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Coefficient of Engine Flexibility as a Basis for the Assessment of Vehicle Tractive Performance

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Abstract

The paper attempts to analyze full load characteristics of over 500 combustion engines. Using statistical tools, the author determined the value of the coefficient of flexibility. Engine flexibility is the capability of the engine to adapt to varying loads. Importantly, in the investigations, the author took into account the parameters calculated in the course of the investigations on a chassis dynamometer, i.e., actual, not taken from technical specifications of brand new vehicles. Different stages of operating wear allow a better characterization of the population. Subsequent utilization of the results in tractive calculations is more reliable. The engines were divided into in six groups, depending on the type of fuel system: fuel injected gasoline and turbocharged gasoline, spark ignition LPG, naturally aspirated diesel and turbocharged diesel. However, engines running on alternative fuels are characterized with a greater flexibility than the fuel injected base engines. Conformity of flexibility of fuel injected and LPG IV generation engines have been observed, which confirms the appropriateness of engine adaptation to alternative fueling. Gasoline engine supercharging allowed a reduction of the maximum engine speed of the maximum torque, which extends the range of analyzable speeds for flexibility and consequently, the flexibility as such.

Keywords: Vehicle, Tractive performance, Flexibility coefficient, Engine characteristics

1 Introduction

Yet another indicator showing vehicle tractive and operational abilities is engine flexibility coefficient E (Eq. (1)) that is the factor of the torque flexibility e_T and engine speed flexibility (range) in Ref. [1]. It shows the capability of engine adaptation to variable loads and speeds (Figure 1).

$$E = e_T e_n = \frac{T_{\max}}{T_{P\max}} \frac{n_{P\max}}{n_{T\max}}, \tag{1}$$

where $T_{\max}$ is the maximum torque value, $T_{P\max}$ is the torque value at maximum power, $n_{P\max}$ is the engine speed value at maximum power, $n_{T\max}$ is the engine speed value at maximum torque.

By flexibility, we also understand the acceleration time on individual gears. On a chassis dynamometer we may simulate the motion resistance using the coefficient values and using the flexibility option determine the times of acceleration on selected gears.

Yet, in the case of the coefficient of flexibility (E) it is a bit different. If the vehicle drives on the IV gear near the engine speed of the maximum power (point 1 in Figure 2) and if the vehicle drives onto a hill, because of the collective resistance (dotted lines) its engine speed will drop to increase the torque (point 2 in Figure 2) and reach point 3. As we can see, we need a surplus of torque ΔT that will allow the increase of the motion resistance of the vehicle. When analyzing the flexibility coefficient the full load characteristics is analyzed in the reverse order. Coefficient E is decisive when analyzing the vehicle motion and enables predicting certain behaviors on the road. Its value in connection with an appropriate analysis may turn out useful when designing roads, artificial hills in particular

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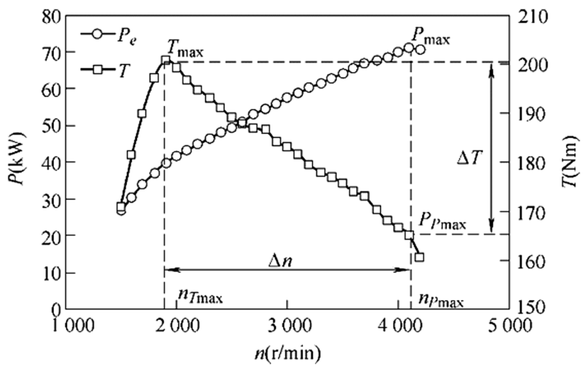

Figure 1 Full load engine characteristics—characteristic points needed to determine the flexibility coefficient

Table 1 Division of engines in terms of flexibility [1]

Not flexible	Low flexibility	Medium flexible	Highly flexible	Extremely flexible
Up to 1.6	1.6–2.0	2.0–2.8	2.8–3.8	More than 3.8

Table 2 Values of the coefficients of flexibility for selected engine types

Engine	Grishkievich [2]	Prochowski [3]
Carburetor gasoline	1.5–2.5	1.7–2.9
Naturally aspirated diesel	1.45–2.0	1.2–2.0

(entrance to overpasses) or when designing road portions preceding natural land elevation.

2 Literature Review

Literature information on the subject dates back to the first half of the 20th century, when by Ref. [1] along with the description of the coefficient provides a division of engines in terms of their E value (Table 1).

