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Effect of the Aerodynamic Elements of the Hatchback Tailgate on the Aerodynamic Drag of the Vehicle

Michal Fabian[1*], Róbert Huňady[1], František Kupec[1], Tomáš Mlaka[2]

[1] Faculty of Mechanical Engineering, Technical University of Košice, Letná 1/9, 042 00 Košice, Slovakia
[2] D.G. Engineering; Sládkovičova 5, 984 01 Lučenec, Slovakia
* Corresponding author's e-mail: robert.hunady@tuke.sk

ABSTRACT

The paper deals with the possibilities of reducing aerodynamic drag and modifying airflow in the rear of a hatchback vehicle. This body type is characterised by the formation of turbulent flow behind the vehicle, which has a significant effect on the fouling of the tailgate, including the window. By modifying the geometry of components such as the roof spoiler and additional aerodynamic finlets on the sides of the rear window, the airflow is optimised to reduce aerodynamic drag and thus fuel consumption. Three spoiler designs are proposed, one of which is processed to prototype quality using CAD tools. The body of the vehicle with this design is subjected to CFD analysis and evaluated in terms of the given criteria. The results of the simulations are compared with a model of a production vehicle and a sports version vehicle to assess the effect of the geometry on the flow parameters.

Keywords: aerodynamics, computer fluid dynamics, aerodynamic drag reduction, passenger vehicle, roof spoiler, finlets.

INTRODUCTION

Aerodynamics deals with the flow of air or other gas and the way in which objects such as airplanes, cars, turbine blades and the like pass through these media. As these objects pass through the air, there is a mutual reaction and thus a change in flow. The findings from the analysis of the flow around the objects are used mainly by the aerospace and automotive industries. When the aviation industry is mainly concerned with providing the lift needed to fly an aircraft, in the automotive industry it focuses on reducing aerodynamic drag. At a time when European legislation by emission standards is pushing motor vehicle manufacturers to reduce emissions, aerodynamics is being offered as one of the ways to achieve the required emission values given by legislative requirements. Saving every gram of fuel makes sense. One way to reduce fuel consumption and emissions is to make a significant contribution to improving vehicle aerodynamics, as at speeds above 100 km/h, aerodynamic drag represents the greatest drag of a moving vehicle.

The influence of aerodynamics is already visible in the beginnings of the automotive industry. This is evidenced by Camille Jenatzy's torpedo-shaped vehicle, which in 1899 exceeded a speed of 100 km/h [1]. This period in the late 19th and early 20th centuries can be called the first phase of the application of aerodynamics in car design, when designers sought inspiration in the product shapes of other technical fields. They were inspired by e.g. airships from the air force or the already mentioned military torpedo. The second phase in the development of vehicle aerodynamics dates to the 1930s, when the automotive designer Paul Jaray, inspired by the shapes of the jets, purposefully creates the bodies of the so-called jet shape. One of the most famous designs are the TATRA 77 (1934) and TATRA 87 (1937) cars [1].

His successor Wunibald Kamm creates the BMW 328 from 1940. Not to mention the legendary VW Beetle by Ferdinand Porsche, which began to develop in 1931. For us, the modern third phase of vehicle aerodynamics, which is focused on optimizing body details dates to '70s of the 20th century. The design of vehicles of this stage is focused on maximum functionality and efficiency. Janseen and Hucho in [2] describe the optimization of Volkswagen Golf Mk.1 and Scirocco Mk.1 body details. Hucho then publishes his findings in [3], where he deals with the issue of body optimization in wind tunnels. In the summary publication [2] Hucho describes the history of the implementation of aerodynamics in the construction of car shapes and summarizes the theory in this area. The seventies of the twentieth century deal not only with reducing aerodynamic drag, e.g. Marte et al. [4], Morelli et al. [5] and Shibata et al. [6] but other problems related to aerodynamics such as aerodynamic noise are also beginning to be investigated. The issue of aerodynamic noise is dealt with e.g. Chanaud and Muster [7].

Furthermore, the relationships between aerodynamics inside the engine compartment, which are discussed by Emmelmann and Berneburg in [8], and the impact of aerodynamics on emission reduction, which are discussed by Rouméas et al. in [9], are being investigated. The named authors and their work should be taken as a selection of the best known, because many other scientists and entire development teams of automobiles also deal with this issue.

With the advent of computer technology and simulation software, experiments from wind tunnels have been transferred to computer laboratories. Most calculations are performed on virtual car models. Shankar and Devaradjane [10], Chode et al. [11] and Song et al. [12] address this issue. In 2016, Thomas Schuetz and his team published 26 co-authors, one of whom is W.H. Hucho monograph [13], in which he summarizes the current theory of aerodynamics and expands it with modern simulation calculation methods CFD (Computational Fluid Dynamics), which simulates aerodynamic calculations in a virtual computer environment. Katz deals with the issue of aerodynamics in motorsport in [14]. Kumar et al. [15] discussed the optimization of specific car parts. They performed a comprehensive analysis of the vehicle with aerodynamic optimization of the shape of the rear bumper with the air duct at angles from 0° to 13°. According to the results, at certain angles, the wake region behind the vehicle was reduced and thus the aerodynamic drag decreased from 0.3454 to 0.2322. The best results were obtained with a 12° angle of inclination of the air channel. The analysis was performed by CFD software ANSYS Fluent.

