ANALYSIS OF PARAMETERS AFFECTING FUEL CONSUMPTION BASED ON STATISTICAL MODELLING

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Abstract

Fluctuating fuel prices and the importance of road transport in the context of the environmental impact of transport make the research related to fuel consumption analyses still up-to-date and socially important. The article presents the methodology for determining the statistical model of fuel consumption based on the analysis of the significance of driving parameters. The fleet of trucks (sets of tractor truck and semi-trailer) was selected as the research object due to their dominant share in the road commercial transport sector in the transport of goods. In order to calculate determinants of fuel consumption, the classic method of least squares was used, as a result of which an optimal statistical model of fuel consumption was developed using the elimination method. The model developed was also verified based on the real data.

Keywords:

fuel consumption, truck, classical method of least squares

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Introduction

Constant changes in the fuel market and the growing share of costs related to fuel consumption by vehicles in transport companies mean that research in this area and the development of technologies supporting the reduction of fuel consumption in vehicles are still a significant scientific challenge of numerous leading research and development units and the entire automotive sector. The economic environment, including fuel prices, affects the entire transport sector. Fuel costs are one of the key factors determining the competitiveness of land transport [1]. On the crude oil markets, the majority of transactions concern two types of crude oil – European Brent and American WTI (West Texas Intermediate). The chart below presents changes in crude oil prices in 2010-2020, broken down into two leading sectors (WTI and Brent) and the spread, i.e. the difference between the unit prices of these products. This highlights the dynamics of changes on the fuel market. A very unfavourable phenomenon on the fuel market is the creation of a deficit when consumption significantly exceeds production. This phenomenon has a direct impact on the prices of transport services, but also on the availability of these services. On one of the world's leading markets – for several years on a very large growing wave – i.e. the Chinese market, this phenomenon began to gain alarming proportions from the beginning of the 21st century and further forecasts are also not optimistic (Fig. 2).

Fig. 1. WTI (CL.F) and Brent (CB.F) oil prices in 2010-2020, source Stooq 2020 [2]

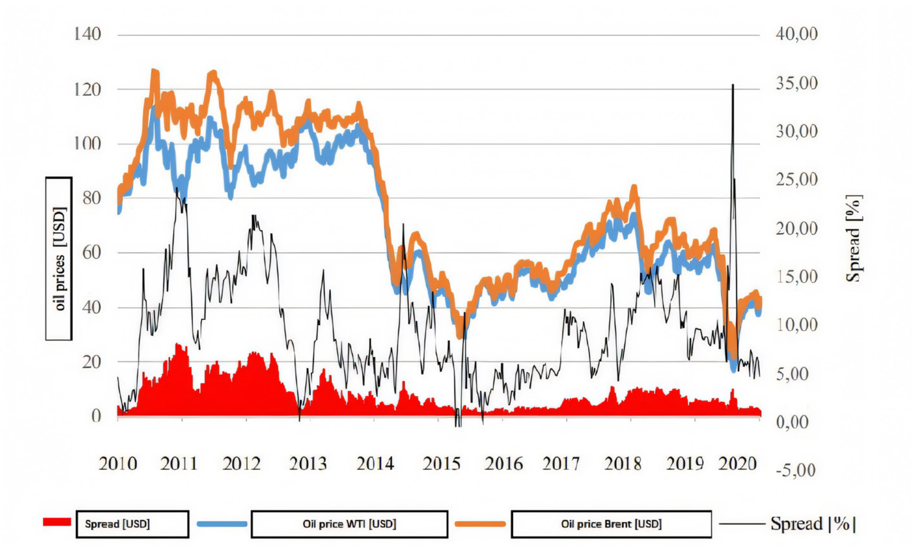
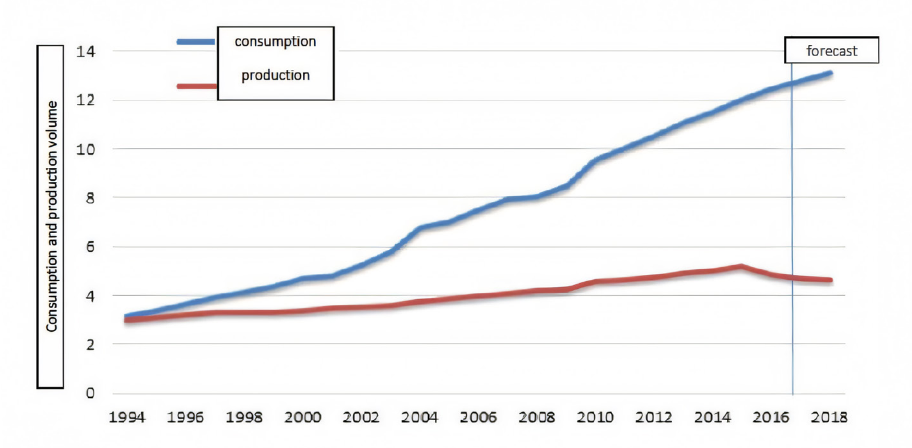


