ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/12314005.1165664

IMPACT OF OUTER DIAMETER AND ENERGY EFFICIENCY CLASS OF TYRE ON FUEL CONSUMPTION OF A PASSENGER CAR AT CONSTANT VELOCITY

Wawrzyniec Gołębiewski

West Pomeranian University of Technology
Department of Automotive Engineering
Piastów Avenue 19, 70-310 Szczecin, Poland
tel.: +48 91 4494045
e-mail: wawrzyniec.golebiewski@zut.edu.pl

Abstract

This paper presents the simulation analysis determining the effect of wheel outer diameter and energy efficiency class of tire on fuel consumption of a passenger car. Calculations were made assuming the wheel movement on a dry, smooth road surface under set driving conditions. Tests objects were three tyre types of the following sizes: 155/80R13, 165/65R14 and 185/55R14 (provided by the manufacturer of a FIAT Panda vehicle). For testing, a simulation model was used allowing for tyre construction parameters (outer diameter and energy efficiency class). Different values of rolling resistance coefficient were adopted (in accordance with energy efficiency classes) and the values of basic resistance to motion (therefore the sums of rolling resistance and air resistance) were determined for vehicle speeds equal to 15 km/h, 32 km/h, 35 km/h and 50 km/h (being the components of UDC speed profile) and for 70 km/h, 100 km/h and 120 km/h (being the components of EUDC speed profile). Based on the parameters describing a vehicle, motion conditions and tyre sizes, the values of engine rotational speed and load torque were determined. For these parameters, the values of mileage fuel consumption were read. Based on the conducted analysis, it was concluded that fuel consumption for a set vehicle speed was little affected by wheel outer diameter but significantly affected by tyre energy efficiency class. The increase of wheel outer diameter (in accordance with manufacturer's information) induced a small decrease in fuel consumption. The use of high-energy efficiency class (A), in relation to lowest efficiency class (G), allowed the fuel economy even to a dozen or so percent.

Keywords: *wheel outer diameter, tyre energy efficiency class, fuel consumption*

1. Introduction

The transport sector is one of the major segments of the global market contributing to the greenhouse effect. Limitation of greenhouse gas emissions by the European Commission suggests a reduction of average CO_2 emission (and fuel consumption associated with it) for passenger cars to a level of 130 g/km (5.1 dm^3/100 km) in 2015, but also a minimisation of average emission to the value of 95 g/km (3.7 dm^3/100 km) after 2021 [2, 5]. There are different ways of achieving these assumptions – by applying more efficient powertrains and reduced cubic capacity engines with unchanged power (downsizing) or using hybrid vehicles, alternative fuels or all types of electric vehicles.

Another area of interest is reduction of road load that is the forces acting on a car during motion, such as air resistance and rolling resistance. The rolling resistance may even reach over 40% of all resistance to motion (particularly in urban traffic – Fig. 1); hence, the attempts to reduce it are well-founded [14]. Lower value of rolling resistance coefficient significantly reduces fuel consumption and carbon dioxide emissions [13], and it is used in the construction of modern tyres.

The coefficient of rolling resistance is being described by the following relationship [4]:

$$c_r = F_R/L, \tag{1}$$

where: c_r – rolling resistance coefficient, F_R – rolling resistance force, L – tyre load.

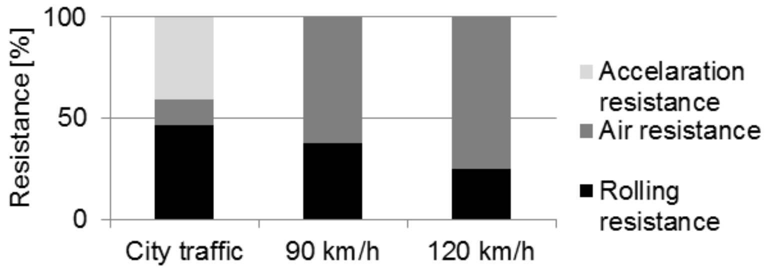

Fig. 1. The proportion of particular resistances of a passenger car resistance [14]

In the 1980s and 1990s, there were developmental trends in car tyre construction to reduce rolling resistance coefficient (Fig. 2).

