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

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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.

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

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 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.

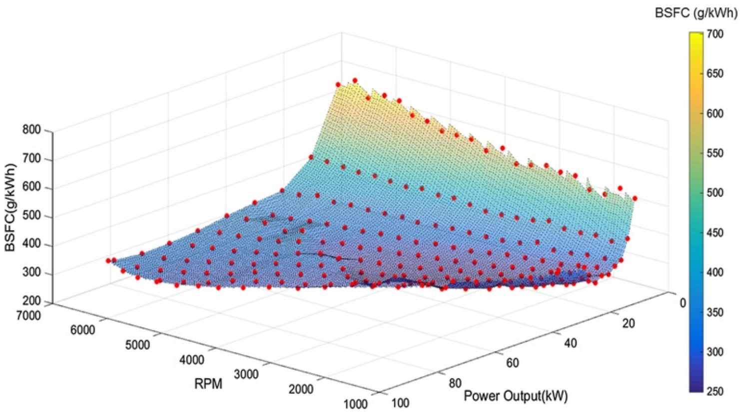

Fig. 1 Typical 3D BFSC map for a production engine.

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.

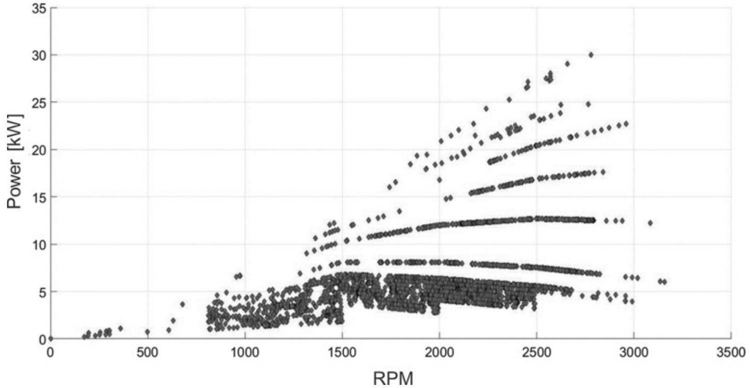

Fig. 2 Driving pattern of power output vs. crankshaft speed for a vehicle operated under the FTP-75 standard test schedule.

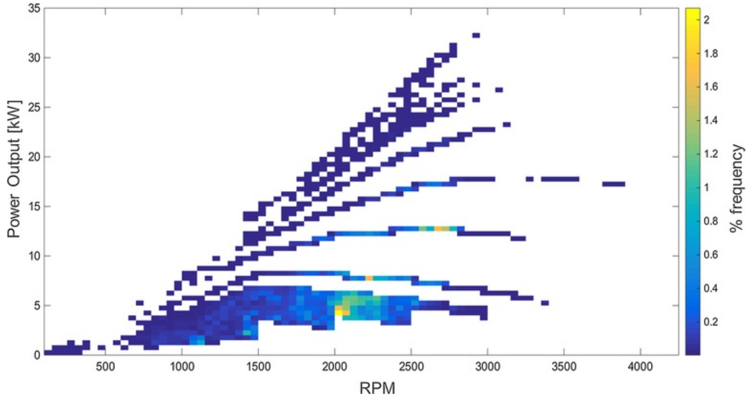

Fig. 3 Color driving pattern for power output vs. crankshaft speed occurrence map under the FTP-75 standard test schedule. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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 engine 3D map using computational tools (Fig. 4). Then, the standard mean BSFC value for the driving cycle and the energy factor can be obtained. It is possible to increase the number of driving cycles and engine sample size in order to achieve a satisfactory value that represents with accuracy the average fleet of each country, reflecting the environmental conditions such as topography and climate, traffic behavior, and different vehicle and engine technologies operating with various fuels.

