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Theoretical Evaluation of Relationships Between Tyre Energy Efficiency Class and Fuel Consumption of a Passenger Car According to NEDC

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Summary. The paper presents the simulation analysis determining the effect of tyre energy efficiency class on fuel consumption of a passenger car. Calculations were made assuming the wheel movement on a dry and smooth asphalt road surface. The tests based on a simulation model were performed on 61 types of tyres, being characterised by different sizes and energy efficiency classes. Different values of rolling resistance coefficient were adopted (in accordance with energy efficiency classes), also, the values of basic and additional resistance to motion were determined. Based on them, engine speeds and load torque corresponding to respective specific fuel consumption were estimated. This parameter allowed the relationship between average mileage fuel consumption and tyre energy efficiency class to be determined on the basis of the NEDC test.

Key words: passenger car, tyre energy efficiency class, fuel consumption.

INTRODUCTION

Fuel consumption is an operating parameter that defines the energy efficiency of a vehicle and the value of this usable indicator being measured under real conditions often varies from that provided by a car manufacturer [7]. Car makers manufacturing a specific range of vehicles conduct determination of fuel consumption under chassis dynamometer conditions (within approval tests). Experiments provide an initial forecast that refers, among others, to emission of toxic compounds and are based on a specific type of dynamometer test, during which the level of exhaust gas and the percentage of respective toxic compounds from the exhaust system are checked. On that basis, fuel consumption is calculated. Under European conditions, the test being applied in determination of this operating parameter is NEDC (New European Driving Cycle) test, which is composed of two sub-cycles: UDC (Urban Driving Cycle) and EUDC (Extra-Urban Driving Cycle) (Fig. 1) [12].

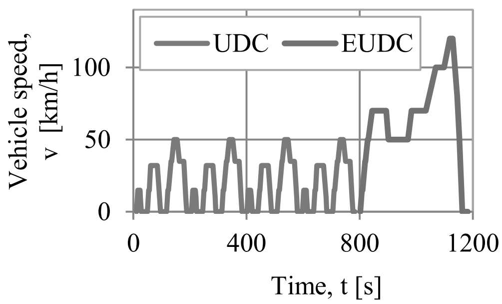

Fig. 1. European mixed driving cycle NEDC [12]

In 1990-2007, overall fuel consumption by vehicles in Europe was characterised by an increase due to increased car sales for individuals (over 53%). To 2011, the usable indicator under discussion decreased by almost 5% because passenger cars could travel ever greater distances and manufacturers introduced a number of modern technological developments including, among others, downsizing and downspeeding of drive units, production of hybrid and electric models, use of alternative fuels, etc. The reduction of fuel consumption also contributed to carbon dioxide emission reductions (Fig. 2) [4].

Negative environmental impact of road transport drive units is responsible for 23% of total CO_2 emission, therefore a reduction of vehicles' energy intensity and emissions has become a major challenge for the European Union [3]. Regulation (EC) No. 443/2009 of the European Parliament and of the Council of 23 April 2009 referring to passenger cars and light-duty vehicles has set down a reduction of this compound emission in 2015 for a moderately new passenger car fleet to 130 g/km (which is equivalent to average fuel consumption of 5.1 dm^3/100 km). The legal act has also set a minimisation of average emission to the value of 95 g/km after 2020 (3.7 dm^3/100 km) [14].

One of the significant parameters affecting fuel consumption and carbon dioxide emission is rolling resistance, the percentage of which can even reach more than 40% of all resistance to motion, mainly in urban traffic (Fig. 3), therefore the attempts to reduce it are well-founded [18].

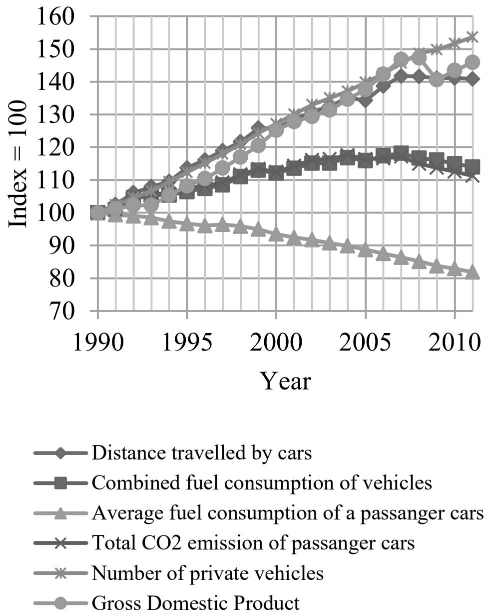

Fig. 2. Trends in fuel consumption and carbon dioxide emission for passenger cars [4]

