AERODYNAMIC CHARACTERISTICS OF CARS WITH TRAILERS IN ROAD EXPERIMENTS

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Abstract. The aerodynamics of an automobile is an important parameter of its exploitation that can significantly affect the dynamics and fuel consumption of the automobile. Small enterprises in Latvia provide road transport services using cars coupled with trailers. It is important to choose the right combination of an automobile and a trailer for such a vehicle-trailer system, as the resistance of air depends on it. Besides, the aerodynamics of a trailer has to be examined only in combination with a certain pulling vehicle. In case loads are transported over long distances, the amount of fuel consumed if loads are transported in a trailer may considerably affect the cost of transport. The paper examines 12 various vehicle-trailer systems for two pulling vehicles and two trailers with different tent use combinations. The best performance results were gained in the case where a trailer was used with a low tent – c_XA = 1.66 for Renault Laguna and c_XA = 1.20 for Renault Trafic.

Keywords: automobile, trailer, trailer tent, aerodynamic resistance, air resistance coefficient, calculation of air resistance coefficient.

Introduction

The current trend regarding small enterprises in Latvia involves transporting goods in small quantities. Microbuses are used for this purpose. If goods of bigger volume have to be transported, car trailers are also used for this activity. Trailers with or without a tent may be used depending on the kind of loads to be transported. When transporting goods, tents are usually used, thus increasing the volume of transported goods and protecting the goods from the external environment and from being stolen.

Usually, such transport companies are unlikely to cooperate with specialised logistics companies. For this reason, the quantity, weight and volume of goods transported one way can significantly differ from these transport parameters on the way back when a load of certain parameters collected specifically for some enterprise is transported. In cases where the transport chain involves water transport – a ferry –, carriers using large-size microbuses as pulling vehicles seek to use small car trailers that are loaded into the microbus. In this way, the cost on the ferry considerably decreases.

The above-mentioned carriers are interested in a number of questions concerning the use of trailers:

- To what extent the geometric parameters of the trailer affect the air resistance in any particular case?
- May the trailer tent remain in place or be taken off if no load is transported?
- May the tent frame remain in place or be taken off if no load is transported?
- What is the air resistance coefficient for a high or a low tent?
- Should a pulling vehicle with a larger or a smaller frontal area be preferred in cases where the trailer's dimensions are big?
- To what extent a change in the air resistance coefficient can affect the consumption of fuel?

To answer most of the questions, a road experiment has to be carried out using trailers of various kinds and pulling vehicles of various sizes. The research aim is to identify the combination of a pulling vehicle and a trailer that involves the lowest air resistance coefficient and its effect on the consumption of fuel.

1. Research studies by other authors in the field of aerodynamics

An automobile's air resistance is characterised by the aerodynamic resistance coefficient c_x. This factor may be determined experimentally. The most expensive and precise determination of the air resistance coefficient is carried out in aerodynamic tubes, using automobiles or their models of the same size. It allows determining a precise aerodynamic resistance coefficient; yet, experiments have to be conducted using expensive equipment, which is not always possible.

In the world, a lot of research studies have been conducted concerning the aerodynamic characteristics of vehicles. In the USA, scientists focused on reducing the fuel consumption through changing the form of the rear part of a large lorry trailer [1]. Lorries, if following one another at a distance of 4 meters, can save 3.2 l of fuel per 100 km. Research studies in optimising the form of roof spoilers and side extenders are still urgent and popular. The optimisation was performed based on a mathematical model [2]. In an aerodynamic tube, research studies on the form of underbody plates and their placement optimisation were conducted in order to achieve a lower aerodynamic resistance coefficient. The research studies were performed employing a 1:14 scale model in a low turbulence wind tunnel. In a standard trial, the air resistance coefficient was reduced from 0.443 by 0.102 in the most effective case [3]. A gap between the pulling vehicle and the trailer plays an essential role in reducing the air resistance [4]. This effect is in place for trailers of any make and size, which includes the segment of cars and their trailers as well. Finnish scientists have made research on buses at a scale of 1:10 and on lorries with large-size trailers in an aerodynamic tube. They optimised both the form of the cab and the rear part of the semitrailer. Research studies have been also conducted for various wind directions relative to the automobile [5]. The tests performed in aerodynamic tubes allow judging in detail about the effects of every element of the automobile body on the air resistance coefficient [6].

