Energy Conversion and Management 150 (2017) 485–499

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Potential fuel saving in a powertrain derived from the recovery of the main energy losses for a long haul European mission

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ARTICLE INFO

Keywords:
Modelling
Efficiency
Energy recovery
Optimal control strategy
Powertrain
Fuel saving

ABSTRACT

The reduction of automotive fuel consumption and emissions remains one of the main challenges. This paper presents the potential fuel saving in a CNG-powertrain derived from the recovery of the main energy losses. The analysis includes the kinetic energy recovery by a belt starter generator (BSG), the exhaust gas waste heat recuperation by using in a cascade approach, a thermoelectric generator (TEG) and a turbo-generator (TBG)- and the electrification of the main auxiliaries. An additional 48 V board net as well as the addition of a storage system are also included in the study. To support on the design phase of the project and in the operation strategy, a dynamic model in Matlab/Simulink® has been used. The model includes all the new components/major changes required in the vehicle- experimentally validated-. It has been used on backward simulations for the ACEA long haul mission in order to maximize the vehicle's efficiency.

Estimations at rating point (600 Nm and 1200 rpm) result in an electric production up to 4 kW h and a fuel saving of 7.5%. The most convenient technologies in the ACEA cycle turns out to be the KERs followed by the TBG.

1. Introduction

Transport sector accounts for more than 25% of the total world's energy consumption and 23% of it is occasioned by heavy duty trucks with a growing perspective future share [1]. Under the purpose to reduce emissions, policies oriented to lower fuel consumption and emissions are being imposed worldwide [2] leading to a technology evolution towards a higher vehicle efficiency and the use of alternative fuels [3].

In this transport sector, the use of Compressed Natural Gas (CNG) is being one of the most suitable option as cleaner alternative fuel due to its availability and characteristics [4] .

In CNG long distance vehicles, only around 40% of the total available energy from the fuel is actually used for motion purposes and its efficiency is reaching its physical limit [5]. The rest is either waste as heat to the ambient (1/3 through the exhaust system and around 15% to the cooling circuit [5]) or lost between the different heat exchange processes (oil, charge air (compressed air), lubricating, etc.) as can be seen in Fig. 1.

Nonetheless, this significant amount of waste energy is of low quality, as its low exergy limits its complete recovery [7]. Among all the losses stated in Fig. 1, the exhaust gases waste energy is the most important source of losses. In addition, its high temperature compared to the rest of the losses make this, the most useful waste source [8]. In fact, the development and application of new technologies to efficiently recover it, has been a major global concern as it can be seen in [9,10]. Moreover, among the commonly fuel engines, CNG engines present the higher exhaust gas temperatures. Therefore, Natural Compressed Gas engine has been chosen for the application considered in this study.

Despite the big gap of improvement available in the energy waste flows of an engine, most of the previous engine's improvement consider only single/few isolated technologies [11]. In fact, there is an extensive literature in which the most common technology used to recover exhaust heat is the Organic Rankine Cycle (ORC) as it can be seen in a feasibility analysis of this type of systems in [12], in a test bench for different combustion engines in [13], for passenger cars in [14] OR in [15] for heavy duty trucks where 2% of improvement is attained by the introduction for ORC. Moreover, it is easy to find analysis about the potential improvement by the addition of electric turbochargers [16] and in passenger cars [17], thermoelectric generators (TEG) within automobile sector [18], in heavy duty vehicles [19] or modelling analysis of its performance in [20] and Kinetic energy recovery systems (KERs). However, much less studies have been carried out with the use of Turbo-generators (TBG) [21] even though this mature technology

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http://dx.doi.org/10.1016/j.enconman.2017.08.018
Received 4 May 2017; Received in revised form 11 July 2017; Accepted 6 August 2017

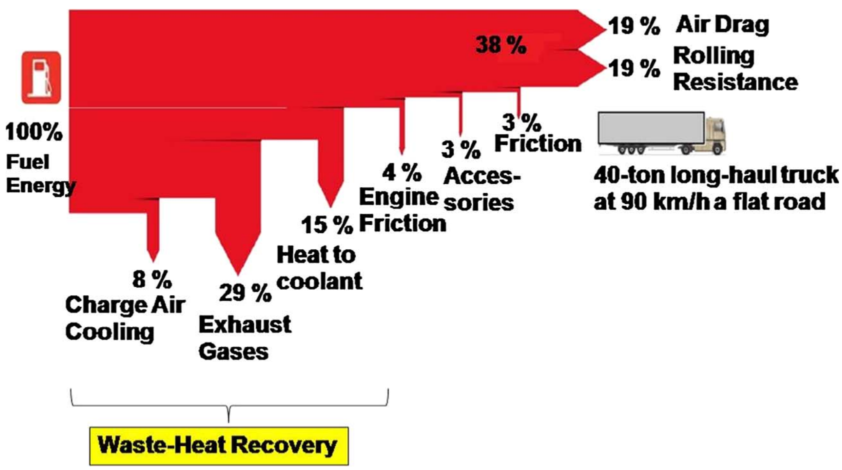

Fig. 1. Energy flow for a long distance CNG engine vehicle [6].