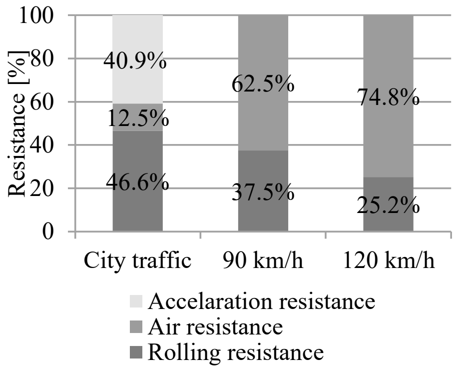

Fig. 3. The proportion of particular forms of resistance to motion of a passenger car [18]

Lower value of rolling resistance coefficient has been applied in the construction of modern tyres. Taghavifar and Mardani [17] have proved that this parameter depends on the vertical load acting on wheels. In the papers [5, 11], the coefficient of rolling resistance has been determined from the following relationship:

$$c_r = \frac{F_r}{L} = \frac{F_r}{m \cdot g}, \tag{1}$$

where:
c_r – rolling resistance coefficient,
F_r – rolling resistance [N],
L – tyre load [N],
m – vehicle weight [kg],
g – gravitational acceleration [m/s²].

There were developmental trends in passenger car tyre construction to reduce rolling resistance coefficient. The average values of this parameter for the tyres being manufactured since 1982 decreased from 0.011 to 0.0099 in 2005 (EPA, Ecos, RMA tests) [9, 13].

In the study by Ejsmond, Ronowski and Wilde [5], these trends have been confirmed, with the highest value reached amounting to 0.019 and the minimum value being about 0.006. These results have been reflected in the report [8].

The studies by Burges and Choi [2] and Holmberg, Anderson and Erdemir [9] have shown that the measure consisting in a reduction of rolling resistance by 10% was responsible for a 2% reduction of energy demand. This was the main reason for implementation of the Regulation (EC) of the European Parliament and of the Council on labelling of tyres with respect to fuel efficiency and other essential parameters [15].

As a result of the above legal act, tyre manufacturers have been obliged since 2008 to inform users about the energy efficiency class of tyres.

Difference in fuel consumption between the vehicles equipped with a set of class G tyres may be 7.5% in relation to Class A ones [15, 16].

The data on a difference in fuel economy between particular tyre energy efficiency classes have not been clearly presented, therefore the authors have undertaken to investigate this subject.

STUDY OBJECTIVE

This study aimed at analysing the value of fuel consumption of a vehicle equipped with tyres with different values of rolling resistance coefficient (energy efficiency classes). The main assumption was the wheels' movement on a dry, smooth asphalt road surface.

TEST OBJECTS, SIMULATION MODEL AND TEST METHODS

Test objects were the tyres of the world's leading manufacturers, which include the following companies: Bridgestone, Continental, Dunlop, Goodyear and Michelin. The tyres were characterised by different energy efficiency classes, from A to G, and sizes, from 155/80R13 to 205/75R15. The graphs showing the number of tested tyres of manufacturers given above, together with respective energy efficiency classes, are presented in Figures 4 and 5.

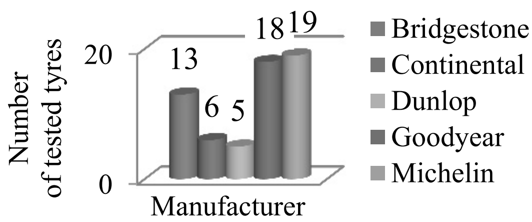

Fig. 4. The number of tested tyres according to manufacturer

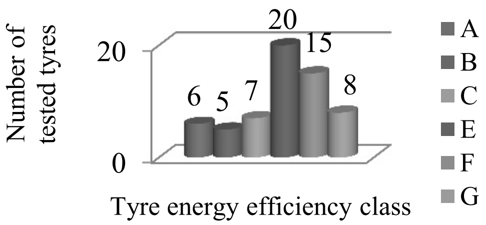

Fig. 5. The number of tested tyres according to energy efficiency class

Different number of the tested tyres of respective manufacturers and energy efficiency classes resulted from their greater availability on the global car market. The tested sample was 61 tyres and was representative of the whole population, consisting of hundreds of available passenger car tyres [8].