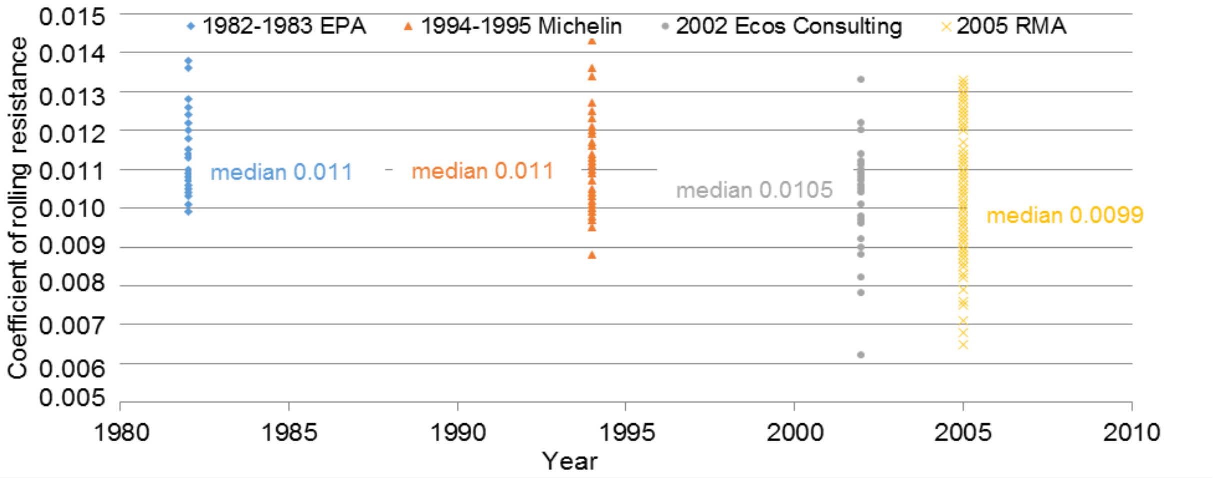

Fig. 2. The value of rolling resistance coefficient for the resistance of a passenger car being manufactured in 1982-2005 [9]

Testing of the values of this parameter for new tyres has been conducted by government agencies (EPA), private consulting companies (Ecos) and tyre manufacturers (Michelin, RMA – a committee of three major tyre manufacturers: Michelin, Goodyear and Bridgestone), with average values of rolling resistance coefficient for the tyres produced since 1982 being reduced from 0.011 to 0.0099 in 2005 [9]. The lowest value of tyre rolling resistance coefficient has been also confirmed in Green Seals Inc. Report [8], as it amounted to about 0.006.

The values of these coefficients are confirmed by the study conducted for several types of tyres interacting with different types of road surface in Europe, reaching the highest value of rolling resistance coefficient amounting to 0.019 and the minimum value of about 0.006 [4].

Implementation of the Directive of the European Parliament and of the Council on the labelling of tyres with respect to fuel efficiency has obliged tyre manufacturers to inform users about the energy efficiency class of sold tyres being evidence of their value of rolling resistance coefficient (Tab. 1). Class A corresponds to the lowest value of this parameter, whereas class G is characterised by its highest value [7, 13]. The percentage of fuel economy resulting from the use of tyres with energy efficiency class higher than G refers to currently used tyres in motor vehicles, which are radial tyres.

Tab. 1. Tyre energy efficiency classes [7]

Class	A	B	C	D	E	F	G
Rolling resistance [kg/tonne]	<6.6	6.6 to 7.7	7.8 to 9.0	Not used	9.1 to 10.5	10.6 to 12.0	>12.0

The construction element of radial tyre is also its marking. Such tyre parameters as tyre size, manufacturer's name, approval mark, type of vehicle, speed symbol, tread pattern marking, carcass material marking, maximum pressure, date of manufacture code, type of tyre can be read from it. These parameters are presented in Fig. 3.

Fig. 3. Tyre construction parameters [8]: 1 – tyre width [mm] = 205 mm, 2 – profile ratio (height to width ratio / aspect ratio) [%] = 55%, 3 – tyre construction – R (radial), 4 – rim diameter code [inches] = 16 inches 5 – maximum load capacity – 88.6 – speed symbol – V

2. Study objective

The purpose of this study was to analyse the values of fuel consumption of a vehicle equipped with tyres with different values of rolling resistance coefficient (energy efficiency classes) and with different wheel outer diameters. Calculations were made assuming the wheel movement on a dry, smooth asphalt road surface.

