REDUCING AIR RESISTANCE AND FUEL CONSUMPTION IN PASSENGER CAR-CARAVAN COMBINATIONS USING ROOF SPOILER PROTOTYPES

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Abstract. One way to increase the load carried by a car is to tow trailers. Experimental research studies were conducted with a Volvo V70 passenger car and a Bailey Ranger 440/4 caravan. The research studies determined fuel consumption when driving at a speed of 90 km h^{-1}. To reduce fuel consumption, a prototype spoiler mounted on the rear part of the car roof was used in the experiments. The experiments were conducted at 2 different angles of inclination of the spoiler prototype, 20º and 30º, as well as with a roof luggage box. Comparisons of fuel consumption were made for a car without a caravan. The experiments were conducted in extra-urban mode while driving along the selected route in the outbound and return directions to assess the impact of road inclination and wind on fuel consumption. The car fuel consumption was determined in a constant speed mode by a fuel consumption measurement device AVL KMA Mobile. The experiments found the lowest fuel consumption for the roof spoiler prototype set at 30º. The fuel consumption with the spoiler was 13.5% lower than without the spoiler. To optimize the aerodynamic shape of passenger cars and large trailers and to minimize the air resistance of a passenger car towing a large trailer, it is recommended to design and implement a variable-angle roof-mounted spoiler.

Keywords: car, caravan, fuel consumption, roof spoiler prototype, road test.

Introduction

Air resistance is a kind of resistance that can increase fuel consumption in cars. The effect of air resistance is greatest at high speeds. If the car pulls a trailer, the volume or weight of the load can be increased, thereby reducing transport costs. Sometimes, special trailers are used to meet specific needs, e.g. to transport large volumes of light loads, or to travel by car and caravan. A bulky goods truck has a large frontal area; therefore, pulling trailers or semi-trailers that are larger than the trailer truck creates additional air resistance.

To reduce the air resistance, trucks are equipped with special spoilers to deflect the airflow across the load compartment. Some spoilers, such as cab roof spoilers, can also be adjustable to adjust the spoiler angle for various semi-trailers. In the case of cars with trailers, the frontal area of the trailer could significantly exceed the frontal area of the car. In such cases, the air resistance could increase several times, which also increases fuel consumption at higher speeds. A car with a caravan can travel as much as 3000-5000 km during a single recreational trip, which increases the cost of the trip due to the increase in fuel consumption, as well as CO_2 emissions.

As the fuel consumption of a trailer truck has a significant impact on the cost of transport, the effect of rolling resistance and air resistance on the fuel consumption of a trailer is researched by conducting coastdown experiments. The experiments showed that a 30.5 tonne vehicle could reduce fuel consumption by 4.7% through optimisation [1].

Michael Gerard Connolly et al. have researched changes in air resistance of passenger cars equipped with various extra elements. Such elements could reduce air resistance by 20%, yet such body design elements might not always be installed on cars used in road traffic [2]. Cihan Bayindirli et al. in their research on 1/32 scale models of trucks and trailers in a wind tunnel found an air drag coefficient of 0.608 for the truck, while for a combination of a truck and a trailer the air drag coefficient increased to 0.704, which was 15.8% higher [3]. It was proposed to reduce the aerodynamic drag of the truck by more angled windscreens and by covering the rear wheels of the trailer with special deflectors [4]. Installing a new design spoiler on the cab roof of a truck can reduce air resistance by 11.4%, resulting in fuel savings of up to 6% [5].

L. Salati et al. have tested 1/10 scale models of trailer trucks and trailers in a wind tunnel. Special wind deflectors were mounted on the front part of the trailer and on the rear part of the trailer to reduce the air resistance by 10% [6]. Jing Peng et al. have tested truck models in the wind tunnel. Modifications have been made to the front part of the cab by extending the engine section to 500 mm and changing the windscreen inclination. This resulted in an 8.5% reduction in aerodynamic drag [7]. By redesigning the

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rear of the trailer truck and designing special deflectors, the air resistance could be reduced by 3%. However, such deflectors increase the overall length of the trailer, which is not desirable [8].

Muhammad Atif et al. focused on improving the aerodynamic drag of a car with a horse trailer by changing the gap between the car and the trailer, the front shape of the trailer, the roof curvature and the tilt angles of the upper and lower diffusers of the trailer. The optimisation of the shapes resulted in a reduction in air resistance, which has led to a 7% reduction in fuel consumption [9]. The shapes of the car and its trailer have been optimised through testing scale models. The best results were achieved by installing special diffusers on the rear of the car and special spoilers on the front and rear of the dual-axle trailer and removing the side skirts. The aerodynamic drag was reduced by up to 24.5% compared with the standard version, reaching C_d = 0.35, which was a very good result for such combination [10].