Research studies were carried out on special testing grounds with real lorry models. Researchers admitted that such tests were affected by such parameters as the wind speed, change in the weather conditions, change in rolling resistance, mechanical friction and other conditions. A new methodology for tests has been developed for measuring the torque and power directly on a lorry's wheel, which allows excluding a number of variable factors in road experiments. The tests were carried out on two different testing grounds. The strength and direction of wind were controlled during the tests. The strength of wind could not exceed 4 m s^{-1} during the tests. A lorry Ford Cargo 1846T with a wind speed measuring device placed on a special support in the front of the lorry was used in the experiments. Force measuring devices were placed on the pulling vehicle front left wheel and both driving wheels and on the semitrailer middle axle left wheel. The power consumed on air resistance was determined as a power difference between the driving and driven wheels [7].

English scientists have performed aerodynamic tests on a model of a car with a two-axle trailer in an aerodynamic tube. They also analysed the trailer ventilation system in case animals, for example, sheep or pigs would be transported in it [8].

2. Most widespread experimental methods for calculating a aerodynamic resistance coefficient

Every automobile has its own characteristic geometrical dimensions. These characteristic dimensions affect the resistance of air when driving the automobile. Air resistance is calculated by the formula [9]:

$$P_w = \frac{c_x \rho_w A v^2}{2}, \tag{1}$$

where c_x – aerodynamic resistance coefficient;
ρ_x – air density, kg·m^{-3};
A – frontal area of the automobile, m^2;
v – speed of the automobile, m·s^{-1}.

In the calculations, the air density was assumed to be 1.225 kg·m^{-3}. According to Formula 1, the frontal area and speed affect the force of air resistance. The aerodynamic resistant coefficient, which also significantly affects the air resistance, changes depending on the automobile shape, various bulges, spoilers and accessories.

The aerodynamic resistance coefficient may be determined in aerodynamic tubes; yet, such experiments are expensive and no aerodynamic tube of scientific level is available in Latvia. The key problem for such experiments is the fact that in real conditions an automobile moves, whereas the surrounding environment – the air – either moves at a lower speed or is stationary in still air. In an aerodynamic tube, the automobile is stationary, whereas the air moves. In many aerodynamic tubes, the air flow under the automobile is not adequate to real conditions, as its wheels are stationary on the ground and do not agitate the air in such experiments. Various methods are employed to obtain precise measurements, for example, conveyer aprons, additional air flows under the automobile and other techniques.

Road experiments are conducted on special testing grounds. Roads for tests have to have asphalt paving. The automobile may be towed by a long cable with a dynamometer. If the force of rolling resistance is determined, the force of air resistance is calculated by subtracting the rolling resistance value from the reading on the dynamometer. The cable has to be at least 50 m long, so that the automobile driving in the front does not create air flow. The automobile model may be placed on a small horizontal platform above the roof of the car. When moving, the reading of the dynamometer fastened to the automobile model has to be recorded. In this case, it is difficult to precisely model correct flow of air under the automobile.

The experimental automobile may be transported on a railway platform. The experimental automobile is placed on a smooth and flat platform that is pushed by a locomotive from the rear. The automobile fasteners let it freely move on the platform. Through the system of fastening levers, the automobile movement force is transferred to the dynamometer or is measured by means of a special tensometer. Discrepancies may arise from the platform vibrations due to the unsmooth road as well as because the base under the experimental automobile does not move [9].

In a simplified way, the coefficients of rolling and air resistance are determined by coasting the automobile. Coasting is done in the following way: the automobile engine is disconnected from its transmission after it has reached a certain speed. The automobile to be coasted has to be equipped with a device for precisely measuring momentary speeds. Coasting is done on a horizontal road in a windless period. The automobile is coasted within two speed intervals: I – at a quite high speed when air resistance is significant, while rolling resistance is approximately the same as at a low speed; II – at a low speed when air resistance is insignificant. Start and finish speeds and the corresponding periods of deceleration when coasting are registered within these speed intervals [9].

