as optimum system of gearbox control.

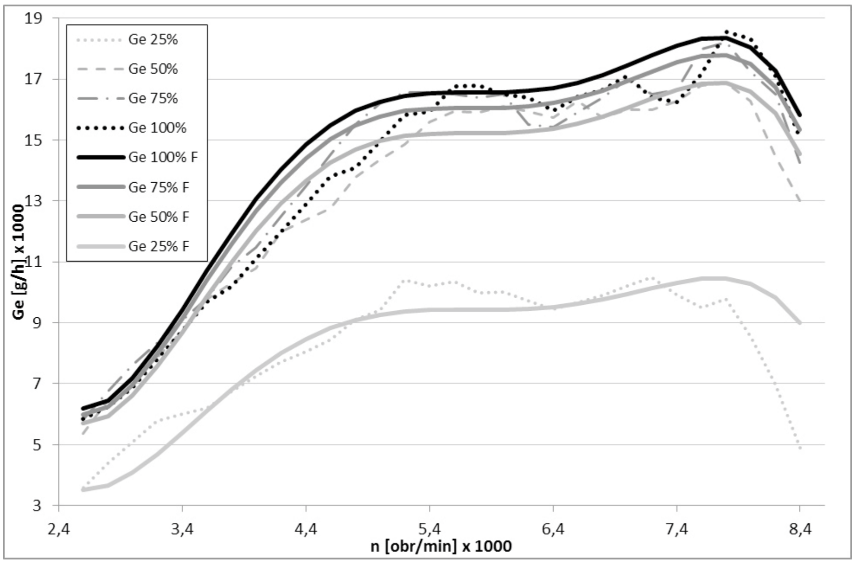

Figure 13.Test stand fuel consumption and theirs function approximations

In optimization case, the run of “u” gear ratio rate is controlled by the relevant algorithm that ensures proper engine functioning with the highest efficiency, whereas in original characteristics the gear ratio rate is changed in such a way as to present in the best way the run of the analyzed cycle. As it was in case of real vehicle research according to the road cycle, the opening angle of a throttle was manually performed.
In case of the scooter motion according to IDC cycle fuel consumption is:
a. 2,376l/100km for the scooter equipped with original control unit,
b. 2,056l/100kmfor the scooter equipped with optimum control unit.
In IDC cycle 15%reduction of fuel consumption was acquired.
Moreover, the algorithm controlling optimized gear ratio rate makes the gear ratio rate of maximum rate not larger then in original solution possible.
Applying optimum control unit gives significant savings during the scooter motion with maximum velocity (45km/h) if is compared this with fuel consumption of scooter with conventional control unit. The scooter acceleration is a little higher then acceleration with conventional unit
When a scooter is driven with maximum acceleration and velocity (range of test distance1km) its fuel consumption is:
a. 4,5 l/100km for a scooter equipped with original control unit,
b. 2,32l/100km for a scooter equipped with optimized control unit.
Fuel consumption decreases in this cycle by 50%.
When a scooter is driven with constant maximum velocity (1km) its fuel consumption is:
a.4,17l/100km for a scooter equipped with original control unit,
b.1,73l/100km for a scooter equipped with optimized control unit.
In these cases fuel consumption decrease exceeds 100%.
In the above mentioned runs the minimum velocity is 5km/h. Its due to two facts:
- control unit starts to gear change at the vehicle velocity that exceeds 10km/h,
- centrifugal clutch (which is not tested during this research) influences the vehicle driven with less than 5km/h. Applying of optimum control unit gives significant savings during the scooter motion with maximum velocity (45km/h) if compared this with fuel consumption of scooter with conventional control unit. Moreover, the scooter acceleration is a little higher then acceleration with conventional unit.

6. Conclusions

1. The gear ratio rate is one of the parameters essential for vehicle performance. So far main attention was paid to the influence of gear ratio rate on vehicle acceleration values. The use of the gear ratio rate for defining engine revs during vehicle acceleration secures optimum engine functioning considering its fuel consumption.

2. The gear ratio rate value for the realized acceleration cycle did not differ much from the gear ratio range for conventional system. In this way similar value of a belt slip and its efficiency was ensured.
3. Fuel consumption in the analyzed cycle decreases by 15% when compared to conventional control. It should be considered a great achievement.
4. The application of electromechanical control unit making gear changing as well as gear ratio rate possible allows to drive the vehicle with revs corresponding to optimum fuel consumption.

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