Transportation Research Part D 65 (2018) 368–374

Contents lists available at ScienceDirect

Transportation Research Part D

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

Energy factors for flexible fuel engines and vehicles operating with gasoline-ethanol blends

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ARTICLE INFO

Keywords:
Ethanol
Energy factor
Specific fuel consumption
Willans line
Spark ignition engines

ABSTRACT

This work investigates the energy factors for fuel conversion from the analysis of brake specific fuel consumption (BSFC) maps of a sample of 15 engines, representative of 75% of current models available in the Brazilian market. The method also employs the engine driving patterns of power output versus crankshaft speed obtained from bench dynamometer tests. The energy factors obtained from the engine analysis was validated against experiments carried out with two production vehicles in laboratory tests following the 1975 US Federal Test Procedure (FTP-75) procedure and road tests following 16 different urban and highway routes. The fuels used in the tests were hydrous ethanol (E100, 6 v/v % water) and a blend of 22 v/v % anhydrous ethanol and 78 v/v % gasoline (E22). The energy factors found from the 3D engine BSFC map analysis were higher than those obtained from the Willans line, currently adopted as a standard, by 52% for E22 and 57% for E100. The results from the 3D engine BFSC maps and the first vehicle following the FTP-75 cycle and 15 road routes were similar, also close to the results from the second vehicle, qualifying them to be representative of modern flexible fuel spark ignition engines and vehicles.

1. Introduction

An accurate energy factor for the conversion of fuel chemical energy into mechanical energy by an engine is necessary to adequately calculate changes on carbon dioxide (CO_2) emission when reducing mechanical loads. Reductions of mechanical loads can be reached by several ways, such as using an efficient alternator, LED illumination replacing incandescent lamps, and solar photovoltaic roof (European Commission, 2017). The energy factor can be calculated from dividing the brake specific fuel consumption (BSFC, g/kW h) by the fuel density (g/L). The concept that the energy factor, given in L/kW h, is inversely proportional to fuel energy density can be used to non-conventional fuels, such as gasoline-ethanol blends. Fuels with lower energy density, such as ethanol and its blends with gasoline, present high energy factors since more volume of fuel is needed to produce the same amount of unitary mechanical energy at the engine crankshaft. Therefore, fuel-dependent energy factors can be calculated by interpolating the respective heat values of the single fuels that composes the fuel blend.

Fig. 1 shows a typical BSFC three-dimensional (3D) map obtained from bench dynamometer tests of a production engine. At high

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https://doi.org/10.1016/j.trd.2018.09.002

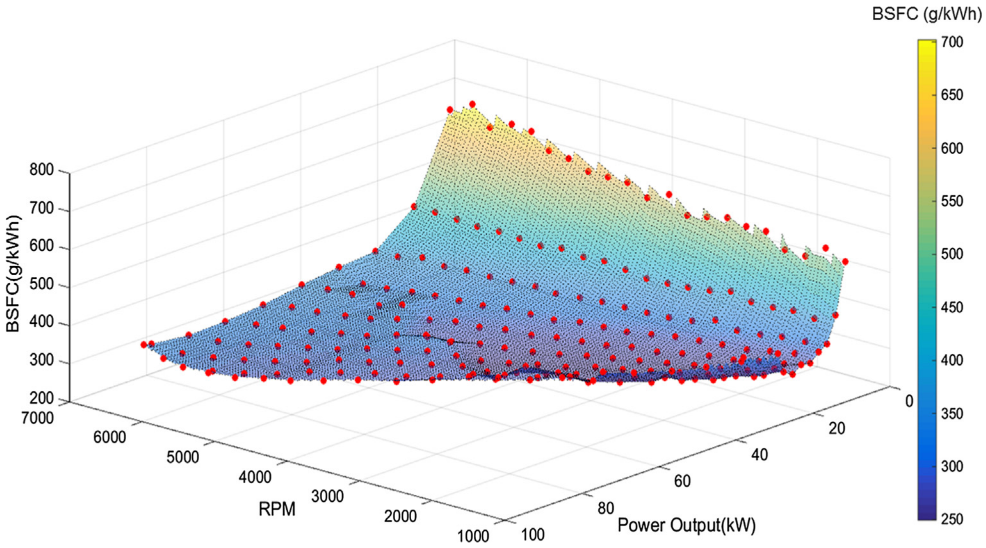

Fig. 1. Typical 3D BFSC map for a production engine.