3. Experimental methodology for calculating the aerodynamic resistance coefficient

Various vehicle-trailer systems were used in the experiment. An automobile Renault Laguna and a microbus Renault Trafic were used as pulling vehicles. The experiment also involved the VAR company's two-axle semitrailer with a detachable tent and a carrying capacity of 2000 kg and the WM Meyer company's single-axle trailer with detachable tents of two kinds and a carrying capacity of 1000 kg.

A scientific mobile radar STALKER ATS was used for measuring speed. The radar measurement accuracy was ± 0.01 $km \cdot h^{-1}$, its range of measurement was 1-480 $km \cdot h^{-1}$, the target detection time was 0.01 s and the measurement distance was up to 2500 m.

An automobile scale QT250 was used to measure the weight of the automobiles and the trailers in the experiment. The experiment was carried out in Jelgava municipality on the motor road Svete-Vilce. The average air temperature +15 ºC; wind speed 1-4 $m \cdot s^{-1}$. The road surface was asphalt paving in good condition with an average rolling resistance coefficient of 0.015-0.020 [9]. The experiment exploited twelve pulling vehicle and trailer variations:

- Renault Laguna without a trailer (R-Laguna);
- Renault Laguna with a single-axle trailer without a tent (R-Laguna+Tr1ax);
- Renault Laguna with a single-axle trailer with a low tent (R-Laguna+Tr1ax+low tent);
- Renault Laguna with a single-axle trailer with a high tent (R-Laguna+Tr1ax+hight tent);
- Renault Laguna with a two-axle trailer without a tent (R-Laguna+Tr2ax);
- Renault Laguna with a two-axle trailer with a high tent (R-Laguna+Tr2ax+hight tent);
- Renault Trafic without a trailer (R-Trafic);
- Renault Trafic with a single-axle trailer without a tent (R-Trafic+Tr1ax);
- Renault Trafic with a single-axle trailer with a low tent (R-Trafic+Tr1ax+low tent);
- Renault Trafic with a single-axle trailer with a high tent (R-Trafic+Tr1ax+hight tent);
- Renault Trafic with a two-axle trailer without a tent (R-Trafic+Tr2ax);
- Renault Trafic with a two-axle trailer with a high tent (R-Trafic+Tr2ax+hight tent).

The coasting method was employed to determine the parameter c_xA – multiplication of the aerodynamic resistance coefficient and the frontal area – for the vehicle-trailer systems. This method was selected as the most available one for road experiments. The vehicle-trailer systems were prepared for the experiment. It involved correcting the air pressure in tyres in accordance with the producer recommendations, preparing the trailer body (assembling, disassembling or change of the tent) and measuring the vehicle-trailer system dimensions and weighing the systems.

The radar STALKER ATS was placed on a support and its beam was directed towards the vehicles moving down the road. Through a cable the radar was connected to a laptop computer. Both devices were switched on and the computer program Stalker ATS was started in the laptop computer. The experiment was carried out by two individuals – a driver and an operator.

The starting position was located approximately 200 meters before the radar. The automobiles were accelerated from the starting position to reach a speed being, on average 5-15 km higher than the speed needed for the measurement. Such a speed has to be reached before the vehicle-trailer system enters the radar detection zone. After entering the zone for the measurement, the driver of the vehicle-trailer system makes a beep and puts the automobile into neutral, while the measurement operator activates the radar. Upon reaching the minimum speed, the driver makes a second beep and the operator stops registering the data.

Coasting was done on a horizontal road. The automobile was coasted within two speed intervals: Interval I – at a quite high speed when the air resistance was significant, while the rolling resistance was approximately the same as at a low speed. The first speed regime was set within a range from 55 km·h^{-1} to 50 km·h^{-1}. Interval II – at a low speed when the air resistance was insignificant; in this case, the start speed was 25 km·h^{-1} and the finish speed was 20 km·h^{-1}.

To exclude the effects of any road gradients as well as wind on the parameters of coasting, the vehicle-trailer systems were coasted on the same section of the road, just driving in the opposite direction. Three measurements were done in each direction. Based on these measurements, average time periods of deceleration were calculated.