has a great potential [22]. Most of them are based on individual approaches so they may miss the best potential of a technology that could come from the combination and proper operating strategy definition based on the consideration of different possibilities/technologies/solutions. In fact, the biggest advantage of the introduction of new technologies could rely on the coupling of the whole system for a target application (driving cycle).

The improvement by means of modifications in the existing components and/or the addition of new technologies only can be optimized when is coupled with the final target driving cycle according to [23] or [24] where various driving cycles are analyzed, the type of engine [25] and with the definition of proper control strategies [26].

Hence, the use of dynamic models that are able to reproduce the real behavior of the vehicle taking into account all the interactions and possibilities among the different components, becomes a very useful tool [27] that can support in the development of the most convenient solution.

Commercial software in the automotive field are very common and used by the main OEMs of different vehicle's types with purposes similar to these (GT-powers, AVL packages, etc.) [28]. In fact, they are very useful to perform standard simulations but none of them had the possibility to integrate all the new features of the case study presented in this work by default [29]. Therefore, a new dynamic model using Matlab/Simulink in order to analyze non standard solutions has been developed. This model could be, at the end, coupled to the previous cited software.

This work presents the analysis of the most attractive operational strategy and the estimation of the potential fuel saving derived from the simultaneous use of several recovery technologies in a CNG powertrain based on simulation results. The followed approach is based on the recovery of waste energy from different sources (kinetic and heat) in order to generate electric energy that is stored for a latter consumption. Thus, a reduction on the fuel consumption is possible, on the one hand, thanks to the substitution of the belt-driven alternator, the mechanical engine auxiliaries such as compressors, pumps and the like by electric auxiliaries (reducing the engine torque request as well as the mechanical friction losses). On the other hand, thanks to the adoption of an electric booster and the use of a water-cooled charge air cooler (allowing the control of the engine inlet conditions). These electric auxiliaries are fed by the electric energy generated through exhaust gas recovery systems and the kinetic energy recovery system by means of an optimized operating strategy of the storage system for the ACEA cycle. This case study considers a combination of technologies that has not been analyzed before [11]. Specifically, a TEG, a TBG and a KERs as electric generators and aims to study the potential improvement in the efficiency of a CNG engine in a long haul driving cycle.

The fuel consumption reduction analysis in heavy-duty powertrains by the recuperation of kinetic energy, the exhaust gas heat recovery and the reduction of friction losses at once employing the technologies proposed in this study (TEG, TBG and KERs) is a challenging proposal not available in literature yet and is analyzed in this work. A final sensitivity analysis including a Diesel engine is also considered.

2. Model concept

The model has been developed using the respective equations that reproduce the behavior of each component in the vehicle and it is implemented in Matlab-Simulink® software [30]. The use of this platform by the main manufacturers as well as its easy implementation allow its integration in other automotive specific platforms like Autonomie, GT-Suite or AVL packages [31].

The following parts of this section focus on the description of the main features included in the model presented in this work.

2.1. Model structure

The model is composed by a modular structure based on experimental data with an error lower than 5% according to the model validation as it is shown in the Annex. Thus, the optimization not only of the isolated components but also of the overall system is possible.

- **Inputs of the model:** the main inputs are the ambient conditions, the water and air specific thermal capacities, the setting engine temperature, the inertias of the components, physical limitations of the different components (maximum/minimum operating temperatures and pressures) and the driving cycle (by means of engine speed, torque request, vehicle velocity and the deceleration periods).
- **Driving cycle:** Any type of cycle could be simulated and the optimal control strategy will depend on the application target. For this work, the ACEA driving cycle has been utilized. This cycle is considered as a representative cycle for a heavy duty trucks in the transportation sector within Europe [32]. Fig. 2 shows the vehicle speed and the engine speed profiles while the engine torque profile can be seen in Fig. 3.
- **Outcome of the model:** the most important result from the model is the benefit. This benefit is expressed in terms of fuel saving and CO2 emissions reduction by the comparison of a reference vehicle (in this work: IVECO STRALIS CNG MY2014) together with a reference engine (in this work: Cursor8 CNG Euro VI) with a new powertrain concept which engine includes improvements explained afterwards. In addition to these benefit, all the thermal properties of the fluid along the whole system, the individual electric production/consumption, the energy balance, the battery level or the cooling