Grishkievich [2] and Prochowski [3] compared the value of coefficients of flexibility E for selected old generation engine types (Table 2).

The problem of engine flexibility was presented by Myslowski and Koltun [4] but we will not find a complex comparison of flexibility for different types of engines (particularly if alternative fueling is applied). The calculations were made based on technical specifications of new vehicles for 206 vehicles (Table 3). Engines adapted for retrofitted alternative LPG fueling do not have this kind of information.

Some of the studies present only selected groups of engines indicating their flexibility. In Ref. [5] it was observed that MAN engines are characterized by $E=2.83$, in Ref. [6] the presented results for V.A.G 1.9TDi the coefficient was $E=2.4$. Some of the publications are based on values of e_T deeming them decisive in the tractive analysis of vehicles. Bogatyrjev et al. [7] for gasoline engines states $e_T=1.25,\ldots, 1.4$ and for diesel engines 1.15, ..., 1.2. Kolchin and Demidov [8] states: gasoline, carburetor engines—1.2,..., 1.35 and diesel engines—1.25,..., 1.4. In Ref. [8] study several gasoline carburetor engines have been compared where the averaged value $e_T=1.24$ and with fuel injected engines $e_T=1.114$, which is to be understood that the latter are less flexible. A comparison of a naturally aspirated and turbocharged diesel engine has been performed indicating a similar value of $e_T=1.19$.

Debicki [9] compared the courses of flexibility of engines used in vehicles of different applications. Based on Figure 3 we can confirm that performance vehicles, which operate at higher speeds, are much less flexible than heavy-duty trucks.

This has also been confirmed in Ref. [6] where the V.A.G 1.9TDi factory engine, compared with an upgraded engine, exhibits better flexibility. Szpica et al. [10] has shown that as the power drops the flexibility grows (Table 4).

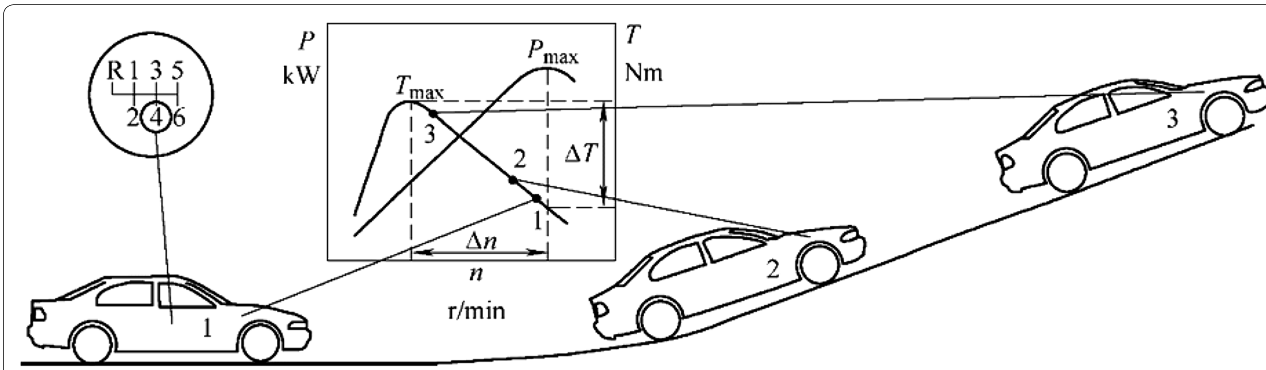

Figure 2 Diagram explaining the principle of the coefficient of flexibility

Table 3 Flexibility of combustion engines [4]

Engine	Gasoline				Diesel	
	Carburetor	Single point	Multi point	Direct injection	Pre-chamber	Direct injection turbocharged
e_T	1.222	1.222	1.141	1.110	1.195	1.441
e_n	1.761	1.745	1.511	1.462	2.023	2.101
E	2.153	2.129	1.724	1.622	2.414	3.027

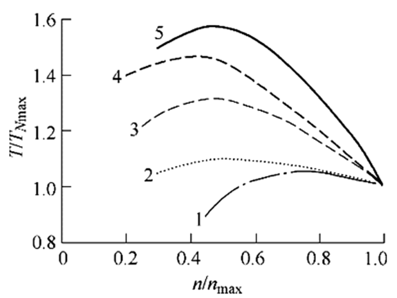

Figure 3 Comparison of the flexibility of different engines [9]: 1. performance vehicle; 2. sports vehicles; 3. passenger vehicles; 4. heavy-duty trucks; 5. off road vehicles

