INVESTIGATION OF FUEL CONSUMPTION OF A PASSENGER CAR DEPENDING ON AERODYNAMIC RESISTANCE AND RELATED ASPECTS: A CASE STUDY

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Summary

The research study investigates fuel consumption of a passenger car depending on aerodynamic resistance and related aspects. Introduction and next chapter describe all the resistance kinds affecting a passenger car while in-motion. Subsequent part outlines particular aspects such as aerodynamic resistance, aerodynamic resistance coefficient, car velocity and air temperature in terms of their effect on fuel consumption of selected passenger car. The most important chapter compares fuel consumption while a passenger car is in-motion on an expressway with closed and open windows with fuel consumption on a first class road infrastructure.

Keywords: Aerodynamic resistance, aerodynamic resistance coefficient, fuel consumption, passenger car

1. Introduction

Nowadays, huge climate changes are present on Earth. Major changes consist of often recorded changing weather. For instance, sea level has been growing constantly. At the end of the last century, without crucial encroachment in human operation, sea level would grow by one or two meters [1, 2].

Transport and especially greenhouse gases production may be considered the most important cause of these climate changes [3]. Undeniably, greenhouse gases production is associated with the fuel consumption of vehicles significantly. Fuel consumption of individual means of transport consists in the rate at which an engine uses fuel, expressed

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in units such as liters per kilometer. Engine designers strive for more power, lower fuel consumption, lighter weight, and better reliability. Short journeys can double fuel consumption [4], especially when the engine is cold. Something as simple as a faulty spark plug can increase fuel consumption by 20-40 percent, with no noticeable change in operation [5].

When a passenger car is in-motion at uniform velocity, its resistance against the motion, referred to as the tractive resistance, includes [6, 7]: a) aerodynamic resistance (O_{aero}) – is related to parameters of a passenger car, b) rolling resistance (O_R) – depends especially on a nature of a transport surface, used tire material, a car mass, and a car velocity, c) climb resistance (O_C) – is stipulated by climbing uphill degree and a car mass, d) resistance to inertia (O_I) – is caused by a car resistance to change its velocity.

2. Resistance kinds affecting a passenger car while in-motion

a) Aerodynamic resistance

While a car is in-motion, aerodynamic resistance always occurs. Aerodynamic resistance [8], aerodynamic lift and aerodynamic pitching moment have great impact on final car driving power at average and high velocities. Increasing emphasis on fuel and energy consumption has encouraged new interest in advanced aerodynamic power of passenger cars. Aerodynamic resistance is the greatest and most significant aerodynamic force affecting a car and driver himself while a car is in-motion [9]. Overall aerodynamic resistance on a car is caused by lots of sources. About 65% amount of aerodynamic resistance value is created by its bodywork [10].

Aerodynamic resistance value may be calculated, as follows (Eq. 1) [11]:

$$O_{aero} = 0.5 * \rho * v^2 * c_x * S \tag{1}$$

where: ρ air instantaneous specific mass [kg.m^{-3}];

v a car velocity [m.s^{-1}];

cx aerodynamic resistance coefficient [-];

S car frontal area dimension [m^2].

It needs to be stated that aerodynamic resistance value varies proportionally depending on car velocity, air pressure and disproportionally depending on air temperature [11, 12].

b)Rolling resistance

Wheels rolling resistance is another tractive resistance always occurring while a car in motion. While a low car velocity on a firm surface, rolling resistance represents a basic tractive resistance force. As a matter of fact, aerodynamic resistance becomes equal to rolling resistance just at a velocity of 85-105 km/h. As for off-expressways, rolling resistance is the only relevant delay force [13].

At least 7 mechanisms responsible for rolling resistance occur, see as follows [13, 14]: 1) loss of energy due to a tire sidewall deflection in a proximity of a contact zone, 2) loss of energy due to tread elements deflection, 3) scrubbing in the contact zone, 4) wheel skip in a longitudinal and lateral direction, 5) road infrastructure surface deflection, 6) aerodynamic resistance on wheel inner and outer side, 7) loss of energy on bumps.

Taking into consideration a car as a whole, overall rolling resistance is represented by a sum of values of individual rolling resistances on all car wheels. Its value may be calculated, as follows (Eq. 2) [15]:

$$O_R = f * m * g * \cos\alpha \tag{2}$$

where: m a car mass [kg],

g gravitational acceleration [9.81 m.s^{-2}],

α angle of a road infrastructure slope [°],

f rolling resistance coefficient [-].