Experiments were conducted with a simulation model allowing for the construction parameters of tyres, including their size and energy efficiency class (Fig. 6). This way, the following elements were determined:

– values of basic resistance to motion (sum of rolling resistance and air resistance) for steady vehicle speeds being the components of UDC speed profile and the components of EUDC speed profile,
– values of the sum of basic and additional resistances to motion (rolling resistance and air resistance and inertial resistance, respectively) for the values of accelerations used in NEDC.

Respective vehicle speeds corresponded to engine rotational speeds, while the values of resistance to motion determined the load torque of a drive unit. Rotational speeds were determined on the basis of the following relationship [7, 8]:

$$v = \omega_W \cdot 0.47d = \frac{2\pi \cdot 0.47d \cdot n_W}{60},$$
$$v = \frac{2\pi \cdot 0.47d \cdot n}{60i} \rightarrow n = \frac{60 \cdot v \cdot i}{2\pi \cdot 0.47d}, \tag{2}$$

where:
v – vehicle speed [m/s],
w_W – angular velocity of wheels [1/s],
d – wheel outer diameter [m],
n_W – rotational speed of wheels [min^{-1}],
n – engine rotational speed [min^{-1}],
i – overall transmission ratio.

Using the relationship (3), engine load toque was determined:

$$T_{tq} = \frac{(F_r + F_d + F_I) \cdot 0.47d}{i \cdot \eta},$$

$$T_{tq} = \frac{(c_r \cdot m \cdot g + \frac{\rho_A}{2} \cdot c_d \cdot A \cdot v^2 + m \cdot a \cdot \delta) \cdot 0.47d}{i \cdot \eta}, \tag{3}$$

where:
c_r – rolling resistance coefficient,
m – vehicle weight [kg],
g – gravitational acceleration = 9.81 m/s²,
ρ_A – air density [kg/m³],
c_d – air resistance coefficient,
A – vehicle frontal area [m²],
δ – coefficient of rotating masses.

It should be emphasised that both engine rotational speed and its torque depended on vehicle technical parameters and motion conditions.

A vehicle being used to perform tests was a FIAT Panda passenger car equipped with a MultiJet 1.3 JTD engine. It is a compression-ignition turbocharged direct injection drive unit with electronically controlled Common Rail injection system, the basic technical parameters of which are presented in Tab. 3.

Specifying the resistance to motion and, as a consequence, the value of engine torque needed to overcome it, required the technical and operational characteristics of the vehicle to be used (Tab. 4).

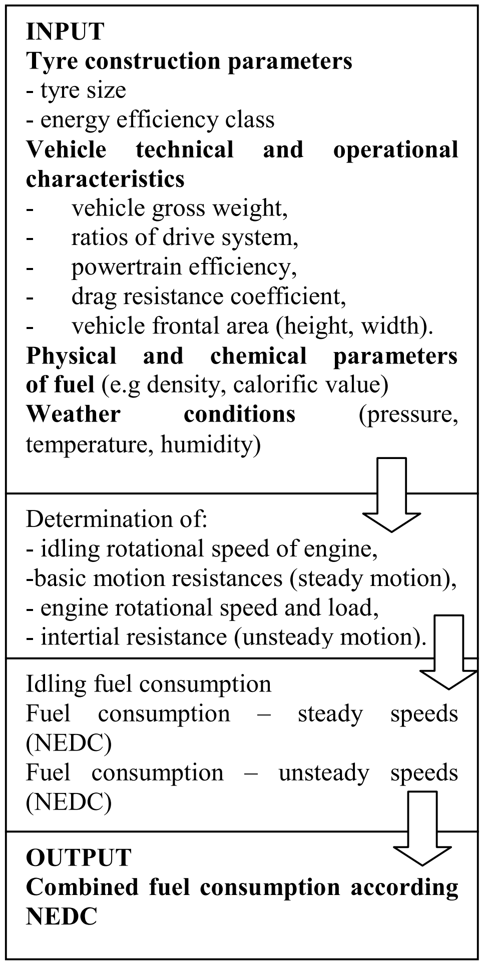

Fig. 6. Simulation model

Table 3. Basic technical parameters of FIAT MultiJet 1.3 JTD 16V engine [6]

Parameter	Unit	Value/ description
Cylinder diameter	[mm]	69.6
Piston stroke	[mm]	82
Compression ratio	-	18.1
Number of cylinders	-	4

