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Research Article

POSSIBILITY OF INCREASING VEHICLE ENERGY BALANCE USING COASTING

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ABSTRACT

The paper deals with coasting as an option of using the vehicle kinetic energy. It highlights the need for changes in the legislation in conjunction with the use of new trends in the management of motor vehicles with regard to safety. The article describes the use of the vehicle is coasting as a part of the driving mode, which leads to the reduction in fuel consumption and in exhaust emission. This solution takes into account all the running resistances and creates a basis for designing appropriate control strategies. These options were analyzed with respect to various drive strategies and kinds of transport.

Keywords: coasting, coast down, driving style.

INTRODUCTION

At present, the drives of vehicles use energy that is largely bounded in fossil fuels. Based on the ever-increasing demands that are placed on each of the transport sector, these resources are gradually depleting and are not unlimited [2, 5, 24]. Given the growing energy consumption in transport and industry, various legislative and technical solutions involved in the saving of non-renewable energy sources, are put into practice.

Area of developing energy-saving vehicles is engaged in the development of systems using renewable natural energy sources [1, 21, 25]. Systems using secondary sources of energy whose source is the vehicle during its operation are developed. The vehicles drive units are designed in order to exploit the acquired immediate energy to the maximum extent (kinetic, potential) [4].

The energy flow through the drive train of the vehicle is bi-directional. However, only the energy that flows from the converter to the vehicle drive is used efficiently. Reverse power flow from the drive to the converter leads to the dissipation of the energy. In conventional road vehicles the combustion engine is frequently used as an energy converter. Combustion engine transforms the chemical energy bound in the fuel into mechanical energy that is used for vehicle propulsion or for the drive of the vehicle equipment.

In a conventional vehicles braking system, about one third of the energy of the power, originally in a form of kinetic energy, is wasted in a form of heat during deceleration [10, 29]. Therefore, recapture of this wasted kinetic energy is mandatory. The total amount of the energy lost in this way depends on how long, how often and how hard the brake is applied [26, 30]. Currently vehicles that are oriented to redirect the loss-making energy back to the power drive system of the vehicle come into prominence and are supported by an intelligent control system. Powertrain of unconventional vehicles consists of a set of converters and energy storage devices of various configurations, what allows immediate utilization, respectively storing of energy for later return to the power drive system. The disadvantages of unconventional road vehicles are the losses resulting from multiple transformations of the energy and low capacity of energy accumulators. Electric vehicles, hybrid vehicles and vehicles burning non-conventional fuels (hydrogen, solid fuel), belong to the group of non-conventional road vehicles that can use the accumulated energy. Regenerative braking system (RBS) is widely used in these electrified vehicles. In regenerative braking control, present research mainly concentrates on the cooperation between regenerative braking and friction braking [8, 28].

A control strategy coordinating the regenerative brake and the pneumatic brake is proposed, in order to recapture the braking energy and improve the fuel economy. There are three different braking control strategies for regenerative braking: non-regen, parallel regenerative brake control strategy, and serial strategy. The non-regen one, is set as a baseline, and only friction brakes are utilized during deceleration; the parallel regenerative brake control strategy features an easy implementation without any other hardware needs to be added; for the serial strategy, it coordinates the regenerative and friction brakes in real time, being advantageous over the parallel one with respect to the brake comfort and regeneration efficiency [14]. The improvement of energy conservation is effected by the braking conditions, because the braking energy loss is different in different braking conditions [16].

Among the systems that use lossy immediate energy of the vehicle there are mainly supercharging internal combustion engines, Turbosteamer, TEG – thermocouples, Vehicle turbine, etc. [15].

COASTING

Until recently it was rumored that in newer cars (with the systems of disconnection of the fuel) it is appropriate to improve the consumption by let in gear and let brake the car by using the energy flowing from the wheels of the vehicle. In a carburettor engine it was better to take the car out of gear because the engine burns fuel at idle anyway.

Recently, new automatic transmissions systems increasingly offer a system called coasting. This is an automatic neutral gear engaged at released accelerator pedal. Producers apparently discovered that the distance which the car passes by inertia ultimately save more fuel, despite the need to keep the engine running at idle.