Rolling resistance coefficient value varies depending on lots of aspects: tire design (as well as material), tire skip, tire temperature, tire inflation pressure, tire diameter, tire aspect ratio, tire radial load, wheel balance, car velocity, etc.

Common rolling resistance coefficient values under various conditions are summarized in Table 1.

Table 1. Common rolling resistance coefficient values under various conditions. Source: authors

Vehicle Type	Surface kind		
	Concrete	Average-hard	Sand/mud
Passenger car	0.015	0.08	0.30
Articulated vehicles	0.012	0.06	0.25
Tractors	0.02	0.04	0.20

c) Climb resistance

Climb resistance is related to the angle of road infrastructure slope and a car mass. As a matter of fact, it represents force affecting a road surface in the parallel direction. While a car is in-motion on oblique road, a car impacts on this road surface at a specific angle. Thus, a car mass is divided to a component part perpendicular and a component part parallel to a road surface. Climb resistance value may be calculated using an equation, as follows (Eq. 3) [14-17]:

$$O_C = m * g * \sin\alpha \tag{3}$$

where: m a car mass [kg],

g gravitational acceleration [9.81 m.s^{-2}],

α angle of a road infrastructure slope [°].¨

d) Resistance to inertia

This resistance arises from a car mass and car acceleration values. Each car part resists to its motion position change. In order to change a car velocity, a car engine must generate certain amount of energy corresponding to inertia force necessary to overcome resistance to inertia.

This resistance kind value may be calculated using an equation, as follows (Eg. 4) [17]:

$$O_I = m * a * \delta \tag{4}$$

where: m a car mass [kg],

a a car acceleration [9.81 m.s^{-2}],

δ rotational mass influence coefficient [°].

Rotational mass influence coefficient is dependent on an engine rotational mass weight (engine volume, fuel mixture ignition type, and engine cylinders number), gearbox system ration and its efficiency, wheels weight and parameters.

3. Data, methods and results

From aforementioned, it can be stated that several aspects may influence the overall car fuel consumption. To specify an influence of a given resistance, an investigation needs to be prepared in order that other aspects are not affected. Engine and gearbox system efficiency represents one of the crucial aspects. In order to reduce this influence, all investigations phases were carried out on a same car in short time-period to avoid an influence of worsening a car technical state. In regard to investigations, Skoda Fabia 1.4 16V, 55 kW, with a spark-ignition engine of volume of 1,400 cm3 was utilized. Prior to investigation itself, wheels were inflated to a recommended inflation pressure, car technical state was controlled, and its alignment according to the manufacturer's guidelines was adhered.

While a car is in-motion, aerodynamic resistance value varies depending on a car velocity v, aerodynamic resistance coefficient value cx, as well as air temperature. In order to avoid an elevation track profile, investigations were carried out on a same surface and it was important to reduce an influence of a car velocity change. Riding on expressway the best complies with such circumstances. On an expressway, it was possible to obtain a necessary car velocity and maintain it during a whole travel road section. Road section under investigation was determined to a length of 7.50. Investigation of fuel consumption was initiated once the defined car velocity was achieved. To reduce an influence of a driver behavior while driving, a car velocity was maintained utilizing a car cruise control. A wind speed was recorded up to three m/s, car windows were closed and a road infrastructure surface was dry and firm.

a) Car velocity influence

If a car velocity needed to be changed due to traffic conditions, investigation would be terminated. Thanks to such an investigation, a car velocity was the only varying value.

Investigation was carried out for car velocities of 105, 115 and 125 km/h.

Compared fuel consumption values recorded during investigations while a car was in-motion on expressway with closed windows are indicated in Table 2.

Table 2. Fuel consumption values on expressway with closed windows when varying car velocity. Source: authors

Car velocity		Fuel consumption		Air temperature
[km/h]	Index of velocity increase compared to velocity of 105 km/h	[l/100 km]	Index of fuel consumption increase compared to original value	
105	1.00	5.4	1.00	31°C
115	1.095	5.9	1.093	31°C
125	1.19	7.1	1.315	31°C

Following the obtained outcomes, it is apparent that with increasing car velocity the fuel consumption increases. If a car velocity varies from 105 to 115 km/h, change is at the value of 109.5% and change in terms of fuel consumption reflects this change by an increase of 109.3% compared to the primary consumption. More interesting change is monitored in terms of a velocity increase up to 125 km/h, i.e. at 119.0% compared to the primary value, a fuel consumption increases to 131.5% compared to the primary value. These increases are caused based on the Equation 1, since a car velocity v occurs as a value in square.

b)Air temperature influence

Air temperature value influences air density value, and thus proportionally also aerodynamic resistance value. To compare fuel consumption values on expressway with closed windows, investigations while a car velocity of 115 km/h and air temperatures at 31°C and 10°C were undergone. Obtained outcomes from investigations are summarized in Table 3.