Parameter	Unit	Value/ description
Arrangement of cylinders	-	in-line
Injection sequence	-	1-3-2-4
Engine cubic capacity	[cm³]	1248
Maximum power	[KM/kW]	70/51
Rotational speed at maximum power	[min⁻¹]	4000
Maximum torque	[Nm]	145
Rotational speed at maximum torque	[min⁻¹]	1750

Table 4. Basic technical data of FIAT Panda vehicle [6, 7]

Parameter	Unit	Value
Vehicle gross weight,	[kg]	1455
First gear ratio, i_{GI}	-	3.909
Second gear ratio, i_{GII}	-	2.158
Third gear ratio, i_{GIII}	-	1.345
Fourth gear ratio, i_{GIV}	-	0.974
Final drive ratio, i_{FD}	-	3.438
Powertrain efficiency, h	-	0.92
Air resistance coefficient, c_d	-	0.33
Vehicle frontal area, A	[m²]	2.19
Fuel density, ρ_F	[kg/dm³]	0.83

ENGINE LOAD CHARACTERISTIC CURVE

Figure 7 presents the load characteristic curve of a FIAT MultiJet 1.3 JTD 16V engine, which was made for selected rotational speeds of crankshaft (tyre size 155/80R13).

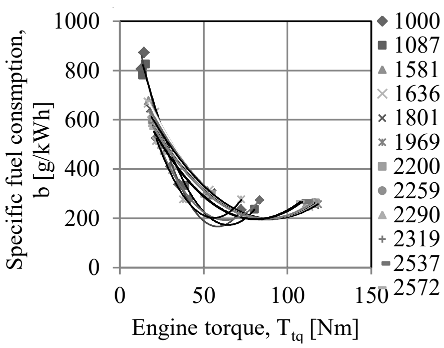

Fig. 7. The load characteristic curve of a FIAT MultiJet 1.3 JTD engine

This graph illustrates the relationship between specific fuel consumption and engine load torque for different rotational speeds of its operation. The characteristic curve was used to determine instantaneous fuel consumption for a vehicle.

INSTANTANEOUS FUEL CONSUMPTION FOR A VEHICLE

The profile of changes in speeds and accelerations defined the energy intensity of vehicle motion which was associated with a specific fuel consumption. Instantaneous fuel consumption was substantially affected by three factors which are taken into consideration in the following relationship [1, 6, 7]:

$$f_c = \alpha + \beta_1 + \beta_2 , \quad (4)$$

where:
α – instantaneous idling fuel consumption [mdm³/s],
β_1– instantaneous fuel consumption at constant speed [mdm³/s],
β_2– instantaneous fuel consumption at variable speed [mdm³/s].

Instantaneous fuel consumption for constant vehicle speeds (corresponding to constant engine rotational speeds) was calculated according to the following equation [1, 6, 7]:

$$\beta_1 = \frac{b \cdot (F_r + F_d)}{3600 \cdot 10^3 \rho_F \cdot \eta} \cdot v , \quad (5)$$

The application of relationship (5) to determine instantaneous fuel consumption for unsteady motion conditions with respect to the use of one gear required also the inclusion of inertial resistance. Then, the relationship took the following form [1,6,7]:

$$\beta_2 = \int_{v1}^{v2} \frac{b \cdot (F_r + F_d + F_I)}{3600 \cdot 10^3 \cdot \rho_F \cdot \eta} \cdot dv , \quad (6)$$

where:
v_1 – initial velocity [m/s],
v_2 – terminal velocity [m/s].

On the basis of combined instantaneous fuel consumption, a combined mileage fuel consumption was determined after taking into account the distance to be travelled by a vehicle.

EFFECT OF TYRE ENERGY EFFICIENCY CLASS ON COMBINED FUEL CONSUMPTION ACCORDING TO NEDC

The application of relationships (6) and (7) allowed the values of mileage fuel consumption to be estimated analytically for different models of the tested tyres according to UDC, EUDC and NEDC (Tab. 5). The values of rolling resistance coefficients were adopted based on the data being presented in literature [8, 13].

Based on the obtained results, the dependence of average fuel consumption (determined for a vehicle weight being equal to 1050 and 1455 kg) on energy efficiency class of the tested tyres according to UDC was showed (Fig. 8).