The parameter c_xA is calculated by the following formula:

$$c_xA = \frac{1.633\delta' m_a (j_1 - j_2)}{(v_1^2 - v_2^2)}, \tag{2}$$

where δ' – coefficient of rotating masses in the neutral gear; it is assumed to be 1.04;
m_a – weight of the automobile or vehicle-trailer system, kg;
j_1 – deceleration of the automobile in the highest speed regime, m·s^{-2};
j_2 – deceleration of the automobile in the lowest speed regime, m·s^{-2};
v_1 – speed of the automobile in the highest speed regime, m·s^{-1};
v_2 – speed of the automobile in the lowest speed regime, m·s^{-1} [9].

The coefficient of 1.633 in Formula 2 is calculated for the air density of 1.225 kg·m^{-3}. Knowing the air resistance coefficient c_xA, one can calculate the power consumed to overcome air resistance, W:

$$N_w = 0.6125 c_x A v^3 \tag{3}$$

After the experiment is over, the Staler ATS program produces the necessary parameters in the coasting regime, and calculations are performed based on Formulas 2 and 3.

4. Result analysis

The automobile streamline parameter c_xA is derived from the experimental data and used to construct comparative graphs (Figure 1). The aerodynamic resistance coefficient c_x may also be derived from this parameter. To perform such a calculation, it is required to determine the frontal area of the vehicle-trailer system by means of a planimeter, for example, from a technical drawing. Since the aim of the present research was not to determine the aerodynamic resistance coefficient for the vehicle-trailer system but to calculate the power needed to overcome the air resistance, the parameter c_xA was employed to obtain more precise results.

The pulling vehicles Renault Laguna and Renault Trafic presented the lowest value of c_xA, 0.69 and 1.01, respectively. The Renault Laguna with the single-axle trailer without a tent presented a c_xA value of 1.75. A slightly better result – 1.66 – was obtained if covering the single-axle trailer with a low tent. This trailer without a tent increased the parameter c_xA 2.53 times. If pulling this trailer by the Renault Trafic, the increase was insignificant. Besides, the highest increase was observed for the trailer with a tent, as the frontal area of the trailer increased. If pulling the single-axle trailer with a low tent and without a tent by the Renault Laguna and the Renault Trafic, very different trends regarding increases in the air resistance were identified, as the combination of the Renault Trafic with a trailer did not increase the frontal area; in both cases, the trailer was fully covered by the frontal area of the pulling automobile. A small increase in the air resistance for the Renault Trafic with the single-axle trailer with a low tent may be explained by the air flow hitting the trailer.

The single-axle trailer with a high tent in combination with both pulling vehicles presented similar values of the parameter c_xA, 2.59 for the Renault Laguna and 2.84 for the Renault Trafic. This similarity for both pulling vehicles may be explained by the change in the frontal area if using a high tent. In the case of the Renault Laguna, the frontal area changed significantly, while for the Renault Trafic it changed slightly, by approximately 5 %.

The cross-sectional dimensions of the two-axle trailer considerably exceeded those of the Renault Laguna. For this reason, an increase in the value of c_xA up to 3.31 might be observed. In this case, the Renault Trafic presented a better performance result, c_xA = 2.84.

