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Eco-driving: An economic or ecologic driving style?

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ABSTRACT

In this work the trade-off between economic, therefore fuel saving, and ecologic, pollutant emission reducing, driving is discussed. The term eco-driving is often used to refer to a vehicle operation that minimizes energy consumption. However, for eco-driving to be environmentally friendly not only fuel consumption but also pollutant emissions should be considered. In contrast to previous studies, this paper will discuss the advantages of eco-driving with respect to improvements in fuel consumption as well as pollutant gas emissions. Simulating a conventional passenger vehicle and applying numerical trajectory optimization methods best vehicle operation for a given trip is identified. With hardware-in-the-loop testing on an engine test bench the fuel and emissions are measured. An approach to integrate pollutant emission and dynamically choose the ecologically optimal gear is proposed.

1. Introduction

The transportation sector is a major producer of greenhouse gas emissions. Fuel prices are constantly growing while non-renewable fossil fuels are becoming scarce. To solve these problems researchers are looking for ways to reduce fuel consumption and emissions of the transportation sector. One of the major current areas of research include most efficient utilization of existing vehicle drive trains. In passenger vehicles an important amount of energy is often wasted. An immediately applicable way to reduce fuel consumption for passenger vehicles is to adapt the use of the vehicle to the system functionality. Vehicle efficiency is not constant over its operating range but depends on the losses of each component in the drive train. It is therefore strongly dependent on vehicle velocity and acceleration. A driver can reduce energy needed to perform a trip by his utilization of the vehicle. The behavior of a driver that minimizes fuel consumption is often referred to as eco-driving.

Due to the reduction in fuel consumption and therefore CO_2 emission eco-driving is generally considered to be an environmentally friendly behavior of drivers. However, due to growing fuel prices, for most drivers the interests are in the reduction of cost. Many studies on energy and/or fuel efficient driving can be found in literature (van der Voort, 2001; Larsson and Ericsson, 2009; Fiat, 2012), as well as studies on CO_2 reduced drivine (Martin et al., 2013). However, only one study was found where emissions not proportional to fuel (other than CO_2) were considered when discussing eco-driving. The work of Johansson et al. (2003) measures fuel consumption and emissions for 16 test drivers that were educated on eco-driving. In his study, Johansson found that due to more time spent in high throttle engine operation some emissions increased.

In this work the trade-off between fuel consumption and pollutant emission will be discussed. Economic, fuel optimal vehicle operation and ecologic, fuel and emission reducing vehicle operations are compared by applying numerical optimization techniques. With the use of hardware-in-the-loop testing the fuel and emissions of the computed drive cycles are

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measured. A method is proposed to integrate fuel and emission optimal gear operation in a dynamic setting. It will be shown that eco-driving can be economic and ecologic.

In Section 2 a vehicle model is developed, which is then used in Section 3 to identify optimal vehicle operation using the dynamic programming optimization method. After a description of the experimental setup in Section 4 the economic and ecologic vehicle operations are discussed in Sections 5 and 6 respectively. The results with a comparison of fuel and emissions are given in Section 6.2.

2. Vehicle model

The algorithms are illustrated on the example of the Peugeot 308 (year 2009), a compact passenger car with a mass (M_{veh}) of 1470 kg. The vehicle can be modeled as a standard drive train, as seen in Fig. 1. It consists of the final drive reduction, a 5-speed gear box, a clutch, auxiliary losses and the internal combustion engine.

In this work only longitudinal forces are considered. The motion of the vehicle chassis can then be modeled with Newton's second law:

$$M_{veh_x} a_x = \sum F_x \tag{1}$$

$$= F_{drive} - F_{res} \tag{2}$$

where F_{drive} is the force that propels the vehicle and F_{res} is a sum of the resistance forces. Here, M_{veh} represents the vehicle's mass and $a_x = a$ the vehicle's longitudinal acceleration. The resistance forces can be calculated as a sum of rolling resistance (F_{roll}), aerodynamic drag (F_{drag}) and road grade resistance (F_{grade}) (Robert Bosch GmbH, 2004):

$$F_{res} = F_{roll} + F_{drag} + F_{grade} \tag{3}$$

$$= C_r M_{veh} g \cos(\theta_{road}) + \frac{1}{2}\rho C_d A v^2 + M_{veh} g \sin(\theta_{road}) \tag{4}$$

where C_r, and C_d are the coefficient of rolling resistance and the vehicle's drag coefficient, g represents the gravitational constant, A is the vehicle's frontal surface, ρ stands for the air density, θ_{road} represents the angle of the road grade and v corresponds to the vehicle speed. The drive force F_{drive}, generated by the vehicle's drive train, is used to propel the vehicle and to overcome the resistance forces F_{res}, that are generally opposing the direction of motion. In this energetic model no slipping of the wheel, on the contact patch between road and tire, is considered. With this hypothesis we can define a relationship between vehicle motion and wheel rotational speed ω_{wheel} using the tire radius R_{tire}:

$$\omega_{wheel} = \frac{v}{R_{tire}} \tag{5}$$

$$\dot{\omega}_{wheel} = \frac{a}{R_{tire}} \tag{6}$$

The inertia to be accelerated can be described by a lumped parameter, considering vehicle weight (M_{veh}) and wheel inertias (J_{tire}):

$$J_{veh} = M_{veh} R_{tire}^2 + 2J_{tire} \tag{7}$$

With Eqs. (5)–(7) we can now rewrite Eq. (2) by

$$J_{veh}\dot{\omega}_{wheel} = T_{drive} - F_{res} R_{tire} \tag{8}$$

where T_{drive} specifies the drive train output torque, which is positive in the acceleration phase and negative when braking. Inverting Eq. (8) and assuming that there is not slipping between the tire and the road (Eqs. (5) and (6)) the drive torque required for a given vehicle speed and acceleration can be determined by

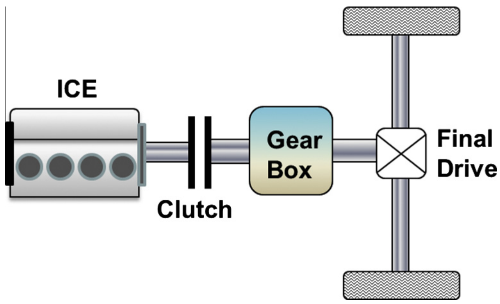

Fig. 1. Peugeot 308 drive train.