Table 4 Dependence of the flexibility on the power output [10]

Power output (%)	100	70	50	30
E	1.178	1.147	1.485	3.591

Having the values of characteristic parameters of the flexibility coefficient E, i.e., e_T and e_n we can determine the full load characteristics of an engine based on the Leiderman-Khlystov relation (in the literature they are named—Leideman's and Leidemann's) [11–14]. Then assuming:

$$\lambda = \frac{n}{n_{P\max}}. \tag{2}$$

Relations $P=f(n)$ and $T=f(n)$ are described with relations (Eqs. (3), (4)) presented Bortnicki and Zadorozny [15]:

$$P = P_{\max}\left(A\lambda + B\lambda^2 - C\lambda^3\right) \quad [\mathrm{kW}], \tag{3}$$

$$T = T_{P\max}\left(A + B\lambda - C\lambda^2\right) \quad [\mathrm{N \cdot m}]. \tag{4}$$

Besides, for $n = n_{P\max}$ the equality $P = P_{\max}$ should be fulfilled and then:

$$A + B - C = 1 \quad \Rightarrow \quad C = A + B - 1. \tag{5}$$

According Grishkevich [2] coefficients A, B and C may be applicable for gasoline engines and diesel engines and their values are calculated from:

$$A = \frac{e_T e_n(2 - e_n) - 1}{e_n(2 - e_n) - 1}; \quad B = \frac{2e_n(1 - e_T)}{e_n(2 - e_n)^2}; \quad C = \frac{e_n^2(1 - e_T)}{e_n(2 - e_n) - 1}. \tag{6}$$

According Litvinov and Farobin [16] for spark ignition engines, without engine speed limiter:

$$A = 2 - \frac{0.25}{T_r}; \quad B = \left(\frac{0.5}{T_r}\right) - 1; \quad C = \frac{0.25}{T_r}, \tag{7}$$

where T_r is the coefficient of torque surplus:

$$T_r = \frac{T_{\max} - T_{P\max}}{T_{P\max}} = (e_T - 1). \tag{8}$$

For diesel engines with engine speed limiter:

$$A = 1 - T_r\frac{e_n(2 - e_n)}{(e_n - 1)^2}; \quad B = 2T_r\frac{e_n}{(e_n - 1)^2}; \quad C = T_r\left(\frac{e_n}{e_n - 1}\right). \tag{9}$$

For engines without engine speed limiter or speed controller a condition $\mathrm{d}P/\mathrm{d}n$ for $n = n_{\max}$ (Eq. (10)) should be fulfilled:

$$A + 2B - 3C = 0. \tag{10}$$

Full load engine characteristics can be used in many aspects, such as modeling of the vehicle in motion-performance with automatic transmission [17, 18], vehicle body behavior [19, 20], performance under different soil conditions [21], when changing lanes [22], when assessing motion stability (vehicle-driver) [23], because additional information allows a virtual diagnostic assessment in real time (as has been proposed in Ref. [24]) or a vehicle acceleration simulation [13].

3 Objectives

The aim of the study was the determination of the coefficients of engine flexibility under different variants of fueling systems. We can obviously make the calculations based on the data provided by the vehicle manufacturers. In such a case however all results would pertain to new vehicles only, which, as confirmed earlier, is not always reflected on the chassis dynamometer tests. Used vehicles, at different stages of their life prevail on the roads, which is why it is important to test larger population to generalize the results.

The problem is important because in literature there is no complex information related to modern engines or alternative fueling. The author also decided to analyze the components of the coefficient of flexibility, i.e., flexibility of torque and flexibility of speed. These two parameters are decisive of the transport capability of a vehicle because not always wider range of torque ΔT is accompanied by a wider range of Δn. This results from the full road characteristics of an engine where the total range of speeds in diesel engines is approximately 70% of that of a gasoline engine. Obviously, vehicles fitted with diesel engines have different gear ratios in the transmission system.

4 Material and Methods

4.1 Subject of the Research

The investigations were carried out on full load passenger vehicle engine characteristics calculated on a chassis dynamometer. The engines were grouped into:

- Indirect fuel injected gasoline engines—234 units.
- Indirect fuel injected, turbocharged gasoline engines—7 units.
- Spark ignition LPG, I and II generation engines—64 units.
- Spark ignition LPG, IV generation engines—23 units.
- Naturally aspirated diesel engines—10 units.
- Turbocharged diesel engines—171 units.