Yasar Kocaefe et al. focussed on the optimisation of a small teardrop-shaped caravan by using a mathematical model. The dimensions of the car slightly exceeded those of the caravan. The simulation was conducted at a speed of up to 140 km·h^{-1} [11]. Some research studies on the effect of a cargo trailer on fuel consumption achieved the best results with the high height trailer canopy frame removed, resulting in a fuel saving of 0.3 l·(100 km)$^{-1}$. Placing a streamlined shape plastic cover on the trailer resulted in a fuel saving of 0.2 l·(100 km)$^{-1}$. For small loads, the researchers suggest carrying the load in the car and not using a trailer, which gives the greatest fuel savings [12].

Very large caravans, usually pulled by pickup trucks, are allowed in the USA. Such combination results in very high air resistance, which is why scientists have produced several scientific qualification papers on reducing the air resistance of such vehicle combinations [13; 14].

There has been research on the potential for reducing the air resistance of a car with a caravan by using car roof spoilers. Such a spoiler can reduce air resistance and fuel consumption, which is the aim of the present research. The present research aims to road test a car with a caravan to identify the effect of changing the angle of the car roof spoiler on air resistance and fuel consumption.

Experimental fuel consumption research methodology

A road test was conducted to identify the effect of change in the air resistance of a car with a caravan on fuel consumption. The road test was conducted using a Volvo V70 and a Bailey Ranger 440/4 caravan. The main technical characteristics of the car and the caravan are presented in Table 1.

Table 1

Technical characteristics of the vehicles tested on the road

No.	Parameters	Parameters	
		Car Volvo V70	Caravan Bailey Ranger 440/4
1.	Production year	2006	1997
2.	Fuel type	Diesel fuel	-
3.	Engine displacement	2401 cm^3	-
4.	Engine power	185 Hp @ 4000 rpm	-
5.	Torque	400 N·m @ 2000 rpm	-
6.	Curb weight	1630 kg	845 kg
7.	Maximal weight	2160 kg	1077 kg
8.	Length	4710 mm	5925 mm
9.	Width	1804 mm	2190 mm
10.	Height	1465 mm	2700 mm
11.	Top speed	225 km·h^{-1}	-
12.	Maximum speed with trailer	130 km	-
13.	Permitted trailer load with brakes	2000 kg	-
14.	Fuel consumption extra urban (NEDC)	6.4 l/100 km	-
15.	Air drag coefficient [15]	0.30	-

The experimental car and the caravan are shown in Figure 1.

Fig. 1. **Car Volvo V70 and caravan Bailey Ranger 440 tested on the road**

The road test used an AVL KMA Mobile to measure fuel consumption. The main parameters of the fuel consumption device were as follows: the density gauge range – 0.5…2.0 g·cm^{-3}; ambient temperature from -10 °C to + 50 °C; fuel supply pressure to the engine – 0.3…3.0 bar (2.0 bar during the road test); voltage – 12 V DC [16].

The road test was done at a constant speed of 90 km·h^{-1}, adjusted by the cruise control system using the fuel consumption measurement device AVL KMA Mobile. The measurement device was installed in the luggage compartment of the car. It was controlled by a laptop computer. The fuel measurement device, in accordance with AVL recommendations [16], is connected to the fuel supply and return lines of the Volvo V70's fuel system. Prior to the experiment, the vehicle engine, transmission, and tires are warmed up by driving to the experiment site, which is located 10 km from the experiment preparation location. The experimental vehicle was equipped with a spoiler at the rear of the roof, which diverted the main air flow across the caravan. The spoiler prototype is attached to the car's roof rack at the rear part of the vehicle (see Fig. 2).