Fig. 2. Summary of crude oil consumption and production in China in 1994-2016 (with forecast) [3].



Due to the instability of the fuel market and varying prices, alternative methods of minimizing costs or their growth dynamics related to fuel consumption are becoming more and more important. Manufacturers of motor vehicles, especially utility vehicles, have been introducing new technologies for a long time, the aim of which is to minimize fuel consumption [5]. Another tool supporting transport companies in this aspect is making drivers aware of eco-driving. This article is devoted to this issue.

The article presents results of own research, the aim of which was to analyse the parameters affecting fuel consumption. The analysed data comes from one of the leading forwarding and transport companies in Poland. As part of the research, a statistical model representing the function of deterministic relationships affecting fuel consumption in trucks was developed.

Eco-driving – role of a driver

The issue of ecology in transport is at the basis of the leading direction and trend in the development of transport, i.e. e-mobility. The paper [6] presents notion of the extended concept of 3E. In this perspective, e-mobility is electro-mobility, eco-mobility and economy-mobility. Such approach enables a comprehensive approach to the design of transport systems and technologies as well as multi-criteria analyses in terms of the economics and ecology as well as electrification of transport.

Adhering to the principles of eco-driving is not difficult. Because all the rules in accordance with the adopted "eco" driving philosophy are not forced and are minor habits. These rules are very natural for the driver. It should be remembered that regardless of advanced technologies and driver assistance systems, ultimately it is the human being who has the greatest adaptability to changing conditions and requirements [7]. Therefore, the impact of the driver on fuel consumption, traffic safety and even the emission of harmful substances (including noise) should not be underestimated. The ability to adjust the driving style to the current weather conditions, terrain gradeline, the technical capabilities of the vehicle and the weight of the transported loads is a key element determining fuel consumption. In addition, one should be aware that the traction efficiency of a car is not constant during its operation, but depends on individual assemblies and subassemblies of the vehicle and additional accessories (including peripheral ones) [8]. As the research [9] has shown, factors such as aggressive driving, high engine speeds, route selection, engine settings, tire maintenance, use of air conditioning, excessive idling, extra weight, or even the wrong engine oil can reduce fuel consumption up to 45%. Thus, eco-driving is a decision-making process that will affect the fuel consumption and emission intensity of the vehicle to reduce the negative impact on the environment [9].

Extensive research on the effectiveness of eco-driving awareness was conducted at the Transport Research Centre in Madrid [10]. The research covered 2 stages: before and after the training on the rules of driving in accordance with the eco-driving guidelines. The scope of tests included 718 vehicles, which covered a total of 8,014 km. During the tests, 128 driving parameters were recorded. Based on the results obtained, it was calculated that cars driven by drivers after training, in accordance with the principles of eco-driving, showed lower fuel consumption by 6.3% on average and lower CO_2 emissions by 6.3%. This, taking into account the short training cycle and the short period of research, should be considered very satisfactory results.

Development of a fuel consumption model

In order to evaluate the impact of parameters and driving style on fuel consumption, long-term studies were carried out. As part of own research, driving parameters of trucks constituting the fleet of one of the leaders in the forwarding and transport sector were recorded. During the tests, the cars carried out all orders in accordance with the accepted procedures, so the transport process covered all real stages. Full-truck loads (40 tons) were transported in accordance with the transport schedule, which also confirms that the obtained databases are representative samples. The period and scope of the research covered various routes, which makes it possible to take into account the impact of type of route, including the terrain gradeline, on the fuel consumption. In order to eliminate the influence of extremely different technical parameters of vehicles, it was decided to test one truck model in a group of vehicles of similar age.