3. Test objects, simulation model and test methods

Test objects were three tyre types with a size provided by the manufacturer of FIAT Panda vehicle (Tab. 2).

Tab. 2. Outer diameter and width of the tested tyres [15]

No.	Tyre type	Size	Width [mm]	Outer diameter [m]
1	winter	155/80R13	155	0.578
2	winter	165/65R14	165	0.570
3	winter	185/55R14	185	0.559

Tyre outer diameters were determined from relationship (3). An illustrative determination of the outer diameter of tyre with size 155/80R13 is as follows:
- width B_0 = 155 mm = 0.155 m,
- aspect ratio p_0 = 0.8,
- rim diameter d_0 = 13 inches = 13 · 2.54 cm = 33.02 cm = 0.33 m,
- height H_0 = 0.8 · 155 mm = 124 mm = 0.124 m,
- outer diameter $d_z = 2H_0 + d_0$ = 0.578 m.

For testing, a simulation model was used (Fig. 4) allowing for tyre construction parameters (outer diameter and energy efficiency class). Different values of rolling resistance coefficient were adopted (in accordance with energy efficiency classes) and the values of basic resistance to motion (sums of rolling resistance and air resistance) were determined for vehicle speeds equal to 15 km/h, 32 km/h, 35 km/h and 50 km/h (being the components of UDC speed profile) and for 70 km/h, 100 km/h and 120 km/h (being the components of EUDC speed profile). Respective vehicle speeds corresponded to engine rotational speeds, while the values of resistance to motion determined the drive unit load torque. Because of engine rotational speeds and load torque, the values of fuel consumption were read using the load characteristic curve of MultiJet 1.3 drive unit.

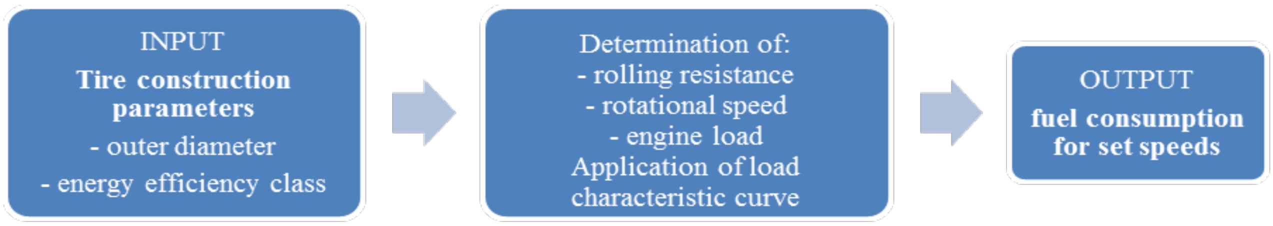

Fig. 4. Model of own study

Engine rotational speed at a specified vehicle speed and for a given wheel, outer diameter was determined from the following relationship [3, 12]:

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

The relation between rolling resistance and tyre outer diameter was described because of the following equation [3, 12]:

$$F_P = F_r + F_d \rightarrow \frac{T_{tqW}}{r_d} = F_r + F_d \rightarrow \frac{T_{tqW}}{0.47d} = F_r + F_d \rightarrow T_{tq} \cdot i \cdot \eta = (F_r + F_d) \cdot 0.47d\,, \tag{3}$$

Using the equation (3), the engine load torque was determined:

$$T_{tq} = \frac{(F_r + F_d) \cdot 0.47d}{i \cdot \eta} = \frac{(c_r \cdot m \cdot g + 0.579 \cdot c_d \cdot A \cdot v^2) \cdot 0.47d}{i \cdot \eta}. \tag{4}$$

Symbols for equations (2-4): v – vehicle speed [m/s], ω_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, F_P – propelling force [N], F_r – rolling resistance [N], F_d – air resistance [N], T_{tqW} – torque on wheels [Nm], T_{tq} – engine torque [Nm], η – powertrain efficiency, c_r – rolling resistance coefficient, m – vehicle gross weight [kg], g – gravitational acceleration, c_d – air resistance coefficient, A – vehicle frontal area [m^2].

