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Management of hybrid powertrain dynamics and energy consumption for 2WD, 4WD, and HMMWV vehicles

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ABSTRACT

Energy consumption for any vehicle is described by energy balance (relationship between "energy in" and "energy out"), which consists of energy produced, energy consumed, internal losses as well as the need to overcome the inertia resistance to motion. Hybrid vehicles show big potential for further reduction in fuel consumption and exhaust gas emissions. Therefore, there is nothing strange in the fact that the hybrid cars are often identified as step on the journey to a more sustainable future. Currently, the powertrain concept allows synchronization of the operation of an ICE and an electric motor and redistribution of mechanical energy flows with the help of transmission shifts depending on the mode of operation of the hybrid powertrain (HPT). Different HPT control algorithms are applied in hybrid vehicle designs, however, the purpose of all of them is to: (i) minimize fuel consumption, (ii) minimize exhaust gas emission, (iii) minimize the system price, and (iv) ensure good vehicle control characteristics. This paper presents the novel algorithms suitable for real-time estimation of economic and ecological characteristics for the hybrid 2WD, 4WD, and High Mobility Multipurpose Wheeled Vehicle (HMMWV) vehicles moving under urban, extra-urban and off-road conditions.

1. Introduction

Over the past 5 years, tremendous progress has been made in the technical management of hybrid powertrain dynamics and energy consumption systems [1–5]. The automotive transmission systems, its prime movers and body parts are continously underdeveloped for wide range of upcoming vehicles, equipping continuously variable transmissions, controllers for cylinder cut-off in superchargeable internal combustion engines (ICEs), devices for regulating the gas distribution phases in an ICEs, Start/Stop function, adaptive cruise control system, electronic control of ignition timing and fuel supply, applications of alternative lightweight materials in powertrains and vehicle structures, optimized cross-sectional shapes of structures to achieve better loading performance without increase in weight, and so on [6–9]. However, along with increasing number of vehicles and the level of people mobility, under heavy traffic one can no longer focus enough on the assistance options for eco-friendly driving as he has to respond to traffic changes and disruptions caused by unplanned and overwhelming traffic situations [10]. Considering the above mentioned, many see hybrid electric vehicles (HEVs) as the bridging technology between conventional IC vehicles and the evolving sustainable transportation system [11–16].

Until recently, the benefits of hybrid vehicles were most obvious in city traffic, because they allow people to drive for up to 40–50 km without noise or exhaust emissions [8]. In addition, hybrid cars do not require the change in the existing transmission and fuelling infrastructure compared with the introduction of electric vehicles, hydrogen or other alternative energy sources [14,17,18]. Militaries worldwide are also interested in realizing the potential energy savings from utilizing hybrid vehicles [19]. As described in Ref. [20], there are no deployed military HEVs since battlefield fuel is approximately 100 times the cost of conventional diesel or gasoline. This is because of the specific challenges unique for hybrid vehicle architectures to a military application, such as the absence of methods to look at vehicle energy in a holistic sense as well as inconsistent duty cycles for propulsion requirements [20]. Currently, the off-road mobility requirements present a unique challenge and off-road HEVs are only recently starting to emerge in the military sector [8,21–24].

Most often the minimization of fuel consumption and exhaust gas emission is chosen as the factor of optimization. In such case the HPT

Abbreviations: 2WD, Two-wheel drive; 4WD, Four-wheel drive; DC, Direct current; DI, Dynamic index; ECM, Electronic control module; EM, Electric motor; EV, Electric vehicle; G-ShM, Gear-shift moment; GPS, Global positioning system; HEV, Hybrid electric vehicle; HMMWV, High mobility multipurpose wheeled vehicle; HPT, Hybrid powertrain; ICE, Internal combustion engine; ITS, Intelligent transportation system; LSL, Low-speed limit; OEM, Original equipment manufacturer; OOP, Optimal operating point; OOPT, Optimal operating point trajectory; PTMS, Powertrain management system; RPM, Revolutions per minute

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control system has to monitor energy losses in each energy generation chain (ICE and electric motor, battery bank) and energy distribution chain (transmission, wheels), and to identify the most efficient operating mode of the powertrain, which would secure the required traction force and the toxicity of the exhaust gas would not exceed the fixed rate. Selection factors of control algorithms of a hybrid vehicle [25]:

1. The optimal operating point (OOP) of an internal combustion engine. The OOP is selected from the external characteristic of the ICE in pursuing the first two targets or a compromise between them.
2. The optimal operating point trajectory (OOPT) of the internal combustion engine. It is selected from the external characteristic of the ICE in such a way that the engine would operate in the range of its highest efficiency under varying loads and speeds.
3. The optimal operating region of the ICE. The target of this algorithm is the same as that of the OOPT but it allows varying the engine operating mode within a wider range.
4. Minimization of the dynamics of the ICE. Engine operation is controlled in such a way that sudden operating speed variation should be avoided; that increases the number of gears but it can work in an optimal mode with continuously variable transmissions.
5. Limiting low-speed operating conditions of the ICE. The control system actuates the engine only when the operating speed provides the required torque. Such algorithm reduces fuel consumption.
6. Reduction of number of the actuation cycles. At present, an automatic start-stop system is started to introduce in the vehicles driven by ICEs. Such system reduces the duration of the engine operation during town driving. During drive start up, the hybrid system only allows the actuation of the electric motor, which runs the vehicle only until it reaches a certain level of speed (most often it is up to 20 km/h) thus reducing the duration of the ICE operation even more.
7. The optimal way of use of a battery bank. The purpose is to maintain such level of the battery charge that it could supply energy any time when the vehicle is increasing speed and to accumulate it during regenerative braking. When the batteries are overcharged the ICE is stopped and the vehicle is driven only by electric traction; when the batteries run down – the power of the ICE is increased and some part of it is transferred to the generator.
8. Maintaining constant voltage in the battery bank. During wide input voltage and load output variations as well as during frequent charge/discharge cycles, the battery's duty cycles decrease therefore their charging level is monitored avoiding their discharging below the lower fixed limit.
9. Energy distribution. The optimal distribution of the energy supplied between the ICE and the battery bank depends on driving conditions. The most rational advantages of the HPT would be used having created separate powertrain control algorithms for possible travel routes of a vehicle.
10. Geographical factor. It is preferred that the hybrid cars are driven only by electric traction in towns.