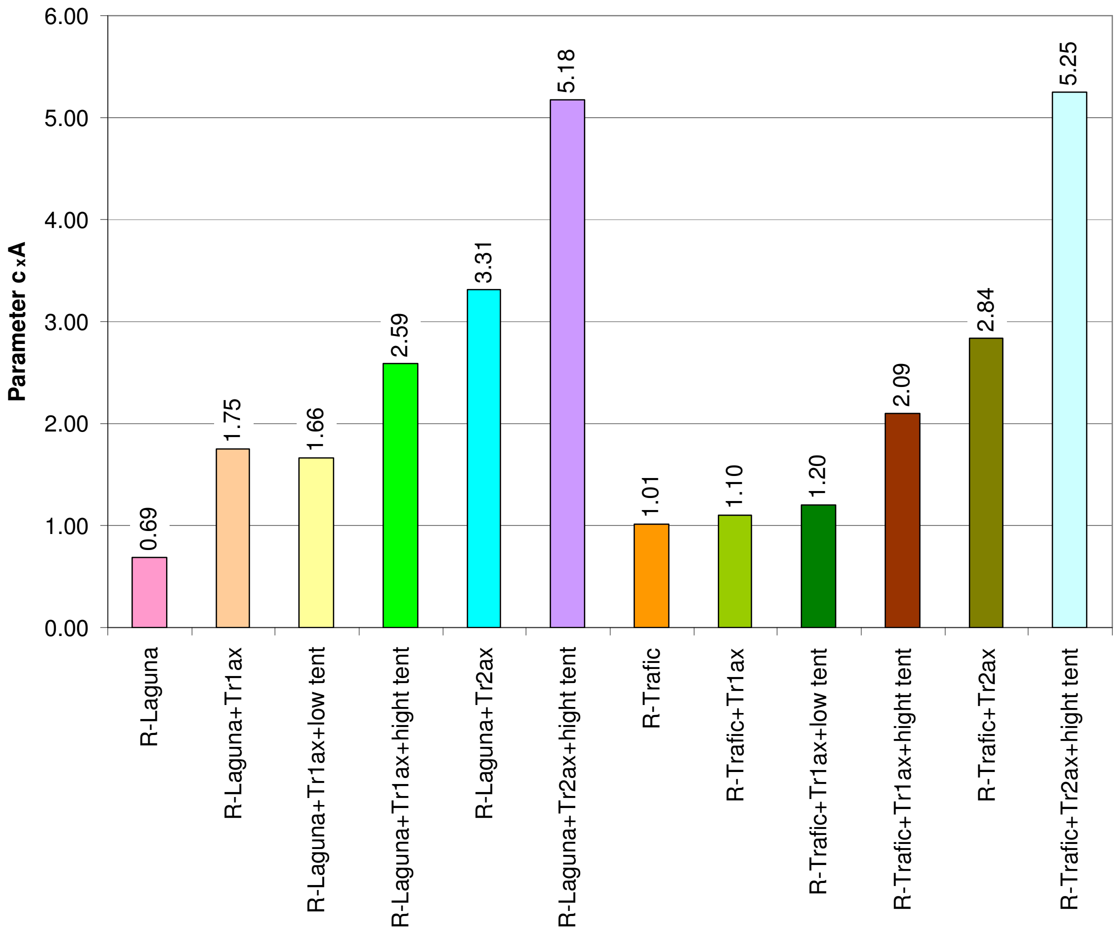

Fig. 1. **Air resistance parameter c_xA for selected vehicles**

The two-axle trailer with a high tent in combination with both pulling vehicles presented a similar value of the parameter c_xA: 5.18 for the Renault Laguna and 5.25 for the Renault Trafic.

The power consumed to overcome the air resistance for the Renault Laguna with a trailer may be calculated by Formula 3, and the results are presented in Figure 2. The speed limit for cars with a trailer is 80 $km \cdot h^{-1}$ or 22.2 $m \cdot s^{-1}$. At such a speed, the Renault Laguna without a trailer needs the power of 5.6 kW to overcome the air resistance. In combination with the single-axle trailer without a tent and with a low tent, at 80 km·h^{-1}, the vehicle-trailer system consumes 12.2 kW and 11.6 kW, respectively, of the engine power. A significant increase in power consumption may be observed if using the single-axle trailer with a high tent as well as the two-axle trailer. The power consumed by the Renault Laguna pulling the two-axle trailer to overcome the air resistance, at 80 km·h^{-1}, increases to 36.6 kW. In countries where the speed limit for such a vehicle-trailer system is higher, it is not advised to exceed the speed of 90 km·h^{-1}, as the power consumed by it to overcome the air resistance exceeds 86 kW at 110 km·h^{-1}, which significantly increases the consumption of fuel.

The power consumed to overcome the air resistance for the Renault Trafic with a trailer may be calculated by Formula 3, and the results are presented in Figure 3.