THEORETICAL ANALYSIS OF THE PROBLEM

A simplified equation of dynamics for torque balance on the crankshaft of internal combustion engine (ICE) is:

$$I \cdot \frac{d\omega}{dt} = M_m(\omega, z) - M_z(\varphi, \omega, t) \qquad (1)$$

where: the individual quantities (I – reduced inertia moment of sliding and rotating masses, M_z – load torque) are reduced to the ICE crankshaft,

z – represents the position of control unit for the fuel dose of ICE,

φ and t are the quantities characterizing the load and

M_m is the torque of ICE.

There are 5 basic general examples of relation between M_m and M_z in the motion equation:

$$I \cdot \frac{d\omega}{dt} = M_m(\omega, z) - M_z(\varphi, \omega, t) \qquad (1)$$

a) Mm > Mz – acceleration with the reaction torque
b) Mm < Mz – deceleration with the reaction load torque

$$I \cdot \frac{d\omega}{dt} = -M_m(\omega, z) - M_z(\varphi, \omega, t) \qquad (2)$$

Mm >< Mz – engine braking with the reaction load torque

$$I \cdot \frac{d\omega}{dt} = -M_m(\omega, z) + M_z(\varphi, \omega, t) \qquad (3)$$

a) Mm > Mz
b) Mm < Mz – engine braking of action load torque

$$I \cdot \frac{d\omega}{dt} = +M_m(\omega, z) + M_z(\varphi, \omega, t) \qquad (4)$$

- vehicle acceleration by action of ICE and action load torque

In case of coasting is the engine disconnected from the gears (Mm = 0) and the movement of the vehicle depends on its kinetic, respectively potential energy (coasting or downhill driving) and current driving resistances.

$$I \cdot \frac{d\omega}{dt} = M_z(\varphi, \omega, t) \quad (5)$$

The possibilities of using this regime depends on many factors, especially on the concept of vehicle powertrain and its handling, character of transport road (highway, city road, handling space of the machine, etc.), type of transport (rail, road, factory, ...) purpose of vehicle as well as if the vehicle is equipped with the assistance and navigation systems etc.

Analyzing the above-mentioned basic formulas (1) to (5) driving conditions may be specified, where there is a change in the power flow from the driving wheels to the powertrain and when it is possible to use the energy of the vehicle for the spin of ICE (zero fuel dose), for the vehicle coasting with released accelerator pedal and disengaged gear (vehicle coasting, ICE idling) and also for the accumulation of kinetic, respectively potential energy in case of its surplus, etc.

EXPERIMENT

Energy storage is not feasible at all times of the vehicle driving the fall line. This can be done only to the moment when the actuator of energy storage system will behave as an energy appliance (energy consumption for its own operation). Using theoretical analysis and using the results of the real driving cycle, it is possible to create an algorithm of controlled braking process, either by storage of energy, immediate consumption or by coasting mode.

To obtain ideas about the energy flows in normal city traffic the experiment was conducted at about 19 km street circuit in both directions. During the measurement following parameters were recorded:

- distance [m], velocity [m s^{-1}], acceleration [m s^{-2}],
- duration of the real driving cycle t [s],
- profile of the route – slope [%],
- braking time interval,
- interval of vehicle operation without depressing the accelerator pedal.

Based on the data from the brake sensor and pedal force sensor the percentage of times when the vehicle is stopped, the driving of the vehicle with released accelerator pedal and driving the vehicle with depressed brake pedal were identified,.

The total duration of the real driving cycle was t = 1618 s (about 27 min.). Less than 30% of the time accounted for the vehicle operation with released accelerator pedal. This time interval was divided into the sections of driving, when the vehicle was braked by service brake and sections, when the vehicle was braked by passive resistances. Percentage of the vehicle braking by service brake during the operation with released accelerator pedal was 9.6% of the total time of deceleration of the vehicle. The remaining 90.4% of the time accounted for the braking by passive resistance.