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

4. Vehicle technical and operational characteristics

The technical data of a vehicle (FIAT Panda) which were used in determination of engine rotational speed and torque are compiled in Tab. 3 [15].

Tab. 3. Basic technical parameters for FIAT Panda 1.3 JTD vehicle

Parameter	Value	Unit	where:
m	1455	kg	vehicle gross weight
i_I	13.439	–	total gear ratio for the first gear
i_{II}	7.419	–	total gear ratio for the second gear
i_{III}	4.624	–	total gear ratio for the third gear
i_{IV}	3.349	–	total gear ratio for the fourth gear
i_{PG}	3.438	–	final drive ratio
c_d	0.330	–	air resistance coefficient
A	2.19	m^2	vehicle frontal area
η	0.92	–	powertrain efficiency

5. Engine load characteristic curve

Based on the parameters describing a vehicle, motion conditions and tyre sizes, the values of engine rotational speed and load torque were determined (Tab. 4 as an illustration for the speed of 15 km/h being obtained at 1st gear).

Tab. 4. Engine rotational speeds and load torque for different tyre sizes

v [km/h]	Size	155/80R13		165/65R14		185/55R14	
		Wheel outer diameter d [m]					
	Energy efficiency class	0.578		0.570		0.559	
		rotational speed n	torque T_{tq}	rotational speed n	torque T_{tq}	rotational speed n	torque T_{tq}
		[min^{-1}]	[Nm]	[min^{-1}]	[Nm]	[min^{-1}]	[Nm]
15 km/h 1st gear	A	1969	2.25	1997	2.22	2036	2.17
	B		2.46		2.42		2.38
	C		2.86		2.82		2.76
	E		3.31		3.26		3.20
	F		3.79		3.74		3.66
	G		4.05		3.99		3.91

A FIAT Panda vehicle was equipped with a MultiJet 1.3 JTD drive unit. It was a compression-ignition turbocharged direct injection engine with electronically controlled Common Rail injection [15]. Its load characteristic curve, obtained during tests on an engine test bench, Department of Automotive Engineering, in accordance with the standard's requirements [11]), is presented below in Fig. 5.

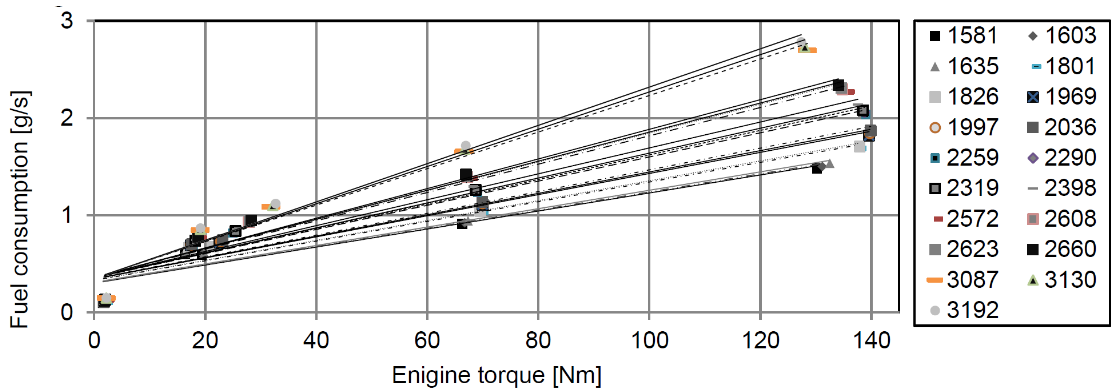

Fig. 5. The load characteristic curve of FIAT MultiJet 1.3 JTD engine

This graph illustrates the relationship between fuel consumption and engine load torque for its different rotational speeds (graph legend on the right). For the measurement points for specific rotational speeds, straight lines with a high coefficient of correlation (close to 1) were matched, being evidence of a good fit of theoretical values to the real ones. This allowed the values of fuel consumption to be determined because of approximate function formula and further transformation of the values of these parameters to the values of mileage fuel consumption.

6. Effect of wheel outer diameter on fuel consumption under set conditions

The procedure under discussion allowed the values of mileage fuel consumption to be obtained for different tyre sizes and vehicle speeds. The graphs of relationships between mileage fuel consumption and wheel outer diameter are presented below (Fig. 6-11).