Table 3. Fuel consumption values on expressway with closed windows when varying air temperature. Source: authors

Car velocity [km/h]	Fuel consumption [l/100 km]	Index of fuel consumption increase	Air temperature [°C]
115	5.9	1.085	31
115	6.4		10

As can be seen, air temperature decrease of 24°C resulted in fuel consumption increase of 108.5% while same car velocity maintained.

c) Aerodynamic resistance coefficient influence

Drivers, in the summer season, usually ride while car windows are open to maintain a suitable air temperature inside a car. Car open windows influence air-flow forces in proximity of a car and also aerodynamic resistance coefficient. To compare fuel consumption values when traveling on expressway while a different car velocity and a same surroundings temperature, specific examinations were carried out (see Table 4). One drive was undergone while windows were closed and the second one was carried out with open windows. Individual outcome values are clearly ordered in Table 4.

Table 4. Fuel consumption values on expressway when varying car velocity as well as windows position. Source: authors

Car velocity		Fuel consumption		Index of fuel consumption increase among closed and open windows	Air temperature
[km/h]	Index of velocity increase compared to velocity of 105 km/h	Closed windows	Open windows		
105	1.00	5.4	1.00	1.019	31°C
115	1.095	5.9	1.093	1.017	31°C
125	1.19	7.1	1.315	1.028	31°C

Driving while windows are open in terms of fuel consumption means an increase of 1.9% at a car velocity of 105 km/h, of 1.7% at a velocity of 115 km/h and of 2.8% at a velocity of 125 km/h. Thus, it can be declared that differences are basically negligible.

d) Ride on a first class road

Car fuel consumption value while a common traffic circumstance, whereby a car velocity is confined by other road infrastructure users and transport regulations, is primary influenced by resistance to inertia and car velocity changes. Fuel consumption values were also compared on a first class road infrastructure between cities of Třebíč and Jindřichův Hradec (South Bohemia region). Driver tended to ride at a constant velocity while some rides were undergone in high traffic intensity (peak hour) and a car velocity was regulated by other cars velocities, i.e. it did not exceed of 75 km/h. Moreover, rides without any other cars close to monitored car (low traffic intensity; peak-off hour), while a car velocity was maintained at 85 km/h, were carried out. Car velocity limitations up to 50 km/h (3 times) and up to 70 km/h (twice) occurred during the ride itself.

Recorded result values of an investigation are shown in following Table 5.

Table 5. Fuel consumption values on first class road infrastructure when varying air temperature, windows position as well as traffic circumstances. Source: authors

Air temperature [°C]	Windows	Fuel consumption [l/100 km]	Traffic circumstances
31°C	Closed	4.8	car flow, velocity up to 75 km/h
		5.1	free road lane, velocity up to 85 km/h
31°C	Open	4.9	car flow, velocity up to 75 km/h
		5.1	free road lane, velocity up to 85 km/h
10°C	Open	5.5	car flow, velocity up to 75 km/h

When driving on a first class road infrastructure, fuel consumption values changed only in terms of a car velocity. Car flow rode fluently, nevertheless velocity did not exceed of 75 km/h. Lower temperature influence is apparent, i.e. fuel consumption value while 10°C of air temperature increased by 12.24% compared to similar traffic circumstances while 31°C of air temperature.

4. Conclusion

As already mentioned, transport activities, mainly greenhouse gases production, can be deemed one of the most crucial aspects resulting in climate changes on Earth. Greenhouse gases production is related to cars fuel consumption considerably. Through streamlining engine combustion processes and installing catalysts, users are able to eliminate a part of greenhouse gases to a great extent; nevertheless greenhouse gas of CO2 cannot be reduced by installing any catalyst. One of the appropriate options is to lower car fuel consumption. Car fuel consumption abatement may be ensured by various methods For example, by engine power efficiency value increase, diminishing tractive resistance values, streamlining transportation paths, etc. While a car is in-motion, tractive resistances act against car free motion and try to interrupt its movement. Car engine must spend a certain fuel volume to overcome these resistance kinds. Values of these resistance kinds are not uniform, during real traffic circumstances however, it is varied depending the way of driving.

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