The graph shows two straight lines corresponding to vehicle weight of 1050 and 1455 kg. Greater gross vehicle weight caused the engine to operate in the higher area of fuel consumption. Maximum fuel economy being described as a difference between fuel consumption for energy efficiency class G and that for energy efficiency class A was equal to 8.56%. The difference in this operating indicator (mean values) between respective energy efficiency classes is as follows: B-A = 1.57%, C-B = 1.63%, E-C = 1.71%, F-E = 1.67%, and G-F = 1.98%.

The values of expanded standard measurement uncertainties for different vehicle weights overlapped almost for

Table 5. Fuel consumption for different tyre types

Tyre type	Vehicle weight [kg]	1050	1455	1050	1455	1050	1455
	Driving cycle type	UDC		EUDC		NEDC	
	Tyre rolling resistance coefficient	Fuel consumption [dm³/100 km]					
	c_r	Energy efficiency class A					
Bridgestone class A 155/80R13	0.00650	5.46	5.71	3.89	4.08	4.46	4.67
Bridgestone B381 185/70R14	0.00615	5.43	5.68	3.87	4.05	4.44	4.65
Continental class A 155/80R13	0.00630	5.44	5.70	3.88	4.06	4.45	4.66
Dunlop class A 155/80R13	0.00650	5.46	5.71	3.89	4.08	4.46	4.67
Goodyear class A 155/80R13	0.00640	5.45	5.70	3.89	4.07	4.46	4.67
Michelin class A 155/80R13	0.00640	5.45	5.70	3.89	4.07	4.46	4.67
	c_r	Energy efficiency class B					
Bridgestone B391 155/80R13	0.00715	5.51	5.77	3.93	4.11	4.51	4.72
Bridgestone Insignia SE 200 89S 195/65R15	0.00760	5.54	5.80	3.95	4.14	4.53	4.75
Continental Ecocontact 5 205/55R16	0.00770	5.55	5.81	3.95	4.14	4.54	4.75
Goodyear Efficientgrip Performance 205/55R16	0.00750	5.54	5.79	3.95	4.13	4.53	4.74
Michelin EnergySaver + 205/55R16	0.00740	5.53	5.79	3.94	4.13	4.53	4.74
	c_r	Energy efficiency class C					
Dunlop SP Wintersport 155/80R13	0.0083	5.60	5.86	3.99	4.18	4.58	4.79
Continental ContiWintCont 165/65R14	0.00850	5.61	5.88	4.00	4.19	4.59	4.81
Continental ContiTouring Contact CH95 205/55R16	0.00825	5.60	5.86	3.99	4.18	4.58	4.79
Michelin Tiger Paw AWP 185/70R14	0.00875	5.63	5.90	4.02	4.21	4.61	4.82
Michelin Energy MXV4 Plus 205/55R16	0.00900	5.65	5.92	4.03	4.22	4.62	4.84
Michelin Pilot Alpine 205/55R16	0.00900	5.65	5.92	4.03	4.22	4.62	4.84
Michelin Steel Belted Radial 205/75R15	0.00864	5.63	5.89	4.01	4.20	4.60	4.82
	c_r	Energy efficiency class E					
Bridgestone Blizzak WS-50 185/70R14	0.01030	5.75	6.02	4.10	4.30	4.71	4.93
Bridgestone Insignia SE 200 85S 185/65R14	0.01020	5.90	6.17	4.06	4.25	4.70	4.92
Bridgestone Insignia SE 200 92S 205/65R14	0.00950	5.69	5.96	4.06	4.25	4.66	4.87
Dunlop SP 40 A/S 185/70R14	0.01028	5.75	6.02	4.10	4.30	4.71	4.92
Dunlop SP Wintersport M2 205/55R16	0.01020	5.75	6.01	4.10	4.29	4.70	4.92
Dunlop Graspic DS-1 185/70R14	0.00920	5.69	5.95	4.04	4.23	4.64	4.85
Goodyear Eagle RS A 205/55R16	0.00918	5.67	5.93	4.04	4.23	4.64	4.85
Goodyear Integrity 185/70R14	0.00968	5.71	5.97	4.07	4.26	4.67	4.88
Goodyear Integrity 195/65R15	0.00955	5.90	6.17	4.06	4.25	4.66	4.88
Goodyear Integrity 195/70R14	0.00978	5.90	6.17	4.08	4.27	4.67	4.89
Goodyear Integrity 205/70R15	0.00965	5.70	5.97	4.07	4.26	4.67	4.88
Goodyear Integrity 205/75R15	0.00946	5.69	5.95	4.06	4.25	4.65	4.87
Goodyear VIVA2 185/70R14	0.01040	5.76	6.03	4.11	4.30	4.71	4.93
Michelin Control Plus 175/70R13	0.01040	5.76	6.03	4.11	4.30	4.71	4.93
Michelin Control Plus 195/70R14	0.00995	5.73	5.99	4.09	4.28	4.68	4.90
Michelin E3B1 155/80R13	0.00960	5.70	5.97	4.07	4.26	4.66	4.88
Michelin Pilot Sport Cup 205/55R16	0.00923	5.67	5.94	4.05	4.23	4.64	4.85
Michelin Steel Belted Radial 195/70R14	0.00948	5.69	5.96	4.05	4.24	4.65	4.87
Michelin Symmetry 185/65R14	0.00982	5.72	5.98	4.08	4.27	4.68	4.89
Michelin Symmetry 205/70R15	0.00939	5.90	6.17	4.05	4.24	4.65	4.87
	c_r	Energy efficiency class F					
Bridgestone Affinity LH30 185/65R14	0.01160	5.86	6.13	4.18	4.37	4.79	5.01
Bridgestone Potenza RE92 185/70R14	0.01065	5.78	6.05	4.12	4.32	4.73	4.95
Bridgestone Turanza LS-H 205/55R16	0.01085	5.80	6.07	4.14	4.33	4.74	4.96
Bridgestone Turanza LS-T 185/70R14	0.01093	5.80	6.07	4.14	4.33	4.75	4.97
Continental Eco 3 155/80R13	0.01110	5.82	6.09	4.15	4.34	4.76	4.98
Goodyear Aquatred 3 185/70/R14	0.01133	5.84	6.11	4.16	4.36	4.77	4.99
Goodyear Comfortread 195/65R15	0.01139	5.84	6.11	4.17	4.36	4.78	5.00
Goodyear Eagle F1 GS-D3 205/55R16	0.01115	5.82	6.09	4.15	4.35	4.76	4.98
Goodyear Integrity 175/65R14	0.01160	5.86	6.13	4.18	4.37	4.79	5.01
Goodyear Regatta 185/70R14	0.01078	5.79	6.06	4.13	4.32	4.74	4.96