Table 1 presents the actual data of the recorded driving parameters, which are a fragment of a comprehensive database.

Table 1. A fragment of the data subjected to the analysis. Own study.

ECO-distance	Total fuel consumption	Average fuel consumption	Average engine speed per minute	Average speed	Traveled distance using cruise control	Number of stoppages	Number of brakings	Number of emergency brake applications	Braking distance	Idling distance	Driving time without accelerator depressed	Retarder use duration
km	l	l/100km	RPM	km/h	km	#	#	#	m	km	%	%
8710,91	2 250,00	24,83	1040,48	72,90	3 984,53	907	3076	543	212263	1 301,77	2,11	5,54%
9887,83	3 062,50	27,84	1044,9	68,82	4 029,59	1139	1139	876	356156	1 094,62	2,38	2,49%
7833,94	1 052,02	28,26	1050,02	69,84	3 475,41	962	962	383	246503	907,56	2,47	5,34%
6963,71	1 986,50	28,53	1054,54	70,21	2 851,77	911	7119	997	299455	408,58	2,67	0,00%
10797,33	3 066,00	28,4	1060,75	70,23	5 057,67	1322	1322	620	349318	1 302,33	2,85	6,26%
11693,46	3 515,50	30,06	1062,84	68,46	4 253,80	1402	1402	1113	477833	1 505,67	2,98	2,66%
9804,39	1 064,32	28,06	1064,32	71,07	4 840,58	1168	7783	536	298185	1 125,47	3,3	6,09%
10701,10	3 203,00	29,93	1066,91	68,92	3 966,29	1271	11574	1026	420873	1 323,76	3,4	2,59%
7256,95	2 179,50	30,03	1068,66	66,21	2 984,81	986	6917	528	241773	1 303,07	3,44	0,00%
11454,89	3 629,00	31,68	1075,57	66,11	2 427,20	1114	1114	259	359174	1 918,57	3,54	4,77%
11771,95	3 281,50	27,88	1079,27	70,59	4 618,37	1054	1054	252	307639	1 767,94	3,56	3,95%
10928,87	3 116,00	28,51	1081,03	69,93	3 967,58	992	6341	251	302293	1 714,95	3,88	4,22%
8343,06	2 333,00	27,96	1090,34	69,62	3 836,71	853	4267	426	159071	946,19	4,03	3,61%
8736,02	1 093,13	25,8	1093,13	71,35	3 589,15	1109	3474	559	114267	981,68	4,13	4,43%
4734,80	1400,50	29,58	1093,32	61,87	1 160,23	1044	3401	462	81022	1 047,01	4,16	4,34%
8116,65	2306,50	28,42	1096,22	69,82	5 063,04	777	4262	212	153393	843,30	4,23	5,20%
7296,28	1 096,53	29,9	1096,53	68,70	2 115,10	873	5237	566	277391	620,56	4,48	2,55%
10547,95	2 846,50	26,99	1097,97	68,71	2 547,11	1134	8147	674	244477	1 279,09	4,48	8,28%

The objective of the analysis of the results was to develop a statistical model of fuel consumption. The classic least squares method (CLSM) was used, which enables the analysis of the significance coefficients of the model parameters as a result of the evaluation of the estimation coefficients and the correlation of empirical and model data. This procedure in subsequent iterations is the basis for the elimination of subsequent parameters in order to select the dominant statistical determinants. The method of least squares allows to estimate and draw trend-lines from a dataset. It is most commonly used with linear regression. As a result of the applied approach, a specific statistical model of fuel consumption was obtained as a combination of the fuel consumption approximation function depending on the driving parameters reduced by the CLSM.

As part of the analysis, subsequent models were defined by parameterizing them with the data recorded during the tests, depending on the average fuel consumption. In subsequent iterations of the analysis, the model was optimized by eliminating one parameter each time. The decision criterion in each case was the *p* coefficient as an estimator of the significance level, i.e. the impact on the dependent variable, in this case on fuel consumption. As a result of subsequent iterations of the CLSM, the fuel consumption model was defined as a complex function of the dominant statistical determinants.

For the models, the values of the linear regression coefficient, standard error, *t*-Student distribution coefficient and *p*. significance coefficient were determined each time. The coefficient of determination R^2 was used as a measure of matching the model to the empirical data. Based on these values, subsequent independent variables were eliminated.