The measurements were taken on the car of 5 different combinations: the car without the caravan; the car with the caravan; the car with the caravan and a 20° roof spoiler; the car with the caravan and a 30° roof spoiler; the car with a roof box and the caravan (see Fig. 2).

a) b)

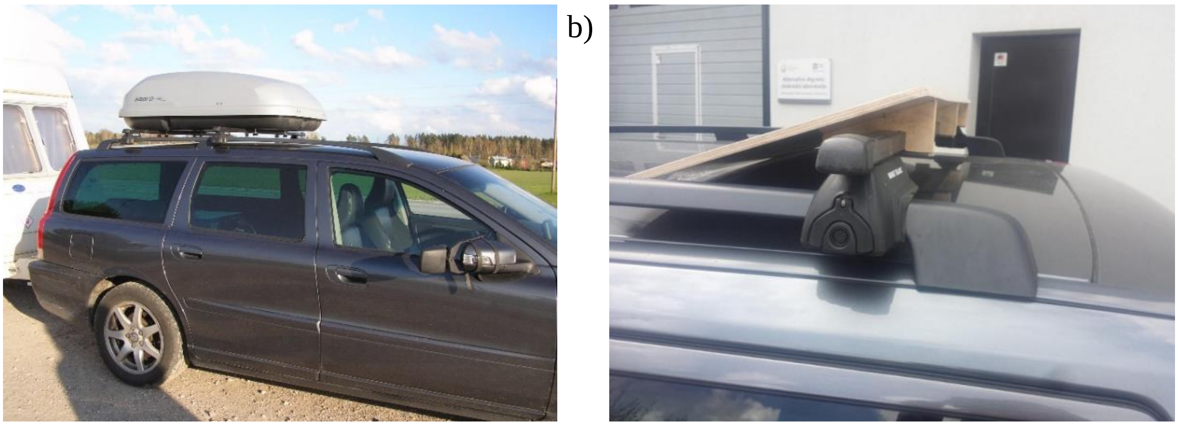

Fig. 2. **Volvo V70 with a) roof box b) roof spoiler prototype**

The road test was done on a road section between Jelgava city and Dorupe village on the P97 motorway (see Fig. 3), driving back and forth in at least 3 trips. The experiments were conducted between 11:00 and 15:00, a period characterized by low traffic intensity. If during a measurement another vehicle travelled in the opposite direction or overtook the test vehicle, the measurement was considered invalid and subsequently repeated. One round trip constituted one replication. In this way, the potential slope of the road and the direction of the wind, which blew at an angle of about 45º towards Jelgava during the road test, were taken into account. The rolling resistance coefficient was in the range of 0.012–0.014. The road slope angle does not exceed 1°. Meteorological conditions during the road test: air temperature 13-15°C, wind speed 2-3 m·s^{-1}.

Fig. 3. **Experimental road section, the wind direction during the experiments is indicated by green arrows**

During the road test, the tyre pressure of the car was 2.5 bar, the caravan 3.0 bar. The tires used on the vehicle, 215/55R16 Michelin Primacy 3, have 70% tread remaining. The starting point for the fuel consumption meter was a specific marker on the side of the road, e.g. a road sign. A criterion for the duration of the measurement was 60 seconds. After each road test stage the appropriate equipment, caravan or spoiler, were installed and the road test continued. After the road test, the fuel consumption measurement data were exported to Excel and processed based on a 60-second measurement data segment.

Fuel consumption, l·(100 km)$^{-1}$, is calculated using the following equation:

$$Q = \frac{V10^5}{tv}, \tag{1}$$

where V – amount of fuel consumed during the experimental measurement, l;
t – duration of the experimental measurement, s;
v – vehicle speed during the experiment, m·s^{-1}.

Results and discussion

After processing the experimental data, the fuel consumption was converted to the distance travelled, analysing the speed of the car during the road test. The fuel consumption determined experimentally is shown in Figure 4.

The fuel consumption of the car without the caravan at a steady speed of 90 km·h^{-1} was 4.96 l·(100 km)$^{-1}$. This was a positive result for a car with a 2.4 litre engine capacity. When the caravan was attached to the car, fuel consumption increased to 10.77 l·(100km)$^{-1}$, which was 117% more. The main reason for the increase in fuel consumption was the air resistance, as the frontal area increased from 2.27 m^2 to 5.32 m^2.

A 20° spoiler at the rear of the roof reduced fuel consumption by 1.05 l·(100km)$^{-1}$. Increasing the spoiler angle to 30° resulted in 1.45 l·(100km)$^{-1}$ less fuel consumption than in the case of the car with the caravan. A. S. White in his studies found that installing a deflector on the car roof at a 45-degree angle can reduce the aerodynamic drag of a car–trailer combination by 23% [17]. In our research, a similar effect was achieved, but the best results were obtained with a spoiler mounted at a different angle. This is related to the specific shape characteristics of the car and trailer, as well as the drawbar length. The decrease in fuel consumption was 13.5% less than in the case of the car with the caravan.

