Fuel Consumption and Driving Resistances

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ABSTRACT

The climate of our planet is changing, which, scientists believe, is caused by the production of greenhouse gases (GHG). To stabilize the concentrations of those gases in the atmosphere, it is necessary to decrease their production. Since transport is one of the major sources of GHG emissions, the most obvious solution is to decrease fuel consumption by vehicles. The amount of fuel used by a vehicle depends directly on the force of driving resistance, including rolling resistance and air resistance. The aim of the article is to indicate one of the easiest possibilities of decreasing these resistances. A small change in the shape of a vehicle's frontal area leads to a significant reduction in air resistance.

KEYWORDS: driving resistance, air resistance, fuel consumption

1. Introduction

The climate of our planet is changing. This leads to the melting of glaciers, an increased frequency and severity of whirlwinds and rainstorms, as well as increases in average yearly temperatures. These changes seem to be caused, at least partially, by anthropogenic production of greenhouse gases. One important step toward combating GHG emissions have been Kyoto conferences devoted to the discussion of climate change and the measures necessary to be taken to prevent anthropogenic interference with climate. As a result, one hundred and forty one countries committed themselves to a reduction of GHG emissions. Europe is responsible for around 21 % of global GHG production and agreed to reduce GHG emission levels by 8 % with respect to their production in 1990.

The share of the particular human activities and their impact on the production of greenhouse gases, converted to CO2 equivalent, are presented in Figure 1. It is apparent that transport is the second most important producer of GHG. Transport performance in tonne kilometers and passenger kilometers increases with the growth of GDP and industrial production. A growth in transport (particularly in road transport) leads to a growth in GHG emissions because higher performance of transport is connected with higher fuel consumption. Besides other pollutants, approximately 2.5 kg CO_2 are emitted to the air for each kilogram of petroleum fuel combusted.
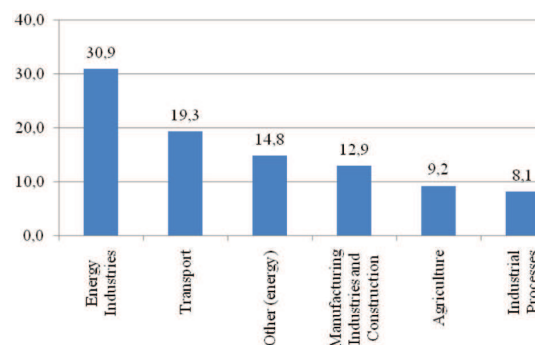

Fig. 1. Share of activities in greenhouse gases production expressed in CO_2 equivalent [data modified according to
Source: http://epp.eurostat.ec.europa.eu/portal]

Legislation aims to control the negative consequences of transportation by imposing more rigorous limits on exhaust emissions. These legislative arrangements create a basis for alternative fuel exploitation, improvements in engine combustion process,

and better construction of vehicles. The easiest and quickest reduction of GHG emissions can be achieved by decreasing a vehicles` fuel consumption through rational driving and by simple technical modifications aimed at lowering driving resistances.

2. Driving resistance

2.1 Rolling resistance

Rolling resistance is caused by the wheel rolling on a flat surface. The tyre must change its shape from circular to more flattened. The tyre tread is compressed when it enters into contact with the road, and after leaving the contact area, it has a tendency to return to its original shape. This is the reason why pressure in the contact area is not homogenous (see Figure 2). The rotation of the wheel causes the total force F_z of the pressure in the contact area to move forward in the direction of wheel movement. It has the same value, but an opposite direction to the gravitational force $F_{z'}$. These two forces shifted by distance e and together form torque M_f with a direction opposite to the torque which caused the movement of the tyre. This is how rolling resistance arises. The higher difference between the pressure in the front and the rear part of the contact area, will cause the larger distance e and moment M_f. The intensity of this moment changes with the pressure inside the tyre and also
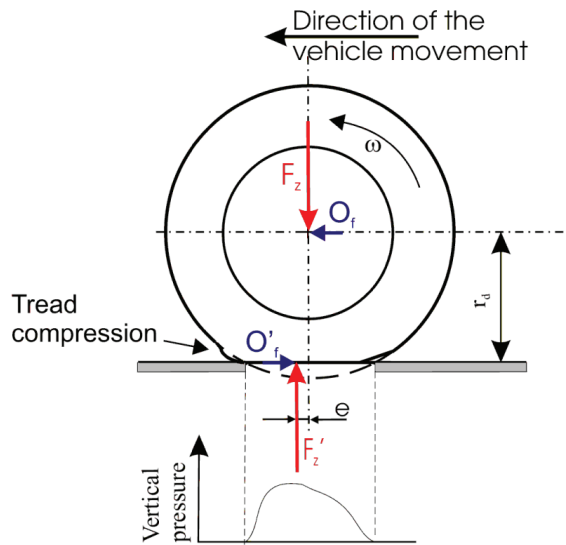