Goodyear Sp Sport A2 SL 205/55R16	0.01133	5.84	6.11	4.14	4.33	4.77	4.99
Michelin Cientra Plus 205/65R13	0.01093	5.80	6.07	4.14	4.33	4.75	4.97
Michelin Harmony 185/70R14	0.01073	5.79	6.06	4.13	4.32	4.73	4.95
Michelin Pilot Sport 205/55R16	0.01110	5.82	6.09	4.15	4.34	4.76	4.98
Michelin Symmetry 185/70 R14	0.01083	5.19	5.43	4.13	4.33	4.74	4.96
	c_r	Energy efficiency class G					
Bridgestone Affinity LH30 195/65R15	0.01260	5.93	6.21	4.23	4.43	4.85	5.08
Bridgestone Firehawk SZ50EP 205/55R16	0.01203	5.90	6.17	4.20	4.40	4.82	5.04
Continental class G 155/80R13	0.01210	5.90	6.17	4.20	4.40	4.82	5.05
Goodyear Eagle GT II 205/55R16	0.01210	5.90	6.17	4.20	4.40	4.82	5.05
Goodyear Integrity 185/65R14	0.01278	5.95	6.23	4.24	4.44	4.86	5.09
Goodyear Regatta 2 195/65R15	0.01253	5.93	6.21	4.23	4.43	4.85	5.07
Michelin Cientra Plus 175/70R13	0.01305	5.97	6.25	4.26	4.46	4.88	5.11
Michelin Pilot Sport 205/55R16	0.01328	5.99	6.27	4.27	4.47	4.90	5.12

