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Impact of control strategies on the emissions in a city bus equipped with power-split transmission

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ABSTRACT

The continuously variable hydromechanical transmission is an interesting solution for high power vehicles subject to frequent changes of speed, in which the comfort is a significant requirement.

Despite their low average efficiency with respect to the mechanical transmissions, the hydromechanical transmissions allow to release the engine speed by the vehicle speed, and to open the possibility for the optimal control of the engine. It follows that the performance and emissions of the powertrain is heavily affected by the logic control.

The aim of the paper is to investigate the emission reductions that can be obtained using a Power-Split transmission.

Therefore, a hydromechanical transmission has been sized and tested on a 12-ton-city bus by using a one-dimensional model developed in an AMESim environment. Four different control strategies of the powertrain were applied to the model. The CUEDC-ME standard cycle for the characterization of emissions in heavy vehicles was used as a reference mission.

The simulation results showed that the hydromechanical transmission reduces consumption or the emission levels with respect to the traditional transmission when managed according to appropriate control strategies. By means of emission values normalized with respect to the standard limits, it is possible to identify a control strategy that allows the reduction of emissions in every usage condition of the vehicle at the expense of a slight increase of consumption.

The suggested procedure could help the manufacturer to satisfy the emission standard requirements.

0. Introduction

The scientific research pursued the goals of the fuel consumption and emission reduction in vehicles by means of various techniques: improvement of internal combustion engines, advanced propulsion systems (hybrid electric and hybrid hydraulic), fuel cells, and use of biofuels.

The continuously variable transmissions (CVT) can be placed within the advanced propulsion systems. They appear to result in discrete advantages of consumption, as well as comfort. CVT Belts, for example, are able to match efficiency and performance, but they are limited in high-power applications. In fact, for heavy vehicles, the hydro-mechanical

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transmissions (also called Power-Split transmissions) are recommended. They allow the handling of great power, with high reliability and relatively small dimensions (Kress, 1968; Renius and Resch, 2005; Macor and Rossetti, 2011; Rossetti and Macor, 2013). For those characteristics, the Power-Split transmissions are used in agricultural and industrial machinery (the first commercial application was the Fendt Vario tractor, 1996), but they could become a competitor of the hybrid powertrains in the light trucks and SUV sector.

The efficiency in the Power-Split transmission is slightly lower than that of its traditional competitor (the Power-Shift transmission) since a quota of the engine power is transmitted through a hydrostatic group, which is notoriously inefficient. By contrast, it separates the wheel speed from the engine speed, making it possible to optimally manage the engine itself. The fuel consumption reduction, however, is not the only objective in vehicle design. The emission regulations for vehicle approval impose increasingly stringent emissions limits, forcing manufacturers to improve combustion and post-combustion treatments.

A contribution to the emissions' reduction could come from "green" engine management, which is permitted by the Power-Split transmission. In other words, the operating point of the engine should follow, in the engine map, a path of minimal emissions, similar to that for minimum fuel consumption (Pfiffner et al., 2003; Srivastava and Haque, 2009). However, this path should be different for the various chemical species since their formation has different and antithetical genesis (e.g. CO and HC with respect to NOx). The simultaneous minimization of the emissions of all the pollutant chemical species is therefore not possible, and appropriate criteria may favour one or the other class of emissions according to criteria of Pareto optimality.

It is evident that the regulation criterion plays an important role in achieving the objectives, and the literature has already addressed that issue.

For vehicles equipped with powertrains having one or more degrees of freedom, such as CVT vehicles and hybrid vehicles, the engine control strategies have been divided into two groups: rule-based strategies and optimization-based strategies (Bayindir et al., 2011; Pisu, 2007). In the first group, the rules are designed based on heuristic considerations, human experience and mathematical models, without a priori knowledge of the driving cycle (Shabbir and Evangelou, 2014; Kheir et al., 2004; Rajagopalan et al., 2003; Montazeri-Gh and Mahmoodi-K, 2015). In the second group, the control strategies are determined by the minimization of a cost function generally representing the fuel consumption (Wu et al., 2004; Hiremath et al., 2013; Stelson et al., 2008) or a combination of consumption and emissions (Lin et al., 2003; Montazeri-Gh et al., 2006; Finesso et al., 2014).

The control strategies of CVT powertrains found in literature are mainly focused on fuel consumption and rarely even on emissions. For example, Pfiffner et al. (2003) and Srivastava and Haque (2009) described some simple criteria based on the search of minimum consumption condition on the engine map. In Bonsen et al. (2005) a rule-based method was used to compare the CVT with the stepped gear transmission by means of a composite cost function containing fuel consumption and acceleration times. Deacon et al. (1999) proposed a control strategy for diesel-CVT powertrain based on the optimum lines, which included the emissions. The strategy also took into account the vehicle drivability by means of a fuzzy logic approach.

In the powertrains with hydromechanical transmission, however, the problem of the strategy that takes into account also the emissions has never been addressed. In fact, Ahn et al. (2015) presented an integrated engine-hydromechanical transmission control algorithm for a tractor considering as objective function the efficiency of the engine-transmission group. From the simulations a 7.5% increase in fuel economy was found with respect of the existing optimal control strategy.

In Macor and Rossetti (2013), the potential in fuel consumption reduction of the Power-Split transmission was examined for the case of an urban bus. It was shown that when the maximum efficiency of the engine is managed, it can offset the Power-Split losses and lead to slightly lower fuel consumption than the traditional transmission.

Now, to complete the picture of the potential of the Power-Split transmission, it is necessary to investigate its behaviour with regard to emissions, or rather, its ability to contribute to the reduction of emissions of a powertrain.

Therefore, this paper investigates the impact of different control strategies of a Power-Split powertrain evaluating emissions and fuel consumption at the same time. In this way, a comparison with the existing standards and market requirements involving high efficiencies and heavy restrictions on emissions can be carried out.

The test case is a 12-m bus, whose powertrain comprises a natural gas engine and a Power-Split transmission. The vehicle and its subsystems were modelled and tested on a standard cycle for buses by means of the simulation code AMESim (2014). Four control logics for the engine management were used and compared.

As reference, the same vehicle mounting a traditional Power-Shift transmission was tested on the same standard cycles.

1. The reference vehicle

The reference vehicle is an urban bus whose main data are shown in Table 1. It is equipped with a 200 kW compressed natural gas (CNG) engine, whose data are summarized in Table 2. The bus can be considered representative of the whole 12 m bus class.

2. Powertrain layouts

The Power-Split transmission used for the reference vehicle is a four-shaft hydro-mechanical transmission, which is a well-known layout derived from the more simple input-coupled transmission, substituting the epicyclical gear with an