The results obtained are presented in Table 2.

Table 2. The results of the CLSM estimation in the first iteration (10 parameters) – model 1

Parameter	linear regression coefficient	standard error	Student's *t*- coefficient	*p* coefficient
const.	22,23794	6,16505	3,607100	0,001041
Average RPM	0,00688	0,00424	1,620282	0,114986
Average speed	-0,04702	0,04803	-0,978976	0,334935
Distance travelled using cruise control	0,00017	0,00010	1,639987	0,110803
Number of stoppages	0,00048	0,00125	0,385610	0,702337
Number of brakings	-0,00018	0,00007	-2,728134	0,010257
Number of emergency brake applications	-0,00026	0,00086	-0,304267	0,762895
Braking distance	0,00000	0,00000	1,062696	0,295874
Idling distance	-0,00038	0,00049	-0,780900	0,440600
Driving time without accelerator depressed	0,30864	0,04500	6,858185	0,000000
Retarder use duration	-4,41177	8,77549	-0,502738	0,618591

For model 1 (Table 2) R^2 determination coefficient is 0.8263, which was assumed as a satisfactory Matching of the model to the empirical data. The largest value of the coefficient p is 0.762895 for the parameter "Number of emergency brake applications", which means the smallest impact on the dependent variable, i.e. average fuel consumption. Therefore, in the next iteration, we eliminate this parameter and perform the CLSM algorithm for the 9-parameter model.

Table 3. The results of the estimation of the CLSM in the second iteration (9 parameters) – model 2

Parameter	linear regression coefficient	standard error	Student's *t*- coefficient	*p* coefficient
const.	22,642014	5,936965	3,813736	0,000569
Average RPM	0,006723	0,004156	1,617751	0,115237
Average speed	-0,050213	0,046219	-1,086426	0,285163
Distance travelled using cruise control	0,000173	0,000099	1,758779	0,087886
Number of stoppages	0,000280	0,001043	0,268043	0,790334
Number of brakings	-0,000185	0,000062	-2,996952	0,005147
Braking distance	0,000002	0,000002	1,035651	0,307895
Idling distance	-0,000305	0,000413	-0,737222	0,466197
Driving time without accelerator depressed	0,307944	0,044323	6,947759	0,000000
Retarder use duration	-3,940541	8,518158	-0,462605	0,646684

For the model 2 (Table 3), the R^2 determination coefficient is 0.8258, which was assumed as a satisfactory matching of the model to the empirical data. The largest value of the p coefficient is 0.790334 for the parameter "Number of stoppages", which means the smallest impact on the dependent variable, i.e. average fuel consumption. Therefore, in the next iteration, we eliminate this parameter and perform the CLSM algorithm for the 8-parameter model.

Consecutive analogous iterations enable optimization of the model by eliminating subsequent less significant parameters.

Finally, as a result of the analysis conducted, a 6-parameter optimal model was obtained, presented in Table 4. As can be seen, despite the simplification of the model and the elimination of as many as 4 parameters, the matching coefficient is satisfactorily good (R^2 is 0,8197).

Table 4. The final results of the CLSM estimation in the fifth iteration (6 parameters) – final model

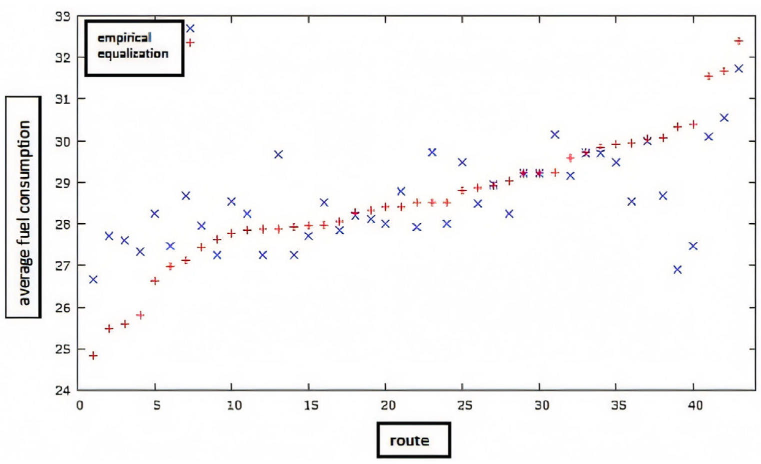
Parameter	linear regression coefficient	standard error	Student's *t*- coefficient	*p* coefficient
const.	22,307021	4,275597	5,217288	0,000008
Average RPM	0,006234	0,003725	1,673453	0,102907
Average speed	-0,038906	0,034195	-1,137775	0,262731
Distance travelled using cruise control	0,000146	0,000090	1,618140	0,114362
Number of brakings	-0,000181	0,000059	-3,092934	0,003817
Braking distance	0,000002	0,000001	1,268140	0,212888
Driving time without accelerator depressed.	0,308573	0,040547	7,610306	0,000001