The engines included in the LPG groups were dual fuel engines and the tests were performed for both types of fuel. The author also had the characteristics of the carburetor engines and they were only used to validate information found in the literature.

4.2 Research Methodology

In the investigations, the authors used a chassis dynamometer (LPS 3000 by Maha, Figure 4). Chassis dynamometers have a wide range of applications in research from calculating different types of engine characteristics to performance of driving cycles [25]. Majority of the chassis dynamometer tests are related to testing exhaust emissions from engines using driving cycles or proprietary solutions [26]. For example in Refs. [27, 28] used the chassis dynamometer to assess the PM emission from diesel engines and Ref. [29] used it as a tool to compare fueling systems. Measurements with the use of a chassis dynamometer are characterized by high reproducibility and the time of adapting the dynamometer to another test object is relatively short compared with engine dynamometers.

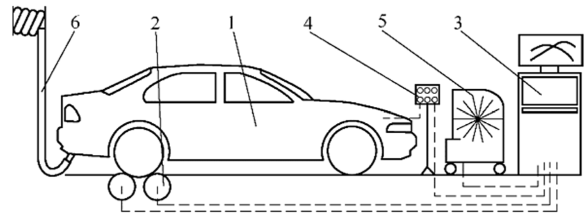

Figure 4 Test stand: 1. tested vehicle; 2. twin-roller type chassis dynamometer with eddy-current brake; 3. dynamometer control system; 4. vehicle signals connector box; 5. fan; 6. exhaust gas extractor

On the LPS 3000 dynamometer operating in the load-applying mode, at a continuous test, the cycle during the measurement is realized assuming a constant acceleration of the roller.

Such a type of chassis dynamometer is a specific solution in the aspect of measurement of the power output. The LPS 3000 chassis dynamometer adjusts the load on a continuous basis.

In the preceding investigations, in the beginning of the research cycle preliminary tests were performed. They aimed at checking the reproducibility of the results on one hand (within 3 consecutively repeated tests no errors greater than 1% of the measurement range were recorded) and determining the full load engine characteristics at different gears on the other. It has been observed that only the gear ratio close to 1 allows an assessment of the full measurement range. For overdrives the risk of exceeding the maximum vehicle speed range declared by the manufacturer occurs. The test stand also has a security system against accidental vehicle takeoff from the rollers during the tests. It is rather important because the turbocharged diesel engines have a rapidly increasing torque at maximum charging, which may result in the vehicle uncontrolled takeoff from the stand. The chassis dynamometer systems calculate the slip between the front and the rear axles by monitoring the speeds of the front and rear rollers and can reduce the load in hazardous situations.

The technical data of the test stand have been shown in Table 5. Because the tested vehicles were not property of

Table 5 Basic technical data of the Maha LPS 3000 dynamometer (Maha Manuals)

Parameter	Values
Roller set R100/1	
Axle load (t)	2.5
Length (mm)	3345
Width (mm)	1100
Height (mm)	625
Weight	Approx. 1200
Roller length (mm)	750
Track min. (mm)	800
Track max. (mm)	2300
Roller diameter (mm)	318
Roller axle separation (mm)	540
Running roller protrusion (mm)	45
Display range	
Test speed (km/h)	Max. 250
Wheel power (kW)	Max. 260
Traction (kN)	Max. 6
RPM (rot/min.)	0–10000
Measurement accuracy of measurement value (%)	±2

the university, the tests were not repeated and the conclusions were drawn based on the preliminary tests.

In the case of this type of chassis dynamometer the research process is realized as follows: upon setting of the vehicles on the rollers and securing it against take-off or displacement and connecting all necessary signals the driving is initiated to obtain the operating coolant and lubricant temperatures. Then, on the gear ratio closest to 1:1 the engine power is increased to 100%. The dynamometer adjusts the engine load starting from 50 km/h automatically, which is sufficient for most of the engines to initiate the measurement. The test is continued until the power starts dropping after reaching its maximum value. Then, we continue to reduce the engine power to minimum, depress the clutch and thus determine the accumulated motion resistance.

The measurement is indirect, as the torque is measured on the wheels by the brake rollers and the power in the initial phase is calculated and displayed on the monitor as the power on the wheels. An example full load characteristics has been presented in Figure 5. During the measurement, the power on the wheels P_w and then, in the coastdown trial, the power of the resistance P_d are determined. The engine power is calculated as $P_e = P_w + P_d$. During the test, the torque T is not displayed to enable finishing of the measurement. It is displayed only after the engine power P_e is calculated.