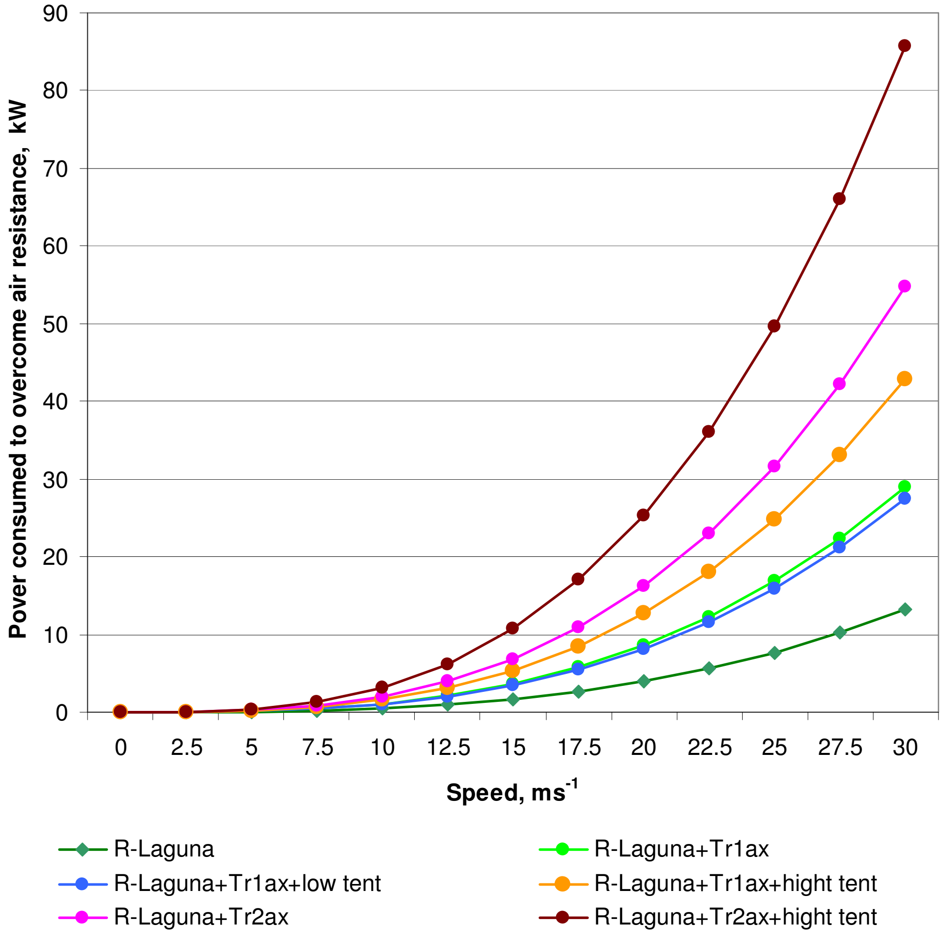

Fig. 2. **Power consumed to overcome air resistance for a pulling automobile Renault Laguna**

The power consumed to overcome air resistance for the Renault Trafic with a trailer is very similar to the case with the single-axle trailer with and without a tent as well as to the case with the automobile without a trailer. In these cases, the power consumption ranges from 7.1 to 8.4 kW at 80 km·h^{-1}.

The Renault Trafic in combination with the single-axle trailer with a high tent and in combination with the two-axle trailer presented a similar trend as for the Renault Laguna with the same trailers. In these cases, the power consumed was 14.6 kW, 19.8 kW and 36.6 kW at 80 km·h^{-1}. It is also advised that this vehicle with a large-size trailer does not exceed the speed of 90 km·h^{-1}, which might significantly increase the consumption of fuel.