Fig. 2. Formation of rolling resistance. (data modified according to Marcín and Zítek 1985)

depends on tyre construction, tyre diameter, road surface, driving speed, axis geometry, temperature, etc. To overcome the moment of rolling resistance, promotion of force O_f to the centre of the wheel is required. The distance between these forces is the dynamic radius r_d of the wheel. The fraction e/r_d can be substituted by rolling resistance coefficient f. The value of rolling resistance can be calculated from the formula:

$$O_f = m \cdot g \cdot f \cdot \cos\alpha, \qquad (1)$$

where:
m - mass of the vehicle [kg],
g - acceleration of gravity [m/s²],
f - rolling resistance coefficient,
α - angle between horizontal and travel plane [°].

2.2 Air resistance

Air resistance appears when the speed of the air flow around the vehicle differs from zero. We will assume that the relative speed of air is equal to the speed of the vehicle, i.e. the air is motionless relative to the ground, and only the vehicle is moving. The size of air resistance can be calculated from the formula:

$$O_v = \frac{1}{2} \cdot \rho_v \cdot v^2 \cdot c_x \cdot S, \qquad (2)$$

where:
ρ_v - specific mass of the air [kg/m³],
v - velocity of the air with respect to the vehicle [m/s],
c_x - drag coefficient,
S - effective surface of the vehicle`s front area [m²].

The specific air mass

The value of the specific air mass depends on the pressure and the temperature. The specific air mass is lower when the temperature is higher, and higher atmospheric pressure causes an increase in the specific air mass. The value of the specific air mass in particular conditions can be calculated from the formula:

$$\rho_v = \rho \cdot \frac{273}{273 + t_s} \cdot \frac{p_s}{p_o}, \qquad (3)$$

where:
t_s – air temperature [°C],
ρ – specific mass of the air 1.29 kg/m³ at temperature t_o = 0 °C and at pressure p_o = 0.101325 Mpa,

For example, according to Wong (1991), a change in the temperature from 0 °C to 38 °C causes a 14 % decrease in air resistance, and a change in elevation (with respect to the sea level) of 1219 m decreases air resistance by 17 %.

Driving velocity

Driving velocity has the most important influence on the value of air resistance. Increasing the velocity from 80 km/h to 90 km/h (i.e. a 12.5% change in velocity) will cause a 27 % increase in air resistance.

Drag coefficient c_x

c_x is a non-dimensional parameter. Its value depends on the vehicle's construction and on the operational conditions. The most important

is the shape of the body, especially its front part, the shape of the chassis, wheels and their covers, the outside mirrors, etc.

Small changes in the shape may cause an extensive change in air resistance. This is shown in Figure 3.
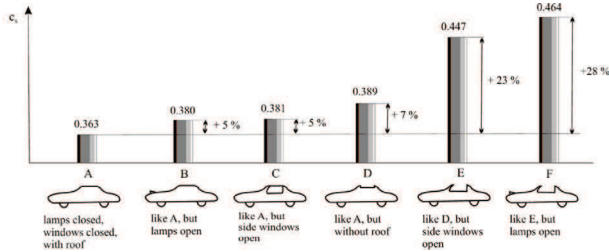

Fig. 3 Small changes in a vehicle's shape and their influence on air resistance

2.3. Grade resistance

If a vehicle moves up a slope, its weight can be divided into two parts. One part acts perpendicularly to the road and the other part acts in parallel with the road. The second part restrains the vehicle from movement (in case of elevation) or supports the movement of the vehicle (in case of declination). This force is called elevation resistance. It is possible to calculate its value from the formula:

$$O_s = \pm m \cdot g \cdot \sin \alpha , \qquad (4)$$

where:
m   - vehicle's mass [kg],
g   - acceleration of gravity [m/s^2],
α   - angle between the road and the horizontal plane,
±   - number sign + is valid for elevation
                        - is valid for decline

2.4. Inertial resistance

Inertia opposes changes in vehicle movement. If a vehicle accelerates or decelerates, its inertia acts against this change. The size of inertia resistance can be calculated using the formula:

$$O_a = m \cdot a \cdot \delta , \qquad (5)$$

where:
m   - vehicle's mass [kg],
a   - acceleration [m/s^2],
δ   - coefficient of influence of rotating parts.