The value of the drive force F_h varied depending on the operating state of the vehicle (acceleration, steady speed driving, driving in and out of the hill). Driving force F_h acquired also negative values, which formed 34.5% of the whole measured section. Negative values of the drive force F_h present real driving cycle segments suitable for controlled deceleration (see equation (2), (3)).

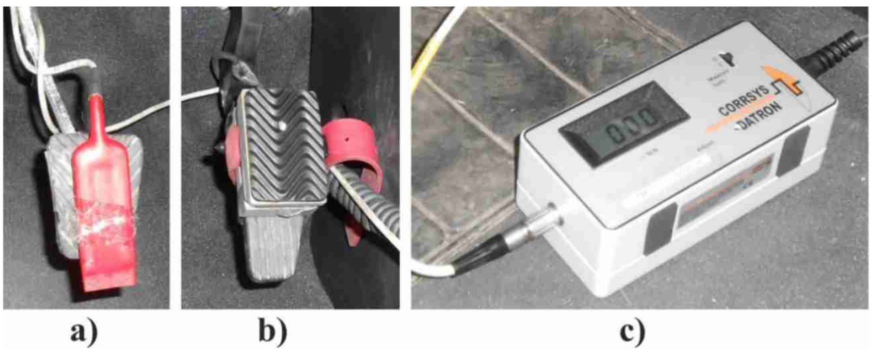

Fig. 1. Sensors of braking (a) and accelerator (b) pedal with the evaluation unit (c)

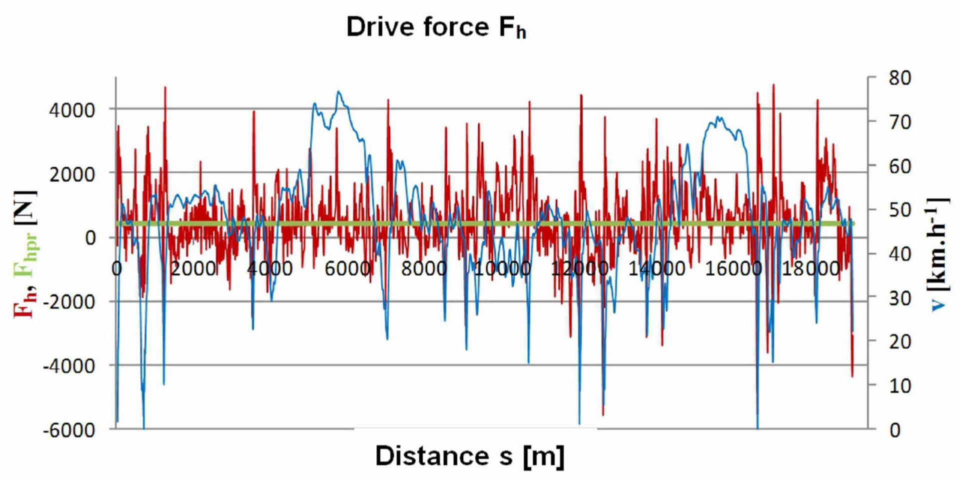

Fig. 2 The course of the drive force calculated from the experiment

THEORETICAL DESCRIPTION OF VEHICLE DECELERATION

The equation of motion for the deceleration has the following form:

$$m_v.b.\delta = -F_b \quad \text{(N)} \tag{6}$$

where: m_v – vehicle weight,
b – deceleration,
δ – rotational inertia factor and
F_b – braking force.

If the vehicle is moving at speed v, without activating the service brake, the deceleration will be affected only by rolling resistance, aerodynamic drag and gradient resistance.

The braking force is in the form:

$$F_b = G_v.f.cos \propto \pm G_v.sin \propto + K.v^2 \quad \text{(N)} \tag{7}$$

where: G_v – vehicle gravitational force,
f – rolling resistance coefficient,
α – the road angel and $K = \frac{\rho}{2}.S_x.c_x$ is the constant dependent on air density ϱ, frontal area of vehicle S_x and vehicle aerodynamic drag coefficient c_x.