The road test was done without a spoiler but with a luggage box on the roof of the car. In this case, a decrease in fuel consumption was 0.09 $l\cdot(100km)^{-1}$. Preliminary research studies have shown that a roof box for a car without a caravan increases fuel consumption by 20% on average, while in combination with a caravan, a roof box has a positive trend in fuel consumption.

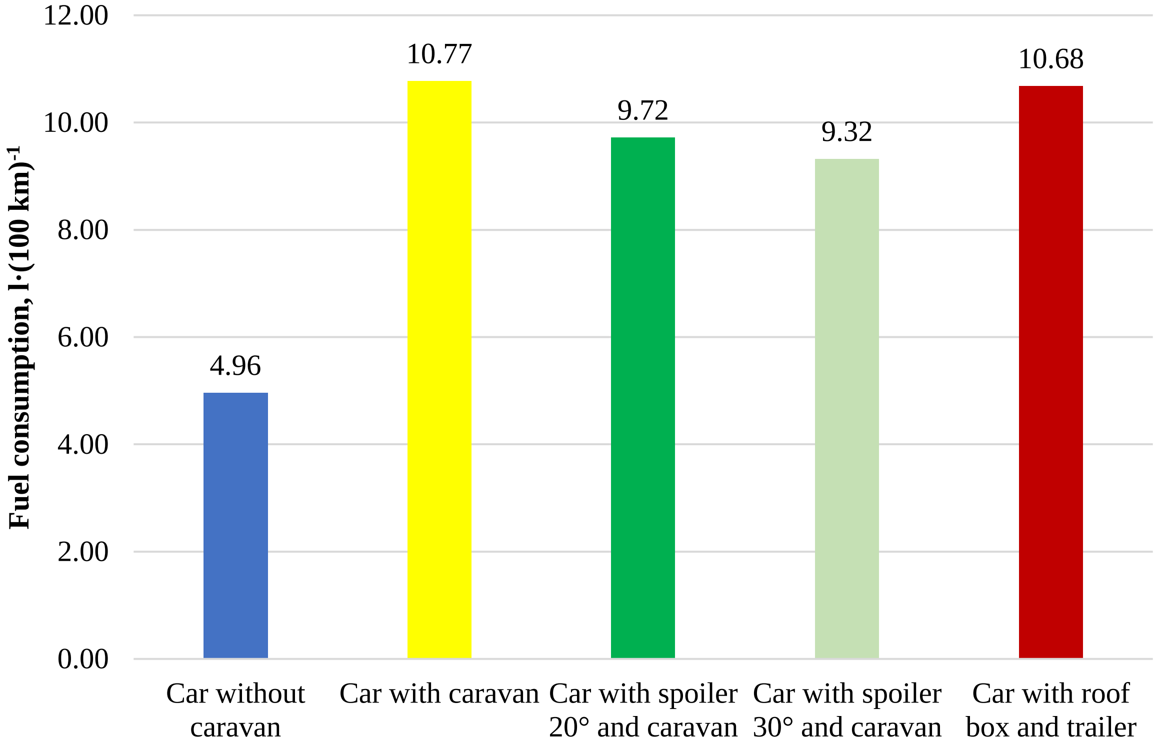

Fig. 4. **Fuel consumption of the car and the caravan**

After processing the fuel consumption data, the cost per 100 km was calculated (see Fig. 5).