The optimal model obtained was verified on real data. This was done by comparing randomly selected real data of the average fuel consumption with the values calculated based on the mathematical model obtained. The actual data came from the vehicle monitoring system (collected in the database of the tested company), while the estimated data came from the calculations based on the statistical model, the parameters of which are shown in Table 4. When estimating fuel consumption, only 6 reduced driving parameters, recorded during the full driving cycle, were entered into the complete test cycle (Table 1). The results are presented as absolute differences and as percentages. A partial list is presented in Table 5.

Table 5. Summary of empirical and model fuel consumption, along with differential values.

No.	Average fuel consumption – actual (P_r) [l/100km]	Average fuel consumption – model (P_m) [l/100km]	Difference between the values $P_r – P_p$ [l/100km]	Percentage difference ($P_r – P_p$)/ P_r [%]
1	24,8297	26,6596	-1,82992	7%
2	27,84	28,2453	-0,405254	1%
3	28,2616	28,1835	0,0781338	0%
4	28,5265	28,0097	0,516755	2%
5	28,3959	28,0117	0,3842	1%
6	30,0638	28,6777	1,38614	5%
7	28,0589	27,8546	0,20432	1%
8	29,9315	28,5432	1,38825	5%
9	30,0333	29,9989	0,034365	0%
10	31,6808	30,5562	1,12464	4%
11	27,8756	29,6618	-1,78619	6%
12	28,5116	29,7091	-1,19746	4%
13	27,9634	28,5271	-0,563705	2%
14	25,8	27,3231	-1,52308	6%
15	29,5789	29,1534	0,425544	1%
16	28,4169	28,7939	-0,376944	1%
17	29,9	29,4663	0,433738	1%
18	26,9863	27,4619	-0,475622	2%
19	26,644	28,249	-1,60498	6%
20	28,9111	28,9299	-0,0187372	0%
21	29,2077	29,2134	-0,0056759	0%
22	30,4009	27,461	2,93988	8%
23	27,43	27,9424	-0,512378	2%
24	25,47	27,7006	-2,23057	9%
25	28,5	27,9326	0,56738	2%
26	31,5479	30,0975	1,45047	5%
27	27,7528	28,5429	-0,790132	3%
28	28,8513	28,4963	0,355001	1%
29	28,3307	28,1233	0,207339	1%
30	30,3318	26,909	3,42273	9%
31	29,0302	28,2393	0,790934	3%
32	27,9455	27,7044	0,241086	1%
33	27,8577	27,247	0,610716	2%
34	27,9332	27,2462	0,686997	2%

Fig. 3. Distribution of the values of the actual average fuel consumption (empirical) and the values determined based on the model developed (equalizing).



Summary

The principles related to eco-driving and the assumptions of designers of systems used in vehicles are often based on theoretical axioms and observations. Of course, in the field of technologies and systems supporting an economical driving style, everything is preceded by simulation studies or laboratory experiments. The article presents the results of real tests and the procedure for estimating fuel consumption determinants and developing an analytical statistical model using the least squares method. An analysis of the significance of parameters affecting fuel consumption based on statistical modelling was carried out. The results obtained allowed to development of an optimal model, and the verification showed an average absolute error of 3%. Taking into account the amount of data available and the lack of additional information affecting fuel consumption, such as weather conditions, terrain gradeline, technical condition of the vehicle or tire pressure. the designated model and the results obtained should be considered satisfactory.

However, further research is needed to obtain more data, for more truck models, and route, weather and vehicle condition data to determine the overall model.

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