engine load operation, represented by the higher power output region, lower BSFC is achieved. On the other hand, at low loads, BSFC is increased (Guzzella and Onder, 2010). The complex surface that represents BSFC variation according to engine power output and crankshaft speed motivates the adoption of simplifying methods of linearization. The best approach to linearize the curve was described by Willans (1888) for steam machines, and later adapted to internal combustion engines to study friction losses and other parameters since it shows a linear behavior for partial loads.

The Willans line represents the relationship between the fuel chemical energy input and the mechanical energy output of an internal combustion engine while the crankshaft speed is kept constant (Pachernegg, 1969). The linearity of the Willans line is assumed in the range of common driving situations. By correlating the fuel mean effective pressure with the brake mean effective pressure, normalized per unit displacement and engine cycle, a straight line is found for the majority of internal combustion engines, where the slope of this straight line is related to the indicated efficiency (Phlips, 2015). Nam and Sorab (2004) identified the linearity of the Willans line for 10 engines of 4 different manufacturers, but the energy conversion efficiency was not defined as a fixed value. Rohde-Brandenburger and Obernolte (2009) suggested the Willans line approach to define the mean energy conversion factor for spark ignition engines as 0.264 L/kW h. The European Commission (2017) adopted this value as a conservative one for its off-cycle CO_2 credits policy.

Soltic (2011) and Phlips (2015) explained the linearity of the Willans line over an efficiency field, showing decreasing efficiency when low loads are demanded from the engine. It is also assumed that the real energy factor could be obtained by measuring vehicles on a bench, replacing the engine power by the power at the wheels. The energy factor obtained this way could be used to correct all parameters leading to deviations of the torque at the wheels (speed, road load settings, and inertia), differently from that obtained from the Willans line approach, since in this case losses in the transmission system are not measured and different driving cycle phases have different average engine speeds (Pavlovic et al., 2016). Thurnheer et al. (2009) mentioned that in partial loads or brake mean effective power (BMEP), even a slight change on load results in considerable changes on the energy factor related to the conversion of fuel energy into mechanical energy.

Thus, the objective of this work is to investigate mean energy factors representative of current engine and vehicle models applicable for operation with gasoline-ethanol blends from E22 (22 v/v % of anhydrous ethanol in gasoline) to E100 (hydrous ethanol containing 6 v/v % water). The energy factors were obtained from measurements made in 15 production engines and a vehicle available in the Brazilian market, in laboratory and road tests. The main novelty of this work is the introduction of energy factors that can give more accurate representation of real driving situation using blends of ethanol as a renewable fuel than the conventionally adopted energy factors obtained from the Willans line approach.

2. Methodology

The use of 3D representation of engine BSFC as function of load (power output) and crankshaft speed is the methodology here proposed to estimate vehicle fuel consumption and, then, the energy factor. For a testing vehicle, data is collected of engine load (power output) and speed (rpm) at a driving cycle to produce a graphical representation of driving patterns as shown by Fig. 2. For better visualization, a map where the frequency of occurrences is symbolized by different colors can be generated (Fig. 3). Lighter colors mean more occurrences of situations at a given load and speed during the driving cycle. In this work, the FTP-75 test schedule was simulated to build the 3D engine maps.

Once the load and speed conditions demanded from the engine during the driving cycle is mapped (see Fig. 1), it is possible to find for each coordinated point the unique value for BFSC by superposing the two-dimensional (2D) driving cycle pattern map over the