3. Calculation

All these resistances manifest themselves during driving and are overcome by the force produced by the engine. The energy for that comes from combustion of fuel. In case of increased resistances, the combustion is increased as well.

In our study, we wanted to demonstrate that even a small change in the vehicle's frontal area can cause a significant change in fuel consumption. As an experimental vehicle, we used a motorcycle, rather than the more common automobile, assuming that, for obvious reasons, the effect of drag is relatively more significant in the case of motorcycles and that an improvement in this parameter will have a more pronounced effect on fuel economy. We used a Suzuki TU 250X motorcycle, produced in the year 1998 (Figure 4).
Masses:
kerb weight   215 kg,
driver weight   80 kg,
freight weight   10 kg.
The instant mass of the motorcycle was 305 kg.

The motorcycle was equipped with a four-stroke air cooled one-cylinder engine (250 ccm, 15 kW), equipped with a carburettor and a five-gear box.

The estimation of the different driving resistances:
Rolling resistance
Bias ply tyres were used in the motorcycle. Its rolling resistance coefficient was f = 0.015, and cosa = 1 (no declination). Thus, the motorcycle's rolling resistance was estimated as

Fig. 4: Experimental vehicle

$$O_f = (215 + 80 + 10) \times 9.81 \times 0.015 = 44.9N \quad (6)$$

Air resistance
The effective frontal area S was calculated using the square network method. S=0.4566 m^2 in our case. The value of the air resistance coefficient was estimated as c_x = 0.9. For the estimation of air resistance, we assumed that these values were constant. Then (assuming that changes in the air pressure and temperature were insignificant) air resistance depended only on the relative speed of the vehicle. The drag for velocities 60 km/h, 80 km/h and 100 km/h was calculated.

$$O_{v,60} = 0.05 \times 0.9 \times 0.4566 \times 60^2 = 74N \qquad (7)$$

$$O_{v,80} = 0.05 \times 0.9 \times 0.4566 \times 80^2 = 131.5N \qquad (8)$$

$$O_{v,100} = 0.05 \times 0.9 \times 0.4566 \times 100^2 = 205.5N \qquad (9)$$

Grade resistance

Grade resistance was calculated for a 5% and a 10% slope:

$$O_{s,5\%} = (215 + 80 + 10) \times 9.81 \times \sin 2.866° = 149.6N \quad (10)$$

$$O_{s,10\%} = (215 + 80 + 10) \times 9.81 \times \sin 5.739° = 299.2N \quad (11)$$

Inertial resistance

With the coefficient of influence of rotation parts δ = 1.1 and acceleration a = 1.5 ms⁻², inertia resistance is

$$O_a = (215 + 80 + 10) \times 1.5 \times 1.1 = 503.3N \quad (12)$$

However, inertial resistance and elevation resistance typically act over a limited period of driving, while drag (as well as rolling resistance) exerts its effect on the vehicle during the whole period of its movement. Therefore, when the influence of speed changes is limited by a proper driving technique and/or by choosing an appropriate route (highway), drag easily becomes the major factor.

To improve the drag of the vehicle, a frontal shield with an area of 1569 cm² was installed. The total frontal area of the motorcycle with a driver was 4566 cm². Thus, the area of the shield was only 1/3 of the total frontal area.

To measure the effect of the drag change on fuel consumption, two testing rides were performed. One ride was made without the shield and the other with the shield. All the remaining relevant conditions of the ride were the same for both rides, unless stated otherwise.

The ride without the shield was performed on the highway from Škofje in Slovenia (45°34`47.49``N 13°47`47.51``E; elevation 27 metres) to Bratislava in Slovakia (48°08`52.48``N 17°04`17.20``E; elevation 152 metres). The vehicle covered the distance of 550 km in 6 hours, 57 minutes and 29 seconds. The average speed was 79.05 km/h. The air temperatures varied from 11 °C to 14 °C. The vehicle consumed 18.37 l of fuel. The average consumption was 3.34 l/100 km.

