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Improvement of powertrain efficiency through energy breakdown analysis

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HIGHLIGHTS

- Energy breakdown analysis for the vehicular powertrain.
- Model for road vehicles simulation in different missions.
- Implemented powertrain management strategies: intelligent gearbox, Stop&Start, free wheel.
- Innovative hybrid powertrain turned to engine thermodynamic cycles minimization.
- Evaluation of fuel savings associated to each management strategy.

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ABSTRACT

A vehicular powertrain can be thought as an energy conversion chain, each component being characterized by its efficiency. Significant global efficiency improvements can be achieved once is identified the system energy breakdown, individuating the losses connected to each powertrain component; it is then possible to carry out the most appropriate interventions.

This paper presents a simulation study of a diesel-fuelled commercial vehicle powertrain based on the above summarized point of view. The work aims at individuating the energy flows involved in the system during different missions, proposing an intelligent combination of technical solutions which minimize fuel consumption. Through a validated Matlab–Simulink model, able to indicate the powertrain energy breakdown, simulations are carried out to evaluate the fuel saving associated to a series of powertrain management logics which lead to the minimization of engine losses, the recovery of reverse power in deceleration and braking, the elimination of useless engine cycles.

Tests were performed for different real missions (urban, extra-urban and highway).

The results obtained point out a –23% fuel consumption (average value for urban, extra-urban and highway missions) compared to the traditional powertrain. Clearly, such result affects positively the CO_2 emission.

1. Introduction

Transport absorbs about 1/5 of world energy consumption, of which about 80% is imputable to road vehicles [1–3]. This sector has a high potential from the point of view of energy savings, being characterized by the presence of numerous energy converters (the single vehicles) spread over the territory, each operating with a rather low average global efficiency.

A road vehicle may be thought as an energy conversion chain transforming chemical energy of the fuel into the work needed for motion. The rationalization of vehicles energy conversion chain is of crucial importance for pursuing the objectives established in terms of CO_2 emissions reduction: from 2012 on, the European Emission Standard imposes an average CO_2 emission limit of 120 g/km t for the new passenger cars sold.

Since small-medium size vehicles are largely the most numerous, significantly affecting the consumption and emissions of the sector, it is necessary to act on this segment through the adoption of powertrain architectures that, in combination with an intelligent control system, allow to optimize the efficiency of the whole road vehicles fleet with reduced costs.

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Nomenclature

F	fuel consumption (kW h)
P	power (kW)
R	reverse energy ratio (–)
W	work (kW h)

Greek

γ	efficiency derating factor (–)
ϕ	idle consumption ratio (–)
η	efficiency (–)
$\bar{\eta}$	average efficiency during a mission (–)
η^*	design efficiency (–)

Subscripts

C	related to conservative forces
d	direct (from engine to road)
g	global
i	internal
m	mechanical
r	reverse (from road to engine)
R	related to resistance forces

Superscripts

0	related to idle condition
$+$	related to positive power output

Different Authors [4–17] faced the issue of powertrain optimization through modeling. The simulations goal was to study hybrid powertrain systems coupled to their control strategies, evaluating performance and economy and carrying out an optimization by tuning the main design parameters. Among the cited approaches, some involve the existence of a previously defined full-hybrid architecture, with dedicated components, which is optimized through the definition of proper management strategies leading to consumption reduction (see e.g. [8] and [12]); other approaches provide the "hybridization" of an existing commercial powertrain through the introduction of electric components and the downsizing of thermal engine (see e.g. [9] and [10]). In all cases, the hybrid architecture to be employed is set and, on this basis, an optimization is worked out. A frequent optimization approach is the Equivalent Consumption Minimization Strategy (ECMS) [18–20], envisaging the minimization instant by instant of the fuel required for motion through the proper combination of the electric and thermal machines exploitation.

In this paper, a commercial powertrain is modified through the introduction of a set of interventions aimed at the maximum possible consumption reduction. The approach here proposed is different from those previously cited, in the sense that it individuates the most proper modifications aimed at the reduction of the energy losses connected to each powertrain component, through an energy breakdown analysis; the latter, considering the powertrain as an energy conversion chain, helps understand the paths of the energy flows and highlight the losses associated to each component. This allows to individuate the critical issues regarding efficiency and to carry out the proper interventions (e.g. gearbox management optimization, hybrid system management, etc.). In particular, as will be explained in the following sections, the most relevant losses are concentrated in the thermal engine.

The approach employed in this paper envisages a rule-based strategy which minimizes the number of thermal engine cycles required to accomplish a mission; such strategy permits to reduce the engine thermodynamic and mechanical losses, increasing the average efficiency over a driving cycle. The main advantage of this approach with respect to the ECMS is the simplicity, as no conversion between different energy forms is required.

The energy breakdown-based approach leads to the definition of management strategies and technical choices different from those nowadays in vogue. In fact, for example, the proposed hybrid powertrain keeps the original thermal engine and requires a very low battery capacity. Moreover, thermal engine will not be used for battery charging, unless strictly necessary.

The powertrain analysis was conducted by the use of a Matlab–Simulink model, able to correctly reproduce the powertrain of a generic road vehicle and calculate the main parameters involved in the energy chain, such as engine working data, energy flows, fuel consumption, pollutants emission. The simulator envisages a modular structure including the different powertrain components, of which the operational map knowledge is required. The model modularity is advantageous, since it allows to simulate the operation of very different powertrain configurations. The model input data structure permits to easily define the configuration of the specific vehicle simulated, through the setting of parameters such as front area, mass, drag coefficient, engine characteristic curves, powertrain architecture (with hybridization degree ranging from "full thermal" to "full electric") and control logic parameters.

The simulator was named VECTRA (VEhicle EConomy in TRAnsport). In the paper, the capability of VECTRA to simulate several vehicle configurations emphasizing the energy breakdown over different real missions [14] is demonstrated through the progressive application to a commercial powertrain of a set of efficiency improving interventions, the effectiveness of which is evaluated one by one.

However, the main goal of this paper is not proposing an innovative simulator for vehicular powertrains: VECTRA is only a useful and agile instrument aimed at testing the solutions coming from the energy breakdown approach. Nor the goal of this paper is sizing the powertrain main components; the paper aims instead to prove – in real vehicle operating conditions – the efficacy of the approach based on the energy breakdown analysis, which is the actual innovation proposed; such goal was achieved, as demonstrated by the results obtained in Section 5 attesting, for the proposed hybrid powertrain configuration, a 23% decrease of fuel consumption with respect to the basic powertrain.

2. Energy analysis of a vehicular powertrain

In order to analyze the energy flows involved in the road vehicle, its powertrain was divided into its main components [21]. From this point of view, it is possible to consider the vehicles as composed by a sequence of energy converters; each converter is qualified by an efficiency value, through which it is possible to identify the contribution of the different powertrain components to the total energy loss.

In Fig. 1 is depicted the scheme of a vehicular powertrain. From the fuel energy (flowing from the fuel tank to the wheels, as indicated by the arrows) are subtracted the losses in the engine thermodynamic cycle (η_i), the losses related to friction in the engine parts in sliding contact (η_m), the losses related to gearbox and differential gear (η_t).

The chain of energy converters composing the vehicle powertrain is characterized by a global efficiency, intended as the ratio