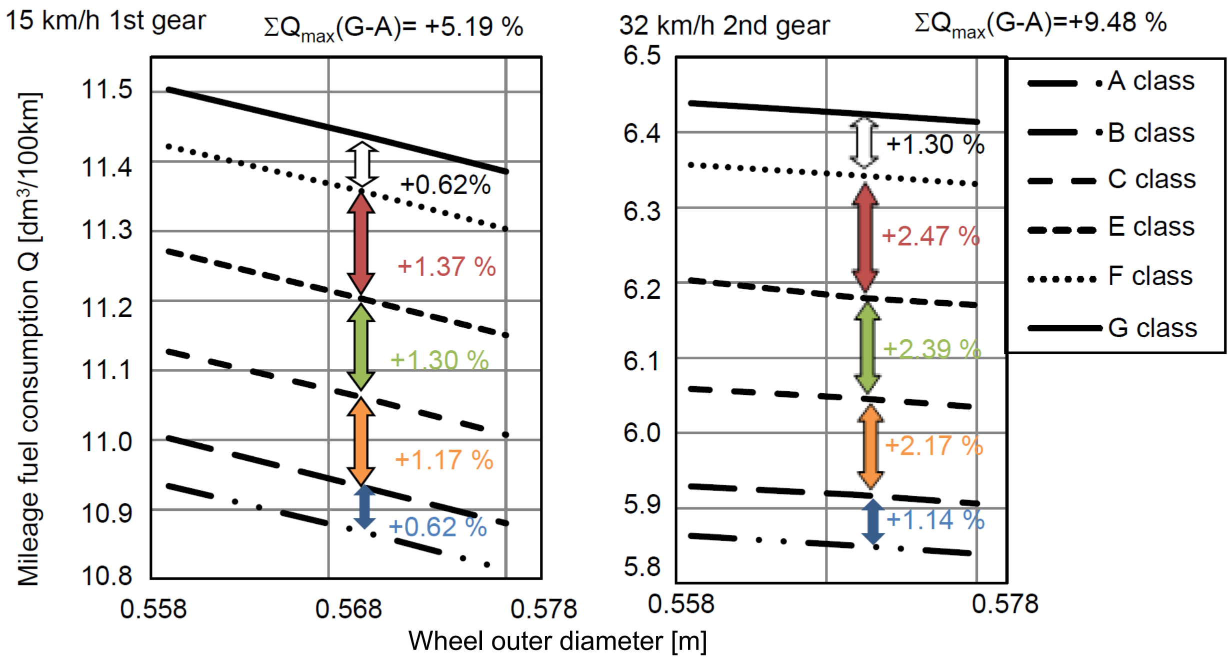

Fig. 6. The relationship between mileage fuel consumption and wheel outer diameter (for the speed of 15 km/h and 32 km/h)