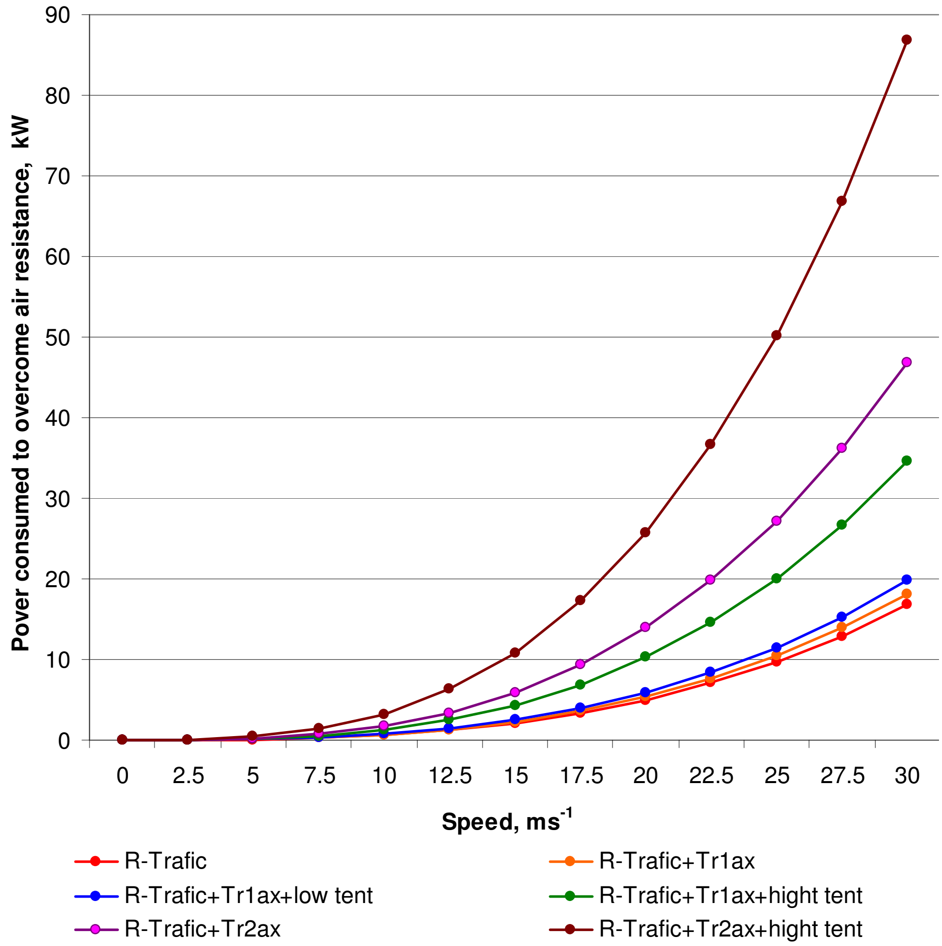

Fig.3. **Power consumed to overcome air resistance for an automobile Renault Trafic**

Conclusions

1. Research studies on vehicle-trailer systems are in the spotlight, as decreasing the air resistance leads to saving fuel.
2. Traditional methods such as an aerodynamic tube and road experiments with dynamometers on the driving and driven wheels are employed to determine the aerodynamic resistance coefficient. Road experiments can give results of higher accuracy.
3. If pulling a car trailer, it is advised to cover the trailer with a low tent, which improves the air resistance parameter c_xA by 5.14 % in case the trailer is pulled by a Renault Laguna and by 9.1% if the frontal area of the trailer is much smaller, as it was in the case with the Renault Traffic.
4. If a single-axle trailer is pulled by a Renault Laguna at 80 $km \cdot h^{-1}$, the power consumed to overcome the air resistance is insignificant, 11.6-12.2 kW; yet, it increases to 18.1 kW if using a high tent.
5. If a two-axle trailer with a tent is pulled by a Renault Laguna at 90 $km \cdot h^{-1}$, the power consumed reaches 49.6 kW.
6. If pulling a single-axle trailer by a Renault Trafic, the power consumed to overcome the air resistance does not exceed 18 % compared with that consumed if pulling no trailer. The relatively small change may be explained by the large frontal area of the pulling vehicle in comparison with the frontal area of the trailer.
7. If pulling a two-axle trailer with a high tent by both the Renault Laguna and the Renault Trafic, in both cases the losses of power to overcome the air resistance are similar, 36.1-36.6 kW, respectively.
8. If pulling an unladen trailer, it is advised to take the high tent off to reduce the power consumed to overcome the air resistance.

9. In all experimental cases pulling a trailer at the speed more than 90 $km \cdot h^{-1}$ significantly increases the power and amount of fuel consumed to overcome the air resistance.

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