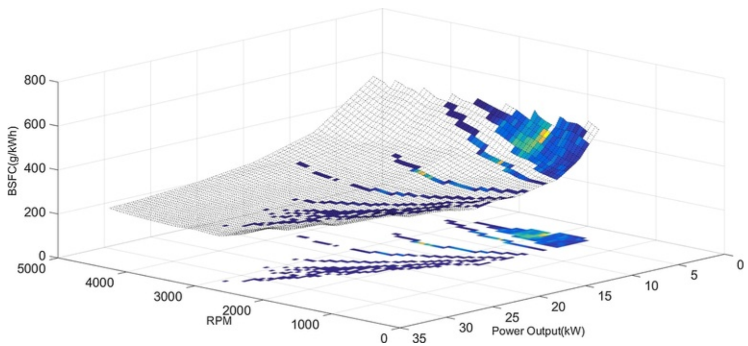

Fig. 4 Driving pattern intersection with 3D BFSC map.

Using a bench test dynamometer, the BSFC 3D maps were obtained for 15 engines from 8 different manufacturers in the Brazilian market, all naturally-aspirated. Thirteen of the engines were flexible fueled, that is, they could operate with blends of E22 and E100 at any proportion (Table 1). Of the engines tested, 4 were 3-cylinder and 11 were 4-cylinder. The total cylinder volume displacements of the engines tested were 1.0 L (6 engines), 1.3 L (2 engines), 1.6 L (1 engine), 1.8 L (4 engines), and 2.0 L (2 engines). To build the 3D map of each engine, a wide range of specific fuel consumption values was measured by changing the engine crankshaft speed from idle to maximum limit, and the power output from zero to rated value (Fig. 5). The engine BSFC 3D maps obtained were stored in a file containing all data necessary to calculate the energy factor as function of engine load and speed.

Table 1 Engines tested by manufacturer, displacement, number of cylinders, and fuel.

Manufacturer	Displacement	Cylinders	Fuel
A	1.0 L	3	E22-E100
	2.0 L	4	E22-E100
B	1.8 L	4	E22-E100
C	1.8 L	4	E22-E100
D	1.0 L	3	E22-E100
	1.8 L	4	E22
	2.0 L	4	E22-E100
E	1.0 L	3	E22-E100
	1.0 L	4	E22-E100
F	1.3 L	4	E22-E100
	1.8 L	4	E22-E100
G	1.0 L	3	E22-E100
	1.0 L	4	E22-E100
	1.6 L	4	E22-E100
H	1.3 L	4	E22

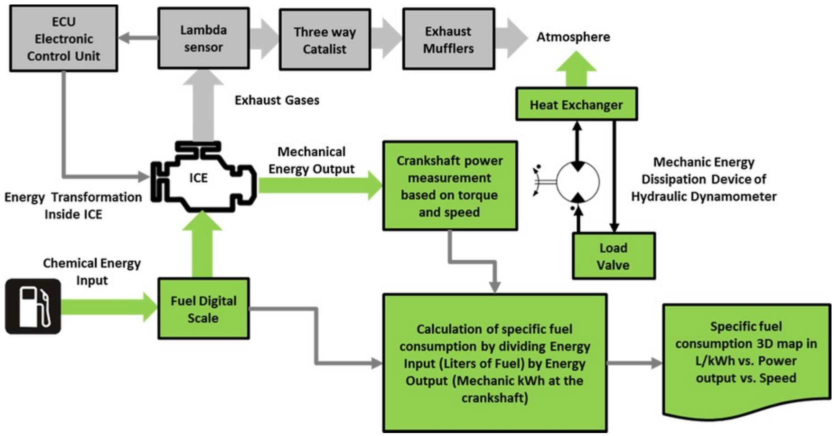

Fig. 5 Workflow used to obtain the specific fuel consumption 3D map.

A production compact hatchback automobile (vehicle A) was used to collect power and speed demanded from the engine for various driving routes. The main characteristics of the vehicle A is shown by Table 2. The vehicle was fitted with a strain gage model HBM 1-XY41-3/350 and a slip connector model Michigan Scientific B7-1.24W in both half axles to measure the torque on each wheel. The vehicle wheel speed and engine crankshaft were collected through the vehicle CAN BUS, among other signals. The values of torque on the half axles could be used to find the torque on the crankshaft by using the transmission ratios and efficiency. For this purpose, a mean value of 97% of transmission efficiency was adopted based on information from the vehicle manufacturer.

Table 2 Vehicle characteristics.