The control algorithms must make use of the main advantages of these powertrains – a possibility to accumulate kinetic energy while converting it into electrical energy, when the electric motor is operating in a generator's mode [2,4,5]. In conventional vehicles, this energy is lost or converted to heat in braking mechanisms. During acceleration, the electrical energy accumulated in the battery bank drives the electric motor. It was established that driving a car at full capacity in urban driving mode accounts only for 15% of the total route driven, therefore the use of the HPT allows the reduction of the ICE capacity; it results in lower emissions of toxic substances [4]. As the ICE operates efficiently only within a rather narrow interval of the operating speed, HPT enables adjusting the operating conditions of the internal combustion engine for nominal modes, which in their turn have huge influence on fuel consumption and the reduction of exhaust gases. The control algorithms of the HPTs of serial-production cars are mainly tuned for the urban driving cycle. This strategy of control is chosen by taking into account the frequent braking/accelerating and standing modes, during which the ICE is automatically stopped [2,4,5].

To summarise the findings about powertrain technologies (technology vision beyond 2020): hybrid (IC-electric) vehicles needing advanced control and system integration will penetrate the market [26]. Electric hybridisation may be commonplace beyond 2020, both as an efficiency improvement enabler and provider of extra power needed for drive-by-wire systems (electrical or electro-mechanical systems for performing vehicle functions traditionally achieved by mechanical linkages) [26].

2. The build-up of dynamic models

2.1. Modelling of the transmission system inside an automobile

Dynamic models of the analysed vehicles have been developed for determination of loads and their change in the transmission under different driving conditions.

2.1.1. The case of 2WD vehicle

Dynamic model of 2WD vehicle is characterised by synchronization of the powertrain through the road-tyre interaction. Dynamic models for vehicle power unit and transmission system's components have been developed under prevailing multibody analysis of stiffness and damping behaviour of joint elements (of two rotating bodies). Vehicle

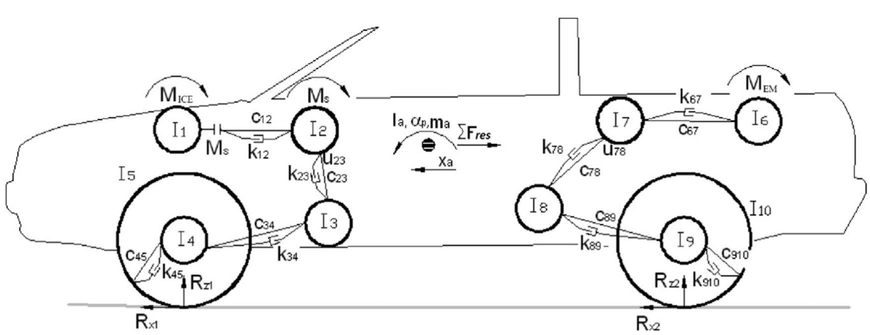

Fig. 1. Dynamic model of the 2WD vehicle [8]. Where: I_a – vehicle's moment of inertia; I_1 – inertia moment of internal combustion engine; I_2 – gearbox inertia moment at i-th gear (I_2=I_7); I_3 – inertia moment of the main drive (I_3=I_8); I_4, I_9 – inertia moment of wheel discs with semi-axles (I_4=I_9); I_5, I_{10} – tyre's moment of inertia (I_5=I_{10}); I_6 – electric engine's moment of inertia; I_7 – EM gearbox inertia moment at i-th gear (I_7=I_2); I_8 – inertia moment of the main drive of EM's transmission (I_8=I_3); c_{12}, k_{12}, c_{23}, k_{23}, c_{34}, k_{34}, c_{45}, k_{45}, c_{910}, k_{910} (c_{45}=c_{910}, c_{34}=c_{89}, c_{23}=c_{78}, k_{45}=k_{910}, k_{34}=k_{89}, k_{23}=k_{78}), c_{67}, k_{67}, c_{78}, k_{78}, c_{89}, k_{89} – stiffness and damping of different elements; u_{23}, u_{78} – transmission reduction ratios, M_{ICE} – ICE output torque; M_{EM} – EM output torque; M_{Gen} – moment of inertia of a EM's rotor (at generator mode); M_s – gearbox output torque; R_{xi} - longitudinal tractive force; R_{zi} – radial wheel load; F_{res} – resistance forces; m_a – vehicle mass; α_p – vehicle yaw angle; x_a – vehicle displacement in a horizontal direction.