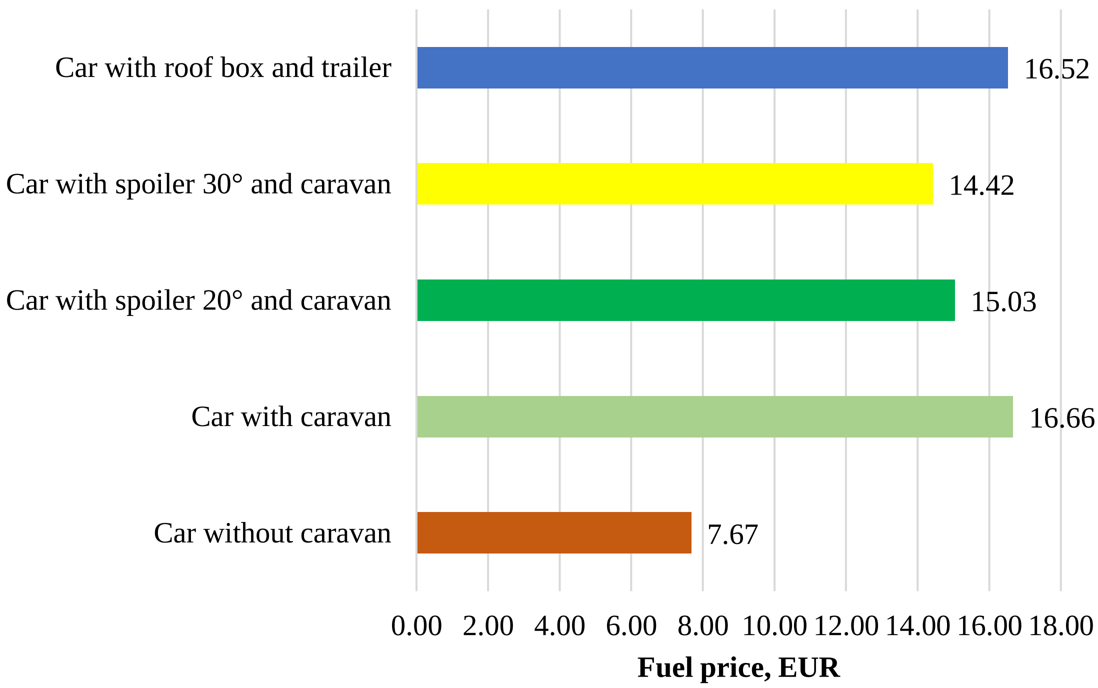

Fig. 5. **Fuel costs per 100 km for the car with the caravan**

Since the cost of diesel fuel per 100 km was calculated considering the price at Neste petrol stations on 08/03/2025, according to the results of the road test, the percentage increase in fuel consumption for the caravan was analogous to the previous analysis.

In long trips with a caravan from Latvia, auto tourists usually travel approximately 3000 km per trip, which leads to a saving of EUR 73.20 if using a 30° spoiler. As the research on the spoiler effect was conducted for a specific car, different spoiler angles might be effective for other cars and caravans. It is therefore useful to design a spoiler with a caravan-specific spoiler angle that can be adjusted by a servomotor.

Reducing fuel consumption on the road also reduces CO_2 emissions. Volvo V70 CO_2 emissions, according to the technical characteristics, amount to 179 $g \cdot km^{-1}$ [15]. With the caravan, emissions reached 389 $g \cdot km^{-1}$. If using the spoiler, the CO_2 decrease was 53 $g \cdot km^{-1}$, and for a 3000 km trip the decrease totalled 159 kg CO_2.

Conclusions

1. Caravans increase air resistance but allow more transport work. When analyzing the air resistance of a car with a caravan, it should be considered that the same caravan with different cars can have different effects on the air resistance.
2. A prototype air drag reduction spoiler for a car with a caravan has been developed, which can be mounted on the rear roof of the car and reduces air resistance.
3. The experimental car with a caravan had 117% higher fuel consumption than the experimental car without a caravan.
4. The Volvo V70 wagon-type car and the Bailey Ranger 440 caravan had the lowest air drag coefficient and, consequently, the lowest fuel consumption of 9.32 l $(100\ km)^{-1}$ with the spoiler positioned at 30° to the rear of the roof. The fuel consumption was 13.5% lower.
5. The 30° spoiler installed on the experimental car resulted in fuel saving of 1.45 l $(100\ km)^{-1}$, which reduced the cost of the trip and the CO_2 decrease by 53 $g \cdot km^{-1}$ compared with the car with the caravan having no spoiler.
6. For cars and caravans of other body structures, spoiler angles might be different, depending on the car body shape, the caravan body shape and the distance of the caravan body from the car body.
7. To optimally adapt the spoiler angle to a particular caravan or other type of trailer, it is necessary to develop spoilers with variable angles. It is recommended to use servomotors with remote control to change the angles so that the lowest values of air resistance and fuel consumption could be adjusted while driving.
8. For the experimental vehicle combination, the installation of a luggage box without a spoiler reduced fuel consumption by 1% compared with the case without additional equipment. This trend was different from that for a luggage box installed on the car without the caravan. Using adjustable-angle spoilers and other car body types is recommended for future research.

Author contributions

D. B.: conceptualization, methodology, validation, experiment, visualization, writing. I. J.: formal analysis, literature analysis, schedule administration, writing – editing, references. J.O.: experiment, visualization, data analysis. All authors have read and agreed to the published version of the manuscript.

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