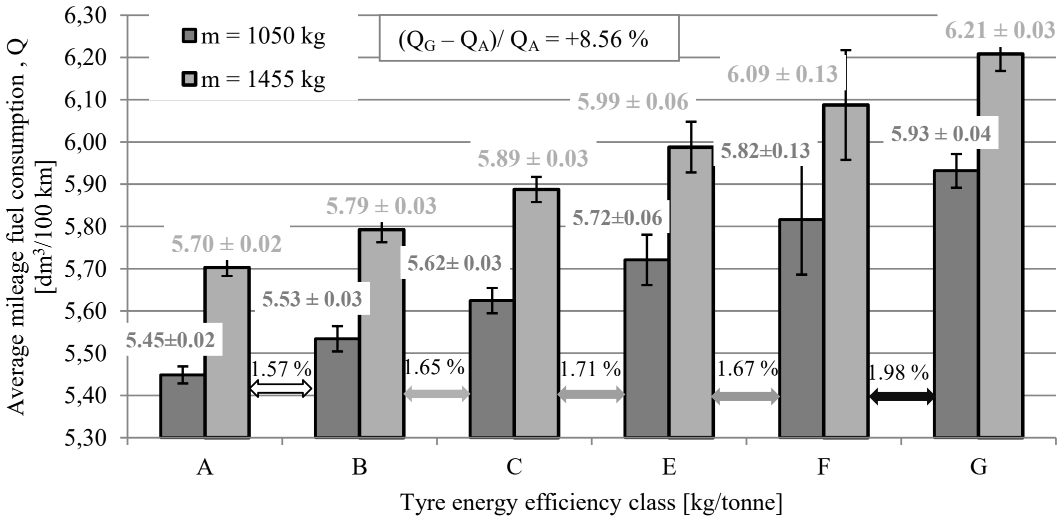

Fig. 8. Differences between mileage fuel consumption for energy efficiency class of the tested tyres (mean values with measurement uncertainties) according to UDC at m = 1050 kg and 1455 kg

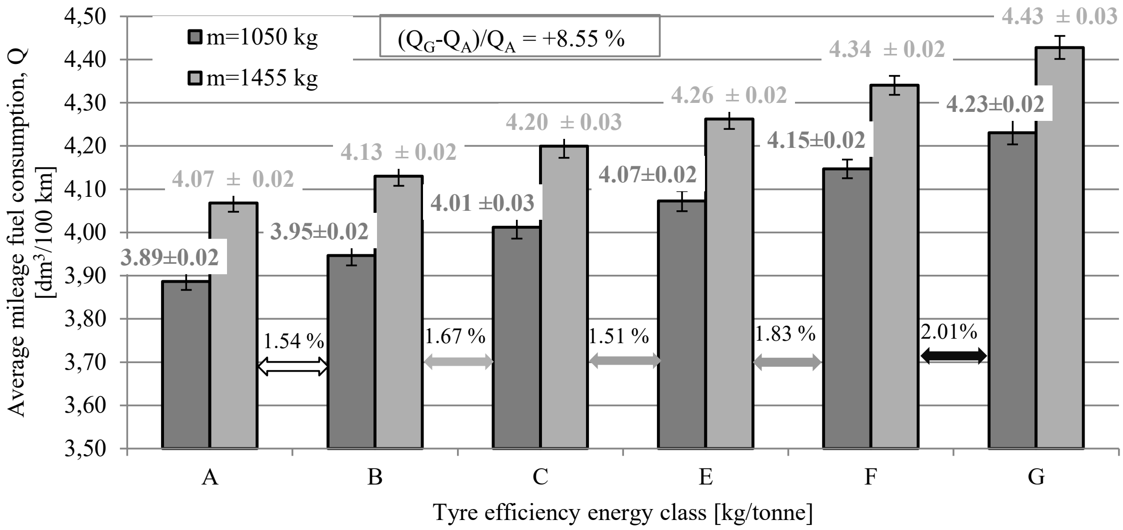

Fig. 9. Percentage differences between mileage fuel consumption for energy efficiency class of the tested tyres (mean values with measurement uncertainties) according to EUDC at m = 1050 kg and 1455 kg