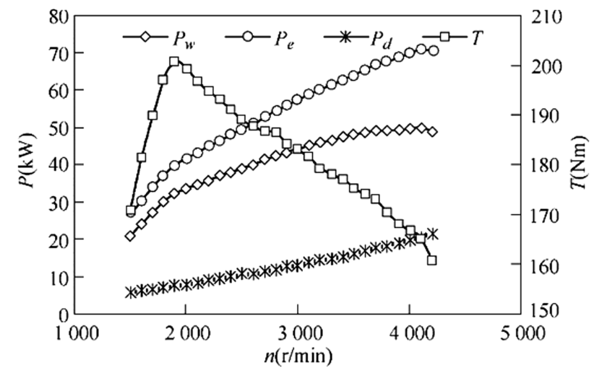

Figure 5 Full load characteristics obtained on the chassis dynamometer (description in the paper)

Based on this type of characteristics, as in Figure 5, following Eq. (1) the characteristics values were calculated. Additionally, the value of the torque surplus T_r was determined applicable in the tractive calculations of the vehicle.

5 Results and Discussion

The results of the measurements were analyzed only in the adopted groups, they were not compared with the factory technical data.

In a statistical analysis, Gaussian distributions were adopted. However one may attempt to use information theory to analyze discrete distributions. The statistical processing covered:

- Arithmetic average:

$$\bar{x} = \frac{x_1 + x_2 + \cdots + x_n}{n}. \tag{11}$$

- Estimator of standard deviation:

$$s_b = \sqrt{\frac{1}{n-1} \cdot \sum_{i=1}^{n} (x_i - \bar{x})^2}. \tag{12}$$

- Median:

$$M = \frac{n+1}{2}. \tag{13}$$

- Sample variance:

$$s^2 = \frac{1}{n} \cdot \sum_{i=1}^{n} (x_i - \bar{x})^2. \tag{14}$$

- Standard deviation:

$$s_o = \sqrt{s^2}. \tag{15}$$

- Bias:

$$A_d = \frac{n}{(n-1)\cdot(n-2)} \cdot \sum_{i=1}^{n} \left(\frac{x_1 - \bar{x}}{s}\right)^3. \tag{16}$$

- Kurtosis:

$$K = \left\{ \frac{n\cdot(n+1)}{(n-1)\cdot(n-2)\cdot(n-3)} \cdot \sum_{i=1}^{n} \left(\frac{x_1 - \bar{x}}{s}\right)^4 \right\} - \frac{3\cdot(n-1)^2}{(n-2)\cdot(n-3)}. \tag{17}$$

Moreover, the following have been determined: the range, the minimum, the maximum, the sum, the counter and confidence level that marks the probability that the result of the measurement falls in the range of the bounded interval limited by the extended uncertainty of the measurement. The results were not eliminated based on the Dixon and Grubbs test because of the wide range of vehicles tested in the groups.

In the results analysis, attention was focused on the flexibility coefficient E, yet, in the tables results for all obtained parameters were given, which may be important when analyzing the influence of different factors on the vehicle tractive performance.

Based on 234 samples we can confirm with 95% probability that direct injected gasoline engines are characterized by the flexibility coefficient on the level of 1.645 ± 0.049 (Figure 6 and Table 6). The distribution of E is a bit flattened against the regular one, which is indicated by the negative value of the kurtosis of a left-side skewness. E is more influenced by e_n and determines its distribution. The interval of the obtained values is $E = 1.062,\ldots, 2.747$.

In the case of gasoline supercharged engines the number of samples is low (7 samples) and statistical conclusion is uncertain. $E = 2.558 \pm 0.386$ (Figure 7 and Table 7). Distribution of E is close to normal. Value E is predominantly influenced by e_n. The interval of the obtained values $E = 1.946,\ldots, 3.112$.