The distance which vehicle will pass during coasting is:

$$S = \int_{t_1}^{t_2} v\ dt \quad \text{(m)} \tag{8}$$

Using the equation (6), the deceleration will be:

$$b = \frac{dv}{dt} = \frac{F_b}{m_v.\delta} \quad (\text{m.s}^{-2}) \tag{9}$$

and than:

$$dt = \frac{m_v.\delta.dv}{F_b} \quad \text{(s)} \tag{10}$$

The theoretical coasting distance will be:

$$S_t = \int_{v_1}^{v_2} \frac{m_v.\delta.v}{F_b}\, dv = m_v.\delta \int_{v_1}^{v_2} \frac{v}{F_b}\, dv \quad \text{(m)} \tag{11}$$

After substitution of the equation (7) will take following form:

$$S_t = \frac{m_v.\delta}{G_v} \int_{v_1}^{v_2} \frac{v\ dv}{f.cos\propto + sin\propto + \frac{K}{G_v}.v^2} \quad \text{(m)}$$

and after the modification the theoretical coasting distance is:

$$S_t = \frac{\delta}{g} \int_{v_1}^{v_2} \frac{v}{K_2 + K_1 v^2}\, dv \quad \text{(m)} \tag{12}$$

Equation (12) represents the base for coasting calculation (disconnected, respectively switched off ICE – according to powertrain category).

The calculation is activated only at the moment when the driver releases the accelerator pedal. The control algorithm activates the interventions of control systems and triggers or switches the vehicle running in coasting or braking mode in conjunction with control of the brake pedal and according to instantaneous driving condition of the vehicle and environmental conditions. Such a process assumes a fully automatized system that meets the hybrid drives, the electric vehicles and the newest vehicles with automatic transmission at present.

POSSIBILITIES OF COASTING

The coasting usage depends on many factors, such as powertrain concept, used route, type of transport and so on. Driving regime for vehicles with manual transmission depends on a driver subjective decision. The driver can switch between modes in gear or engine disconnected from the traction wheels (engine idling) only according to his own experience and feelings. His decisions can be supported by the information of assistance systems (navigation, GPS, ...), or may be affected by the familiarity of the route (repeated driving).

The academic community have long been aware of the effect of driver behaviour on fuel consumption in the private road vehicle, e.g. [6], and in recent years there has been increasing attention paid to the provision of additional in-vehicle information to help drivers save fuel, e.g. [27]. In the vast majority of instances this information is presented visually. If one follows the philosophies behind Direct Manipulation Interfaces (DMI) [11] and the Skills, Rules and Knowledge (SRK) taxonomy of human behaviour [18], one could argue for the combination of action and control surfaces (i.e., to combine the area onto which action is performed with the area from which information is obtained). Considering that eco-driving is largely characterised by differential use of the accelerator pedal or gear stick [17] it is impossible to satisfy the DMI or SRK principles with visual information presented from the dashboard (one does not act upon the dashboard). It is possible, however, for haptic information, that is information of or relating to the sense of touch, to satisfy these tenets.

Research specifically looking into the support of eco-driving with haptic information is available. In Hajek et al. [9] a system is described that provided the participants with a discrete pulse alerting them to upcoming driving events, encouraging removal of the foot from the pedal in order to maximise the coasting phase of the vehicle (note that the term coasting here implies the act of travelling without the foot depressing the accelerator pedal, whilst still in gear), thereby taking full advantage of the vehicles momentum to carry it to an event necessitating slowing or stopping. Assisted drives (i.e., those with the additional information) incurred 7.5% lower fuel consumption than unassisted drives.

Cruise control does not support coasting. The newest vehicles with automatic gearbox allow coasting by automatic changing gear to neutral.

On the contrary, hybrid vehicles are characterized by the highest level of powertrain control management. Therefore, they can fully use the coasting. However, they need the information about the route, including the system of road signs recognition, instantaneous driving condition of the vehicle, weather conditions and systems to identify the instantaneous traffic situation (surrounding vehicles, respectively obstacles) and others.