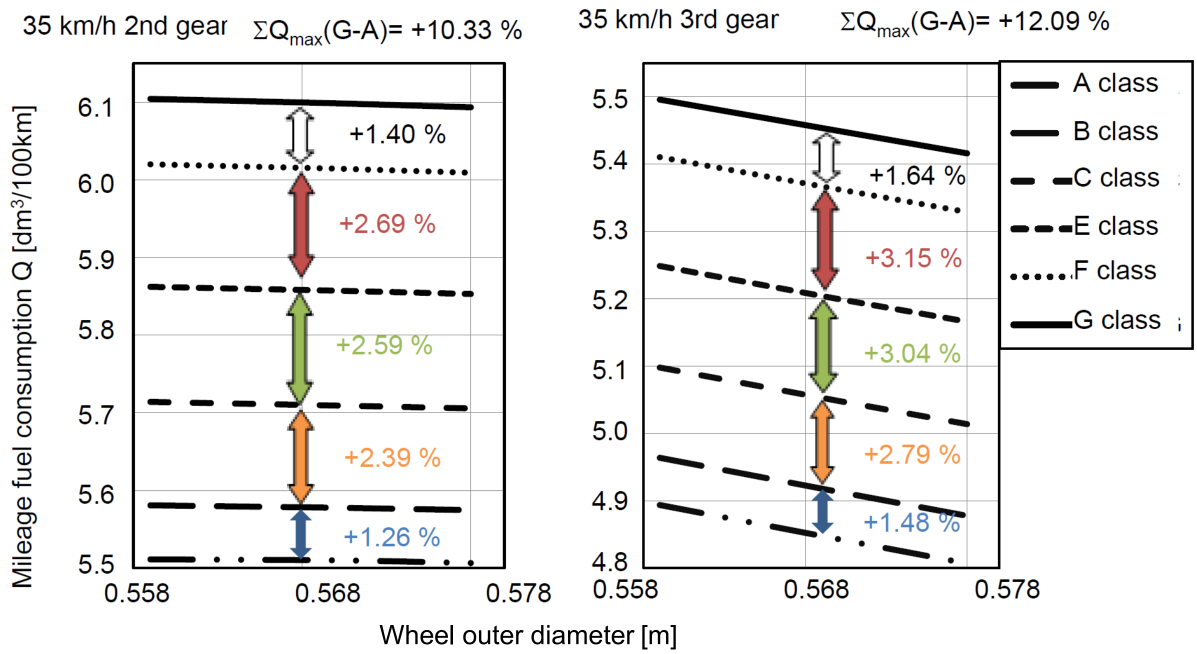

Fig. 7. The relationship between mileage fuel consumption and wheel outer diameter (for the speed of 35 km/h)

It can be concluded based on the relationships being illustrated that an increase in wheel outer diameter decreased fuel consumption for each vehicle speed.

The increase of wheel outer diameter by 0.019 m for the same energy efficiency class was able to decrease fuel consumption by 0.09% (for the speed of 35 km/h being obtained at gear 2) to 1.81% (for the speed of 35 km/h being obtained at gear 3).

The line of fuel consumption for energy efficiency class A was the lowest on the characteristic curve, whereas the line of fuel consumption for energy efficiency class G was the highest. Maximum fuel economy resulting from the application of tyres with energy efficiency class A in relation to energy efficiency class G amounted up to 14.33% (for the speed of 70 km/h). A difference in maximum fuel consumption between class G and class A increased from 5.19% of higher fuel consumption (for the speed of 15 km/h) to 14.33% of higher fuel consumption (for the speed of 70 km/h), and then decreased to 11.16% of higher fuel consumption (for the speed of 120 km/h). For the speed of 70 km/h, this could be caused by a gradual increase in the rolling resistance but above this speed by definitely higher percentage of air resistance in the total sum of resistance to motion.