Table 6 Results of the calculations for fuel injected gasoline engine groups

Parameter	e_T	e_n	E	T_r
Average	1.120	1.458	1.645	0.120
Standard error	0.004	0.018	0.025	0.004
Median	1.105	1.377	1.529	0.105
Standard deviation	0.065	0.271	0.378	0.065
Sample variance	0.004	0.074	0.143	0.004
Kurtosis	0.372	−0.216	−0.392	0.372
Bias	0.853	0.783	0.744	0.853
Range	0.340	1.247	1.685	0.340
Minimum	1.005	1.039	1.062	0.005
Maximum	1.345	2.286	2.748	0.345
Counter	234	234	234	234
Confidence level (95.0%)	0.008	0.035	0.049	0.008

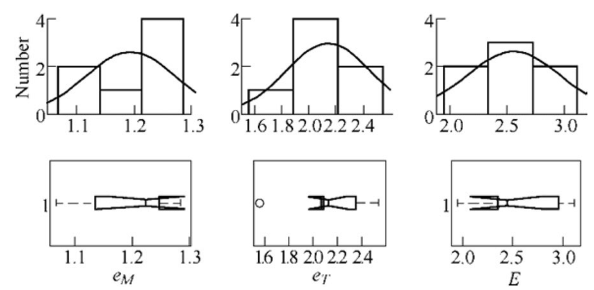

Figure 7 Histograms and box plots for fuel injected, turbocharged gasoline engines groups

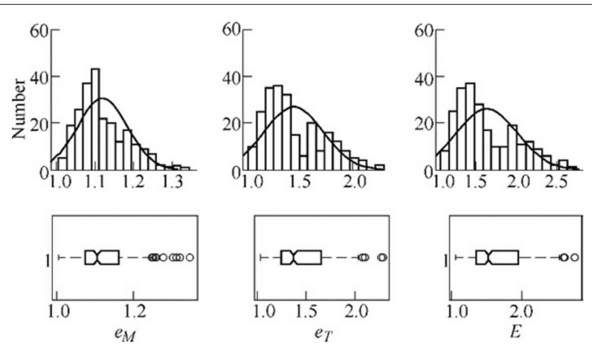

Figure 6 Histograms and box plots for fuel injected gasoline engine groups

Based on 64 samples we can confirm with a 95% probability that gasoline engines with alternative I and II generation LPG fueling are characterized with a flexibility index on the level of 1.808 ± 0.120 (Figure 8 and Table 8). The distribution of E is significantly flattened against the regular one, which is indicated by the negative value of the kurtosis of a left-side skewness. E is more influenced by e_n and determines its distribution. The interval of the obtained values is $E = 1.140,\ldots, 3.892$.

It is similar for IV generation LPG fueling. With 23 samples we can confirm with 95% probability that $E = 1.646 \pm 0.180$ (Figure 9 and Table 9). The distribution of E is slightly flattened against the regular one, which is indicated by the negative value of the kurtosis of a left-side skewness. E is more influenced by e_n and determines its distribution. The interval of the obtained values is $E = 1.150,\ldots, 2.680$.

Traditional, naturally aspirated diesel engines were tested in the amount of 10 units. Hence, the conclusions

Table 7 Results of the calculations for fuel injected, turbocharged gasoline engines groups

Parameter	e_T	e_n	E	T_r
Average	1.194	2.143	2.558	0.194
Standard error	0.030	0.117	0.158	0.030
Median	1.225	2.125	2.444	0.225
Standard deviation	0.078	0.309	0.418	0.078
Sample variance	0.006	0.096	0.175	0.006
Kurtosis	−0.919	2.049	−0.583	−0.919
Bias	−0.592	−0.937	0.229	−0.592
Range	0.217	0.983	1.166	0.217
Minimum	1.068	1.559	1.947	0.068
Maximum	1.285	2.542	3.112	0.285
Counter	7	7	7	7
Confidence level (95.0%)	0.072	0.286	0.386	0.072

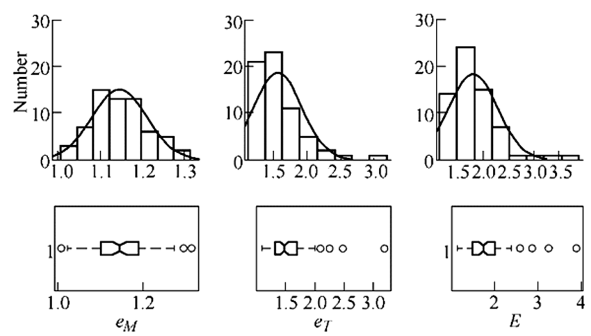

Figure 8 Histograms and box plots for LPG, I and II generation engine groups

Table 8 Results of the calculations for LPG, I and II generation engine groups

Parameter	e_T	e_n	E	T_r
Average	1.147	1.567	1.808	0.147
Standard error	0.008	0.045	0.060	0.008
Median	1.145	1.493	1.748	0.145
Standard deviation	0.065	0.357	0.482	0.065
Sample variance	0.004	0.127	0.233	0.004
Kurtosis	−0.127	6.062	5.345	−0.127
Bias	0.311	1.969	1.842	0.311
Range	0.307	2.079	2.752	0.307
Minimum	1.007	1.111	1.140	0.007
Maximum	1.314	3.191	3.892	0.314
Counter	64	64	64	64
Confidence level (95.0%)	0.016	0.089	0.120	0.016