After the shield was mounted, the driver rode in the opposite direction. Measurement was made on the way from Bratislava (48°08`52.48``N 17°04`17.20``E; elevation 152 metres) to Ljubljana (počivališče Barje) (46°01`44.35``N 14°28`42.51``E; elevation 292 metres). The vehicle travelled the distance of 447.8 km in 5 hours, 24 minutes and 21 seconds. The average speed was 82.83 km/h. The air temperature varied from 10 °C to 17 °C. The vehicle consumed 13.73 l of fuel. The average consumption was 3.07 l/100 km.

An effort was made to reduce the variability of all the assumed driving resistances, except for drag:

Grade resistance

It was necessary to take into account the small differences in elevation changes between both rides. The first ride started from Škofje with the elevation of 27 metres and finished in Bratislava with the elevation of 152 metres.

The travel back started in Bratislava and was finished at a filling station near Ljubljana with an elevation of 292 metres.

The differences in elevation were measured using Google Earth 4.0.2693(beta), 2006 software. The difference in elevation between Škofje and Bratislava (ride without shield) was 125 metres and between Bratislava and Ljubljana (ride with shield) 140 metres. The difference between the two rides was 15 m. On the basis of vehicle consumption, it was possible to calculate the efficiency of conversion of fuel energy into the mechanical energy of driving, which was estimated at 19 %. Thus, the differences between the two rides (in terms of unequal changes in elevations) could contribute around 0.01 l of fuel to the total consumption.

Rolling resistance

The process of estimating rolling resistance has been described above. The value of rolling resistance depends on the velocity of the vehicle, pressure inside the tyre, type of the tyre, surface of the road, elevation and temperature.

The pressure inside the tyres was kept unchanged on both rides. The path was chosen in such a way that there were only small elevation differences. The slope on the highway did not exceed 6 %. The effect of this slope (cosa = 0.9982) on rolling resistance was assumed to be negligible and was not considered in the calculations. The air temperature was similar during both rides. It can, therefore, be assumed, with good reason, that the rolling resistance was the same for both rides.

Inertia resistance

The rides were performed on the same highway, and the driver (same for both rides) was instructed to maintain a constant speed over the entire course of the experiment and not to accelerate or decelerate, unless absolutely necessary. Therefore, it was assumed that inertia resistance was the same for both rides.

Air resistance

Air resistance depends on the velocity of the vehicle. The driver tried to keep constant velocity and did not exceed 100 km/h. The travel from Škofje to Bratislava took 6 hours, 57 minutes and 29 seconds. The distance driven was 550 km. The average velocity during this travel was 79.05 km/h. The travel from Bratislava to Ljubljana took 5 hours, 24 minutes, 21 seconds. The distance was 447.8 km. The vehicle achieved an average velocity of 82.8 km/h. The higher velocity caused a higher air resistance. Assuming a 19 % efficiency (see above), it can be estimated that the higher velocity led to an increase in consumption of 0.92 l.

4. Conclusion

The results of our experiment show that a change in the front shape of a vehicle has an effect on fuel consumption. The elevation resistance, the rolling resistance and the inertia resistance for both driving directions was comparable. The change in fuel consumption was mainly affected by the change in air resistance, which, in turn, was affected by the change in the shape of the vehicle. The results of the measurement are shown in Table 1. The consumption was reduced about 0.27 l/100 km after the shield was installed, which is an about 8.08 % decrease.

When the increase of fuel consumption caused by higher speed and a greater elevation change in one of the routes is taken into account, the "normalized" consumption with the mounted shield will only be 2.86 l/100 km instead of 3.07 l/ 100 km. In this case, a consumption decrease of about 0.48 l/100 km (14.35 %) was achieved.

Table 1. Final Fuel Consumption

Path of travel from	to	Distance [km] [l]	Fuel consumption		Conditions
			[l/100 km]		
Škofie	Bratislava	550	18.37	3.34	without shield
Bratislava	Ljubljana	447.8	13.73	3.07	with shield

This experiment shows that even a small change in the front shape of the vehicle can cause a significant change in fuel consumption. In terms of everyday praxis, this means that driving with open windows, unnecessary use of a roof luggage carrier, a wrongly set roof deflector of a lorry, etc. may significantly affect fuel consumption and consequently increase the costs of vehicle operation and production of emissions.

Acknowledgements

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