Parameter	Vehicle A	Vehicle B
Energy consumption (MJ/km)	1.55	1.43
Body	Hatchback 4 doors	Hatchback 4 doors
Curb weight (kg)	990	945
Passenger capacity	5	5
Cylinder displacement (cm^3)	1368	999
Engine type	Spark ignition	Spark ignition
Bore × stroke (mm)	72 × 84	70 × 86.5
N. of cylinders	4	3
Valves per cylinder	2	2
Compression ratio	12.35:1	13.2:1
Fuel	E22-E100 (flexible fuel)	E22-E100 (flexible fuel)
Rated power (kW)	62.5 @5750 rpm	56.6 @6250 rpm
Rated torque (N·m)	122.6 @3500 rpm	106.9 @3250 rpm
Gearbox	Manual	Automated
Gear ratios	4.100:1	4.273:1
	2.174:1	2.316:1
	1.480:1	1.444:1
	1.121:1	1.029:1
	0.829:1	0.795:1
Differential/final ratio	4.071:1	4.067:1
Length (mm)	3811	3566
Width (mm)	1636	1633
Height (mm)	1480	1502
Tires	175/65R14	175/65R14

The vehicle A was driven on the road to collect engine load and speed data under various urban traffic conditions (Table 3). Fifteen different urban routes of the city of Belo Horizonte, in Brazil, were chosen to test the vehicle with start and finish at the same location (routes 1~~to~~–15). Route 7 was repeated 5 times to account for traffic condition variation in different periods of the day; the other routes were tested once each. The mean vehicle speed ranged from 8.8 km/h to 48.0 km/h among the different road routes, which distances varied from 2.1 km to 27.8 km. After the road tests, the vehicle was tested four times on a chassis dynamometer following the 1975 US Federal Test

Procedure (FTP-75), according to ABNT NBR 6601 (ABNT, 2012) and ABNT NBR 7024 (ABNT, 2017) standards. In the FTP-75 test schedule including highway driving simulation the mean vehicle speed was 50.3 ± 0.4 km/h and the total distance 34.2 km. To monitor the vehicle fuel consumption in the real driving situations, a Peiseler model VAZ-2E flow meter was installed in the fuel line of vehicle A. The flow meter featured volume and time resolutions of 0.01 mL and 1 s.

Table 3 Characteristics of the driving cycles used.

Route	Distance (km)	Mean speed (km/h)	Vehicle	E22 energy conversion factor (L/kW h)	E100 energy conversion factor (L/kW h)
1	18.8	27.5	A	0.44	0.63
2	9.4	17.2	A	0.44	0.62
3	17.7	35.5	A	0.42	0.61
4	18.6	47.2	A	0.41	0.59
5	19.1	32.8	A	0.45	0.63
6	12.0	8.7	A	0.46	0.66
7	27.8	30.3	A	0.43	0.63
8	30.7	48.0	A	0.42	0.61
9	24.7	35.3	A	0.44	0.62
10	2.1	18.6	A	0.45	0.66
11	21.1	42.8	A	0.42	0.61
12	6.3	19.9	A	0.42	0.61
13	24.2	26.7	A	0.43	0.63
14	3.1	19.2	A	0.46	0.67
15	27.5	22.8	A	0.44	0.64
Average	–	–	–	0.44	0.63
16	84.6	32.0	B	0.48	0.65
FTP-75	34.2	50.3	A	0.43	0.63

To confirm the results obtained with vehicle A at the urban routes, another vehicle of different model (vehicle B) was tested in an additional route mixing urban and highway driving (route 16), also starting and finishing at the same location. The vehicle B was tested three times at different periods of the day, under different traffic conditions. For data acquisition during the road tests, vehicle B was equipped with the same instrumentation as vehicle A. Vehicle B characteristics are shown by Table 2, and the mixed route R16 distance and average speed is shown by Table 3.