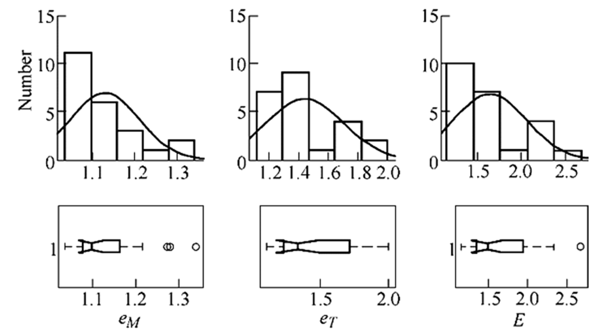

Figure 9 Histograms and box plots for LPG IV generation engine

Table 9 Results of the calculations for LPG IV generation engine groups

Parameter	e_T	e_n	E	T_r
Average	1.130	1.441	1.646	0.130
Standard error	0.017	0.054	0.087	0.017
Median	1.099	1.342	1.491	0.099
Standard deviation	0.081	0.260	0.416	0.081
Sample variance	0.007	0.068	0.173	0.007
Kurtosis	0.918	−0.608	0.246	0.918
Bias	1.265	0.866	1.136	1.265
Range	0.303	0.891	1.530	0.303
Minimum	1.037	1.109	1.150	0.037
Maximum	1.340	2.000	2.680	0.340
Counter	23	23	23	23
Confidence level (95.0%)	0.035	0.113	0.180	0.035

are uncertain. $E=2.044\pm0.276$ (Figure 10 and Table 10). In this manner the conformity of values for this type of engines following in Refs. [2, 3] was confirmed. The distribution of E is flattened against the regular one having a left-side skewness. Values E are determined by e_n. The interval of the obtained values is $E=1.562,\ldots, 2.947$.

Turbocharged diesel engines in the amount of 171 units have shown $E=2.141\pm0.063$ (Figure 11 and Table 11). The distribution of E is close to normal of a slight right-side skewness. E is significantly influenced by e_n and determines its distribution. The interval of obtained values is $E=1.036,\ldots, 3.114$.

Comparing the results (Figure 12), we can confirm that supercharged engines have the greatest flexibility. Gasoline supercharged engines have an average value of the coefficient of flexibility of 2.558, turbocharged diesel engines −2.141. Traditional diesel engines (naturally aspirated) of the value of 2.044 are within the range given in the literature. We can classify these engines as medium flexible according to Ref. [1]. The rest can be classified as low flexibility engines. It is interesting that engines with

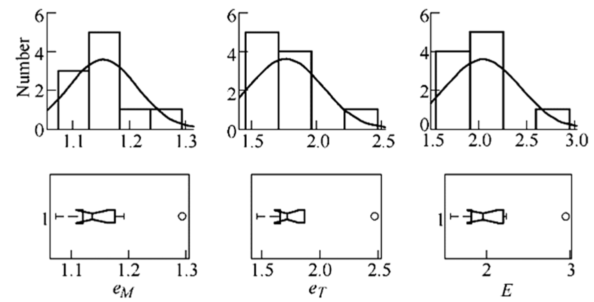

Figure 10 Histograms and box plots for naturally aspirated diesel groups

Table 10 Results of the calculations for naturally aspirated diesel groups

Parameter	e_T	e_n	E	T_r
Average	1.154	1.766	2.044	0.154
Standard error	0.019	0.089	0.122	0.019
Median	1.138	1.718	1.954	0.138
Standard deviation	0.061	0.282	0.385	0.061
Sample variance	0.004	0.079	0.149	0.004
Kurtosis	2.400	4.742	2.946	2.400
Bias	1.250	1.864	1.415	1.250
Range	0.219	1.016	1.385	0.219
Minimum	1.074	1.455	1.562	0.074
Maximum	1.293	2.471	2.947	0.293
Counter	10	10	10	10
Confidence level (95.0%)	0.044	0.201	0.276	0.044