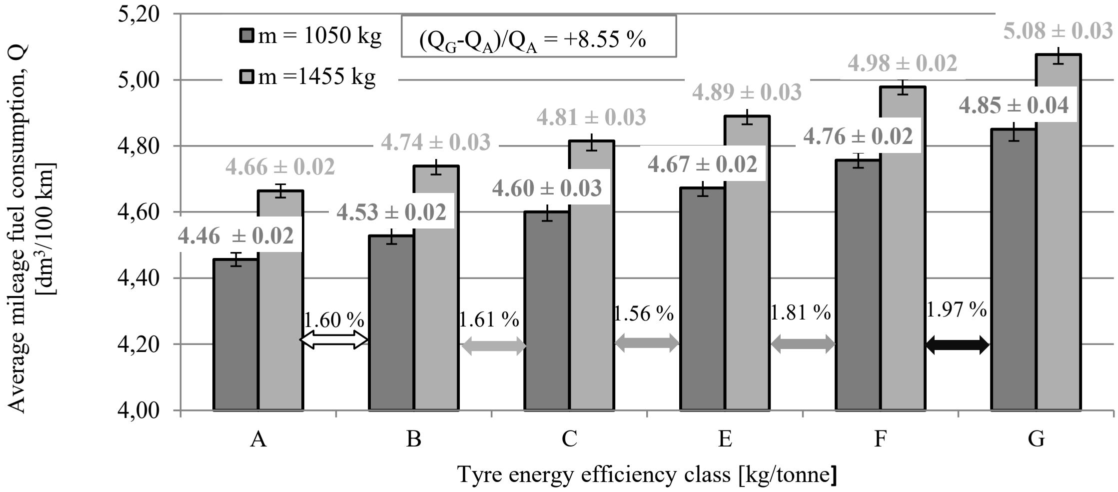

Fig. 10. Percentage differences between average mileage fuel consumption for energy efficiency class of the tested tyres (mean values with measurement uncertainties) according to NEDC (for vehicle weight m = 1050 kg and 1455 kg)

all cases (with a difference for energy efficiency class G). The largest measurement uncertainty amounted to 0.13 dm³/100 km (for energy efficiency class F) and corresponded to the error of 2.2 % (for vehicle weight being equal to 1050 kg) and 2.1 % (for vehicle weight equal to 1455 kg – fig.8).

Figure 9 presents the dependence of average fuel consumption (being determined for vehicle weight equal to 1050 and 1455 kg) on energy efficiency class of the tested tyres according to EUDC.

The graph presents two straight lines corresponding to vehicle weight of 1050 and 1455 kg. Greater gross vehicle weight caused the engine to operate in the higher area of fuel consumption. Maximum fuel economy being described as a difference between fuel consumption for energy efficiency class G and that for energy efficiency class A was equal to 8.55%. The difference in this operating indicator (mean values) between respective energy efficiency classes is as follows: B-A = 1.54%, C-B = 1.67%, E-C = 1.51%, F-E = 1.83%, and G-F = 2.01%. The values of expanded standard measurement uncertainties for different vehicle weights overlapped for all cases (with a difference for energy efficiency class G). The largest measurement uncertainty amounted to 0.03 dm³/100 km (for energy efficiency class C) and corresponded to the error of 0.7%.

Figure 10 presents the dependence of average fuel consumption (being determined for vehicle weight equal to 1050 and 1455 kg) on energy efficiency class of the tested tyres according to EUDC.

Based on the characteristic curve on Figure 10, it is possible to state that maximum fuel economy was equal to 8.55%. The difference in this operating indicator (mean values) between respective energy efficiency classes is as follows: B-A = 1.60%, C-B = 1.61%, E-C = 1.56%, F-E = 1.81%, and G-F = 1.97%. The values of expanded standard measurement uncertainties for different vehicle weights overlapped for all cases (with a difference for energy efficiency class B, E and G). The largest measurement uncertainty amounted to 0.04 dm³/100 km (or energy efficiency class G) and corresponded to the error of 0.8%.

CONCLUSIONS

Based on the conducted analysis, it is possible to state, that differences in fuel economy between respective energy efficiency classes result directly from the type of tested driving cycle, i.e. from the percentages and times of the resistances to motion being considered. Small values of measurement uncertainties may be evidence of a high precision of calculations. The obtained results are of the applicative nature for modern vehicles with compression-ignition engines with small cubic capacity which are equipped with Common Rail injection system. It should be emphasised, however, that the nature of mileages on the graphs presenting the dependence of mileage fuel consumption on tyre energy efficiency class was similar for passenger cars with different drive units, including those with differing fuel supply systems.

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TEORETYCZNA OCENA ZALEŻNOŚCI POMIĘDZY KLASĄ ENERGETYCZNĄ OPONY A ZUŻYCIEM PALIWA SAMOCHODU OSOBOWEGO WEDŁUG CYKLU NEDC

Streszczenie. Artykuł prezentuje wpływ poszczególnych klas energetycznych opon na zużycie paliwa określone według cyklu NEDC.

Badaniom symulacyjnym zostały poddane różne typy ogumienia wiodących producentów światowych.

Wykazano, że stosując opony o klasie energetycznej A zamiast klasy energetycznej G zużycie paliwa według cyklu NEDC może być niższe nawet o 8,55 %.

Słowa kluczowe: przebiegowe zużycie paliwa, samochód osobowy, klasy energetyczne opon.