3 Results and ~~Ð~~discussion

The energy factors for E22 and E100 fuels are shown in Fig. 6, obtained from the BSFC 3D maps and weighted for the FTP-75 driving patterns. The mean energy factors obtained were 0.43 ± 0.03 L/kW h, for E22, and 0.62 ± 0.05 L/kW h, for E100. The coefficient of variation (COV) of these results is 6.0%, for E22, and 7.3%, for E100 (Table 4). These values were obtained from a sample that represents almost 75% of the engine models present in the Brazilian market. Compared with the value suggested by the European Automobile Manufacturers Association (ACEA) method for ethanol-gasoline blend fueled, naturally aspirated spark-ignition engines, of 0.284 L/kW h, using the standard fuel property values adopted for E22 by the Brazilian National Institute of Metrology (INMETRO), the value here found is 52% higher. Also, for E100, the value here found is 57% higher than that calculated by the ACEA method for ethanol-gasoline blend fuels with standard energy and density values adopted by INMETRO, of 0.396 L/kW h.

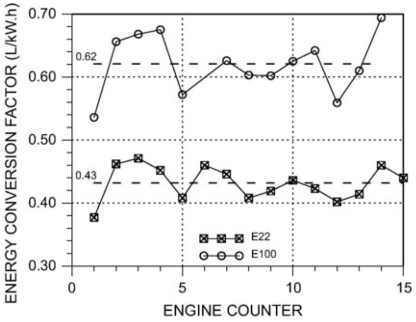

Fig. 6 Specific mean energy conversion factor obtained from graphical evaluation of BSFC map for 15 engine models operated under the FTP-75 cycle.

Table 4 Statistical data of the results from the engine tests: mean value, standard deviation and coefficient of variation (COV).

Manufacturer	Displacement	Cylinders	Fuel Type Engine	E22 g/kW h	E22 L/kW h	E100 g/kW h	E100 L/kW h
A	1.0 L	3	E22-E100	0.28	0.38	0.43	0.54
	2.0 L	4	E22-E100	0.34	0.46	0.53	0.66
B	1.8 L	4	E22-E100	0.35	0.47	0.54	0.67
C	1.8 L	4	E22-E100	0.34	0.45	0.55	0.67
D	1.0 L	3	E22-E100	0.30	0.41	0.46	0.57
	1.8 L	4	E22	0.34	0.46		
	2.0 L	4	E22-E100	0.33	0.45	0.51	0.63
E	1.0 L	3	E22-E100	0.30	0.41	0.49	0.60
	1.0 L	4	E22-E100	0.31	0.42	0.49	0.60
F	1.3 L	4	E22-E100	0.32	0.44	0.51	0.62
	1.8 L	4	E22-E100	0.32	0.42	0.52	0.64
G	1.0 L	3	E22-E100	0.30	0.40	0.45	0.56
	1.0 L	4	E22-E100	0.31	0.41	0.49	0.61
	1.6 L	4	E22-E100	0.34	0.46	0.56	0.69
H	1.3 L	4	E22	0.33	0.44		
		Mean		0.32	0.43	0.50	0.62
		Standard deviation		0.02	0.03	0.04	0.05
		COV (%)			6.0%		7.3%

The results obtained from road tests of vehicle A in 15 different routes with various distances and average speed as dictated by traffic conditions, shown by Table 3, produced average energy conversion factors of 0.44 ± 0.02 L/kW h for E22 and 0.63 ± 0.02 L/kW h for E100. These values fully agree with those found from evaluation of 3D engine BSFC maps for E22 and E100 (Fig. 6), with differences within the uncertainties of the measurements. The energy conversion factors resulted from vehicle A tests on a chassis dynamometer following the FTP-75 test schedule showed values of 0.43 ± 0.00 L/kW h for E22 and 0.63 ± 0.01 L/kW h for E100 (Table 3), agreeing with both the results obtained from the engine BSFC maps and the road tests within the uncertainties of the measurements.