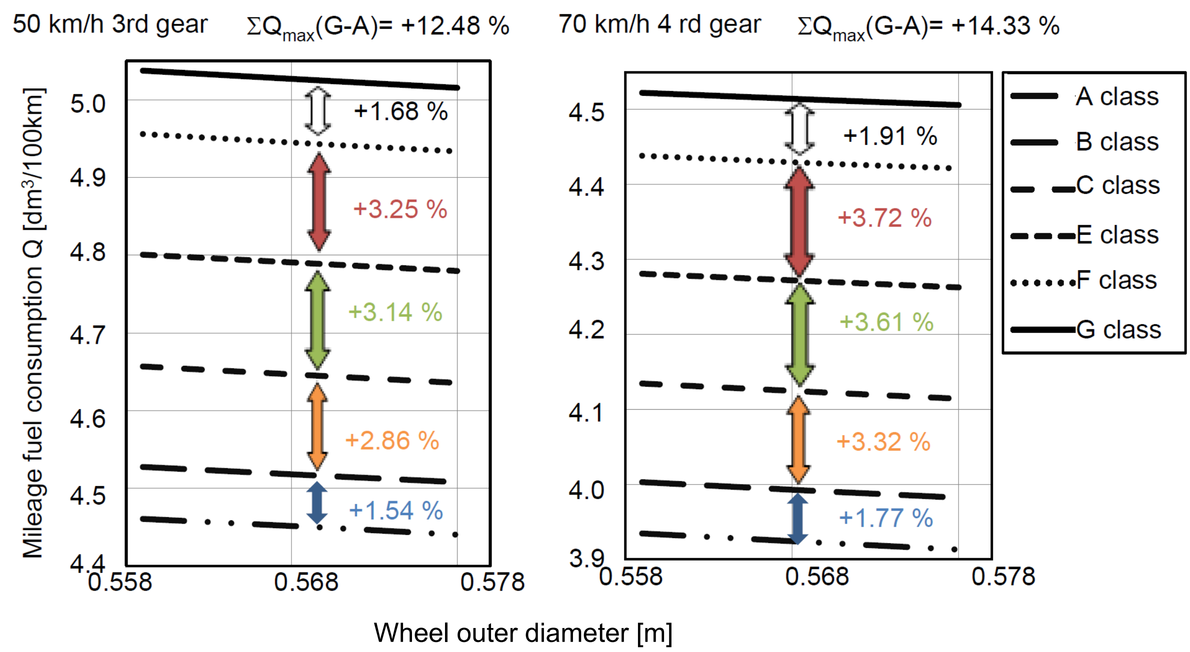

Fig. 8. The relationship between mileage fuel consumption and wheel outer diameter (for the speed of 50 km/h and 70 km/h)

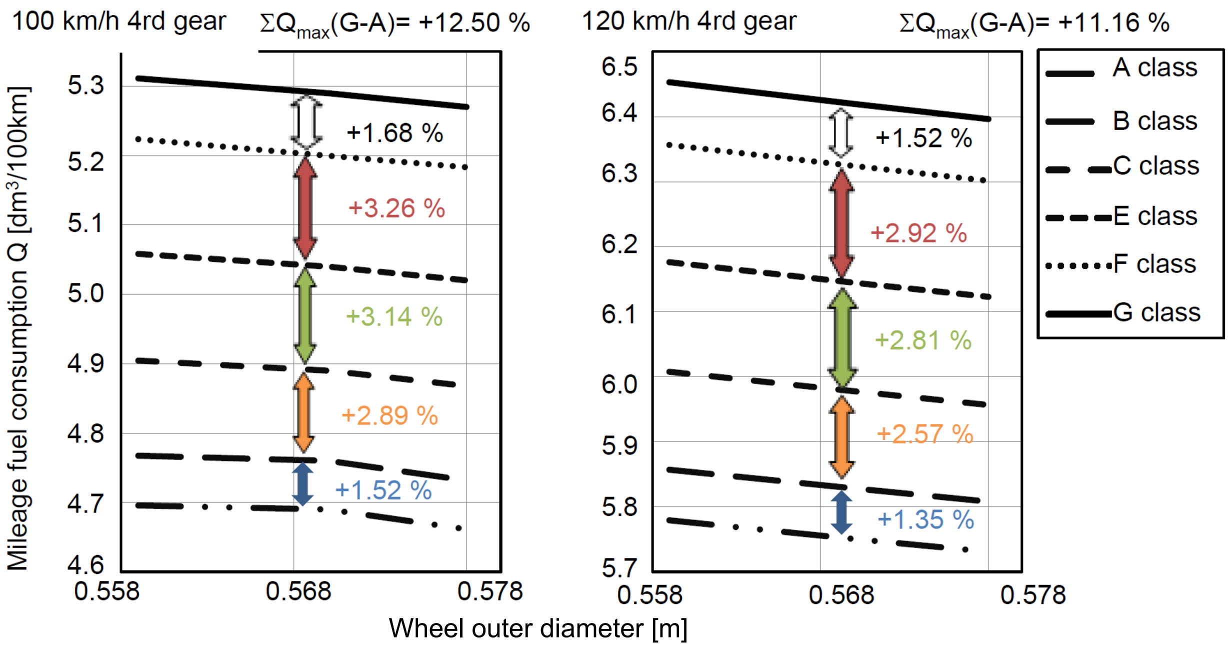

Fig. 9. The relationship between mileage fuel consumption and wheel outer diameter (for the speed of 100 km/h and 120 km/h)

7. Conclusions

The conducted analysis allowed conclusion that fuel consumption for a set vehicle speed was little affected by wheel outer diameter (within the measurement error) and significantly affected by tyre energy efficiency class. The increase of wheel outer diameter (in accordance with manufacturer's information) induced a small decrease in fuel consumption. The energy efficiency class of tyres was more significant. The use of high-energy efficiency class (A), in relation to lowest efficiency class (G), allowed the fuel economy even to a dozen or so percent.

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