The controlled coasting is appropriate to use before sections with limited speed while driving on the highway (repair, maintenance, accidents, etc.) and while driving on the fall line with a maximum gradient. The knowledge of regularly repeated routes is the advantage of using coasting in urban and suburban traffic.

Unstable driving regime in the city is another supporting argument for coasting (65–70% of the total driving time consists of acceleration or deceleration). Coasting cannot be used every time in order to changing traffic conditions and traffic density in the city [19, 22].

The vehicle weight has a significant impact on the coasting efficiency which is positively reflected in the bus transport, road freight and rail transport where the ratio of the weight and the propulsion power is beneficial for the coasting. The precise train diagrams (prescribed speed, stops for passengers, etc.) and low rolling resistance are beneficial at using of coasting in the rail transport [23, 7].

POSSIBILITIES OF DRIVING CONTROL BY USING THE COASTING

As it was already mentioned, only in vehicles with a high degree of automation management it is possible to effectively control the processes in individual vehicle regimes. There are currently the newest vehicles with automatic transmissions, hybrid, autonomous vehicles and electric vehicles.

Oleksowicz wrote that for a hybrid electric vehicle or an electric vehicle equipped with a stepped transmission, such as dual clutch transmission (DCT), automatic transmission with hydro-transmitter (AT), and automated manual transmission (AMT), when the vehicle brakes by electric motor EM, the common control method of transmission is keeping gear position unaltered to ensure the stability and safety, until the braking process is finished [20]. However, in this way the braking energy cannot be regenerated sufficiently due to the limit of the motor maximum torque. When the braking torque provided by EM cannot meet the driver's braking demand, the hydraulic brake system (HBS) should provide extra braking torque, which results in braking energy loss. Therefore, it is meaningful adjusting EM work point by downshifting to maximize the regenerative energy. In fact, downshifting during regenerative braking process can not only increase the energy conservation, but also improve the vehicle reacceleration performance [12, 13].

The maximal elimination of using the service brake in deceleration mode is a basis of driving management. The control system assumes detailed knowledge of the route, including a system for recognizing traffic signs, instantaneous state of vehicle moving (speed, accelerator pedal position, etc.) and the state of the environment (temperature, grade, speed and wind direction, type of road surface, etc.).

The deceleration (coasting) control system is activated at the moment when the accelerator pedal is released. Based on the already mentioned information and instantaneous traffic situation (surrounding vehicles, obstacles ...), the system knows by equation (12) how to calculate the distance which the vehicle could pass by coasting to the final velocity v_2. The system can obtain the information about the final velocity in several ways (road sign, barrier, information from navigation system, detailed knowledge of the route, etc.).

Coasting cannot be linked only to the vehicle coast down. The benefit of this regime can be also applied in driving on the fall line in accordance with the required (permissible) speed v_p. Modern vehicles equipped with intelligent cruise control already fulfil this function.