From the road tests using vehicle B, the energy conversion factors obtained were 0.48 L/kW h for E22 and 0.65 L/kW h for E22 (route 16 of Table 3). These results are close to the average results obtained from the road tests with vehicle A in routes 1–15, differing only by 8.3% for E22 and 3.1% for E100. Therefore, the results obtained with vehicle B are also close to the ones found from the engine BSFC maps, with differences of 10.4% for E22 and 4.6% for E100. Compared with the values obtained by the ACEA method for ethanol-gasoline blend fuels and using the standard fuel property values adopted by INMETRO from the application of the Willans line method, the results obtained from the road tests of vehicle B are 69% higher for E22 and 64% higher for E100. Considering the proximity of the results obtained from both vehicles A and B in laboratory and road experiments to the results from the analysis of 3D BSFC maps, it can be affirmed that the proposed method is a reliable one to calculate energy conversion factors of current flexible fuel engines.

4 Conclusions

The determination of energy conversion factors of flexible fuel spark ignition engines from the analysis of 3D BFSC maps was shown to be a reliable alternative method to the conventional approach using the Willans line. Application of the method to 15 engines representative of 75% of the Brazilian market produced energy conversion factors of 0.43 L/kW h, for E22, and 0.62 L/kW h, for E100, being above the values normally adopted from the application of the Willans line method by 52% for E22 and 57% for E100. The results obtained from road and laboratory tests of two different vehicle models, using various routes and traffic conditions and the standard FTP-75 test schedule, validated the results from the analysis of 3D BFSC engine maps. The agreement obtained from the first vehicle tested in 15 different road routes and under the FTP-75 schedule was within the uncertainty of the measurements, while comparison with the second vehicle tested in a mixed road route showed discrepancies of only 10.4% for E22 and 4.6% for E100. Thus, the results here obtained by the proposed methodology can be taken as an updated representation of energy conversion factors of modern flexible fuel spark ignition engines, applicable for operation with both gasoline and ethanol.

Acknowledgments

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References

European Commission, 2017. Technical Guidelines for the Preparation of Applications for the Approval of Innovative Technologies Pursuant to Regulation (EC) no 443/2009 of the European Parliament and of the Council. Brussels.

Guzzella L. and Onder C., Introduction to Modeling and Control of Internal Combustion Engines System, 2010, Springer Verlag Berlin Heidelberg; Berlin.

Nam, E.K., Sorab, J., 2004. Friction Reduction Trends in Modern Engines. SAE Technical Paper 2004-01-1456.

Pachernegg, S.J., 1969. A Closer Look at the Willans-Line. SAE Technical Paper 690182.

Pavlovic J., Marotta A. and Ciuffo B., CO_2 emissions and energy demands of vehicles tested under the NEDC and the new WLTP type approval test procedures, *Appl. Energy* **177**, 2016, 661–670.

Phlips P., Analytic engine and transmission models for vehicle fuel consumption estimation, *SAE Int. J. Fuels Lubr.* **8** (2), 2015, 423–440.

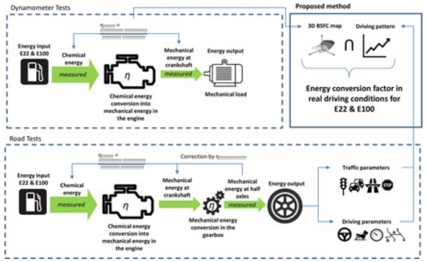
Rohde-Brandenburger K. and Obernolte J., CO_2 potential of lightweight designed cars, *Materialprufung* **51** (1–2), 2009, 55–63.

Soltic, P., 2011. CO2 Reduction and Cost Efficiency Potential of Natural Gas Hybrid Passenger Cars. SAE Technical Paper 2011-24-0110.

Thurnheer T., Soltic P. and Eggenschwiler P.D., S.I. engine fueled with gasoline, methane and methane/hydrogen blends: heat release and loss analysis, *Int. J. Hydrogen Energy* **34** (5), 2009, 2494–2503.

Willans P.W., Economy trials of a non-condensing steam engine: simple, compound and triple, *Min. Proc. Inst. Civil Eng.* **93**, 1888, 128–188.

Graphical abstract



Highlights

- Energy factors were obtained for gasoline and ethanol fueled engines and vehicles.
- Use of 3D engine BFSC maps produced consistent results for flexible fuel engines.
- Energy conversion factor for E22 was 0.43 L/kW h, from laboratory and road tests.
- Energy conversion factor for E100 was 0.62 L/kW h, from laboratory and road tests.

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