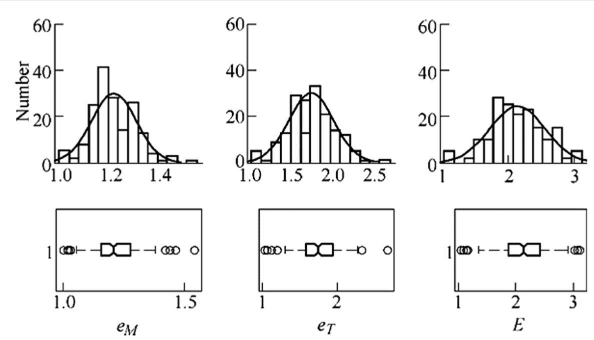

Figure 11 Histograms and box plots for turbocharged diesel groups

alternative I and II generation LPG fueling are more flexible (1.808) than the base fuel injected engines (1.645). This was drawn attention to in Ref. [30].The main parameters responsible for this status quo was the composition of the mixture shifted towards enriched mixture in this type of LPG systems. The values of the fuel injected gasoline engines and IV generation LPG engines are close 1.645 and 1.646, which also indicates appropriate engine adaptation to alternative fueling.

Table 11 Results of the calculations for turbocharged diesel groups

Parameter	e_T	e_n	E	T_r
Average	1.217	1.750	2.141	0.217
Standard error	0.007	0.021	0.032	0.007
Median	1.208	1.739	2.126	0.208
Standard deviation	0.089	0.271	0.416	0.089
Sample variance	0.008	0.074	0.173	0.008
Kurtosis	0.809	0.504	0.037	0.809
Bias	0.477	0.011	− 0.049	0.477
Range	0.543	1.660	2.078	0.543
Minimum	1.002	1.028	1.036	0.002
Maximum	1.544	2.688	3.114	0.544
Counter	171	171	171	171
Confidence level (95.0%)	0.013	0.041	0.063	0.013

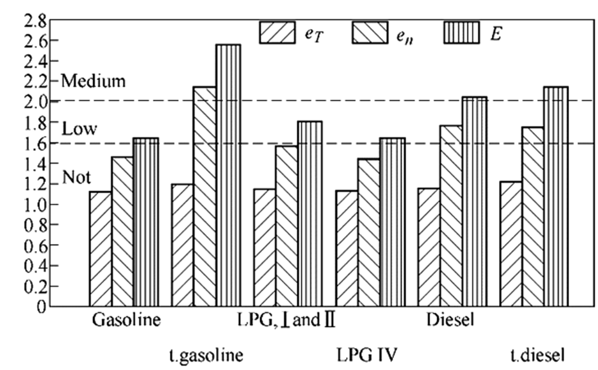

Figure 12 Average values of the determined coefficients

Analyzing Figure 12 we can see that value e_n determines E while in the literature most attention is devoted to e_T. If we want to obtain the highest value of the coefficient of flexibility, we need to provide the maximum of torque at low speeds, which is traditionally done by supercharging. As we already know, flexibility is the capability of reacting of the engine to variable engine loads. It is not only the surplus of torque but also the range of engine speeds at which it occurs.

6 Conclusions

(1) The determined values of the coefficients of flexibility are a complex study related to combustion engines of different fueling systems used in passenger vehicles.
(2) The results are related to the characteristics of engines in service, of a varied level of wear.
(3) The greatest flexibility have supercharged engines, that, in the case of passenger vehicles,

we can classify as medium group. The rest are engines of low flexibility.

(4) Individual cases of highly flexible engines have been observed in the group of diesel engines (2.94), turbo diesel engines and turbo gasoline engines (3.11).

(5) The deficit of values describing the flexibility of engines fitted with LPG systems has been eliminated.

(6) In I and II generation LPG fueled engines the maximum value of $E = 3.89$ was recorded, which confirms very high flexibility.

(7) Engines fitted with I and II generation LPG systems have greater flexibility than their base gasoline fuel injected counterparts.

(8) Conformity of the flexibility for fuel injected gasoline engines with IV generation LPG has been confirmed, which proves appropriate engine adaptation to alternative fueling.

(9) Not in all cases, the number of samples was sufficiently high to adequately represent the population, which is why, some of the results should be treated as uncertain.

(10) Research needs to be continued, based on technical data for new engines to be able to determine the flexibility of utility vehicles, farm tractors, etc.

Authors' contributions

The author read and approved the final manuscript.

Authors' Information

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Competing Interests

The authors declare no competing financial interests.

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