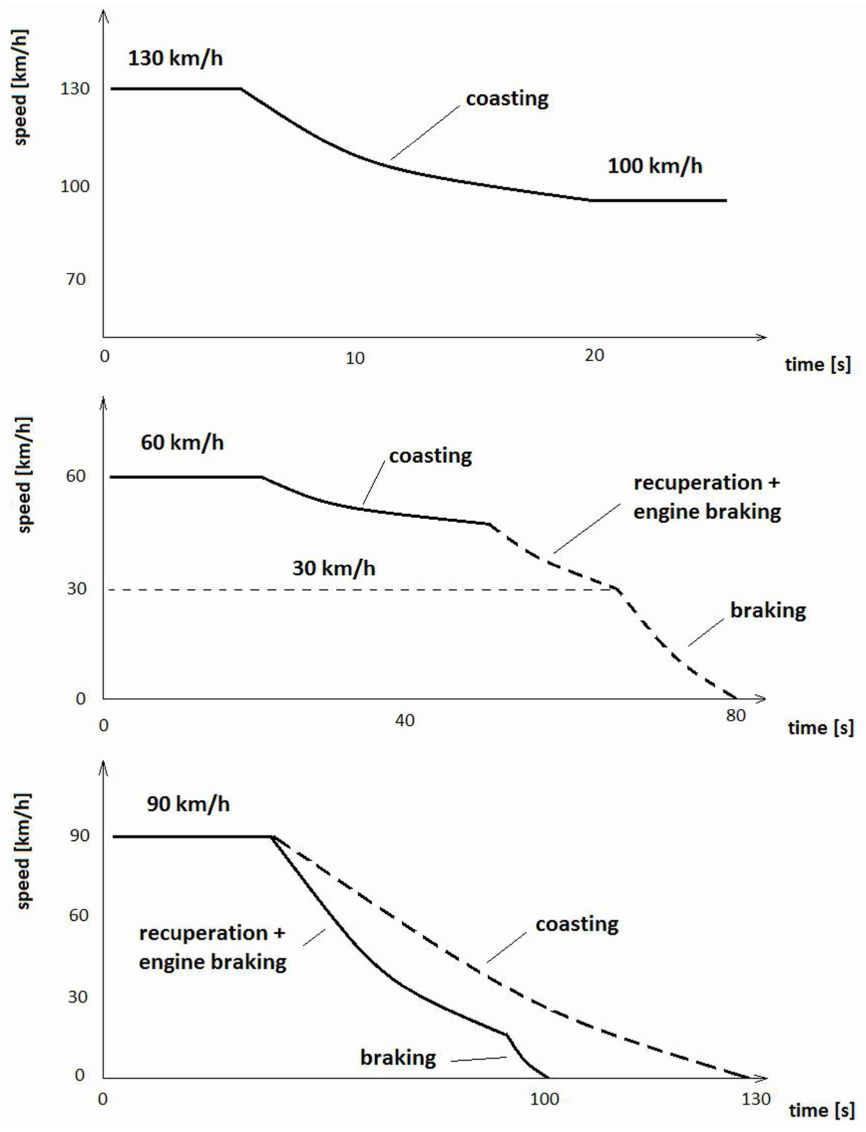

Fig. 3. Examples of vehicle speed course control before the barrier, respectively to vehicle stop

- If $v_p > v_{real}$ – speed adjustment by appropriate fuel dose.
- If $v_p = v_{real}$ – coasting with disconnected, respectively switched off engine – on the fall line.
- If $v_p < v_{real}$ – involving of energy recuperation system. If is not sufficient then engine braking will be applied.
- If $v_p \ll v_{real}$ – if the situation requires higher braking intensity, service brake will be engage into braking.

The semiautomatic system can also fulfil the sequence of braking interventions with using the brake pedal. Driver determines by pressing brake pedal (according to the position and the speed of pressing) intensity of the braking in order: coasting (release brake and accelerator pedal), recuperation, engine braking, braking with service brake.

Figure 3 shows the examples of vehicle speed course control before the barrier, respectively to vehicle stop.

CONCLUSIONS

This paper shows possibile solutions of the problem controlled deceleration of the vehicle and using of so-called coasting in order to achieve higher operational efficiency. As stated in the article, the decision on whether is at any given time deceleration more preferably to accumulate the vehicle energy or to let the engine turn, turn off, or to use idle and coasting is highly dependent on many factors. It is necessary to respect the operation conditions of the engine, the status of the base vehicle battery, ambient conditions, and others, but the priority must be the requirements of the driver on the driving style. The driver must not be therefore limited by these systems, with the exception of an economic mode when the priority becomes the criterion of consumption, durability and so on, to the detriment of for example driving dynamics.

More and more manufacturers deal with coasting issues. Until recently, coasting use was limited by legislation. Nowadays coasting use is approved by Commission Implementing Decision (EU) 2015/1132. The manufacturer Porsche AG submitted an application for the approval of a 'coasting function' as an innovative technology for reducing CO_2 on 13 October 2014. In order to determine the CO_2 reduction it is necessary define the modified testing condition (modified NEDC speed profile). A conversion factor is required in the formulae for the calculation of the potential CO_2 savings to address the difference between CO_2 emissions from the standard NEDC test and those under modified NEDC testing conditions for the baseline vehicle [3].

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