Modifications to the rear of the car using spoilers, added slats and their effects on the overall air resistance of the car have also been discussed by several authors. Hamut et al. in [16] dealt with the effect of rear spoilers on the aerodynamic drag of a land vehicle. The effects of the diffuser position in the floor of the rear of the car and the effect on the lifting and resistance force at 60 km/h with angles of 10º, 15º, 20º and 30º were investigated by Baek et al. in [17]. In dissertation thesis [18], Mustafa C. investigated the aerodynamic effects of a car rear spoiler on a passenger car using the CFD method. Ferraris A. et al. in [19], by optimizing the shape of the elements and adding individual shapes to the whole body, they devoted themselves to the modification of the experimental car XAM 2.0. They obtained their results using the CFD method, while also correlating between the results of virtual and experimental analysis in the Pininfarinna wind tunnel. Salama Y. et al. conducted an aeroacoustic study, which they present in [20]. Using wind tunnel testing, they analyze the impact of ribs and finlets on aeroacoustic properties and determine the positive impact on reducing the broadband noise emitted by the profiles.

Currently, the production of a single model of a European vehicle takes at least 8 years. During this production period, vehicle manufacturers are forced to adapt to the requirements of reducing emissions and increasing vehicle efficiency, which adds to the development and production costs. Thus, opportunities for additional body modifications to reduce the air drag coefficient are provided by facelifts. These are mainly modifications to some exterior components to make them cost-effective. The design changes therefore mainly concern plastic parts, as they are cheaper to produce than sheet metal parts.

This paper presents how the process of modifying the selected components is carried out. The aim is to modify the airflow behind the vehicle in order to reduce the aerodynamic drag of the vehicle and thus increase its efficiency. In the case at hand, this flow will be guided by modifying the spoiler and adding side finlets, which are part of the rear doors of the vehicle. In addition to reducing the vehicle's drag, a secondary beneficial effect is to move the air further away from the vehicle along its length, resulting in a reduction in pollution of the rear window of the tailgate.

AERODYNAMICS OF ROAD PASSENGER VEHICLES

A vehicle moving on the road is exposed to various resistances. The total resistance of a moving vehicle is the sum of rolling resistance, acceleration resistance, gravity, and air drag. In order to moving of the vehicle forward, it is necessary to overcome these resistances.

The value of the air drag coefficient c_D is used to calculate the air drag. Air drag depends not only on the shape of the body, but also on other factors, such as its size, surface roughness, air density, velocity, but also the flow, whether it is laminar or turbulent. Individual body shapes have different coefficients of air drag, while a body with a circular cross-section has a drag coefficient of 0.47, a cube-shaped body has a drag coefficient of 1.05, but if we rotate this body by 45° so that the edge of the cube faces forward, the drag coefficient decreases to 0.8. A body that has a jet shape (tears or drops) has a drag coefficient of only 0.05 [21]. The individual shapes and their coefficients of air drag are shown in Figure 1.

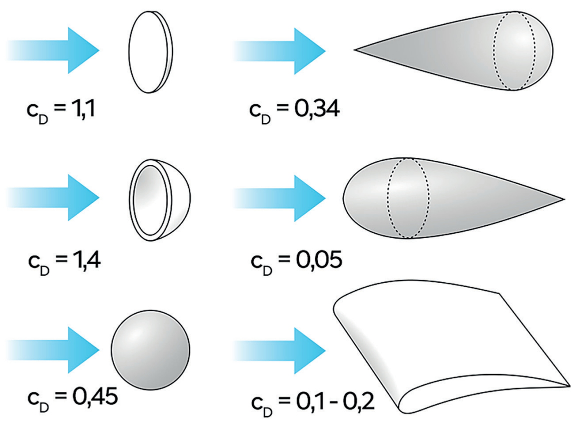

Fig. 1. Coefficients of air drag of basic shapes.

The aerodynamic properties of vehicles are a consequence of aesthetic economic and functional properties. The performance, handling and comfort of road passenger vehicles are significantly affected by the aerodynamic properties of vehicles. Low air drag is a prerequisite for lower fuel consumption. But the other aerodynamic properties of vehicles are not negligible and depend on the air flow around the vehicle. These features include, for example: crosswind stability, wind noise, body, headlight or glass contamination, engine, transmission and brake cooling, and finally interior heating and ventilation.

At lower speeds, the rolling resistance of the rolling wheels of the vehicle is also dominant. The wider the tires, the greater the contact area with the road and the greater the rolling resistance. However, in addition to the aerodynamic drag of the vehicle, it can simply be said that rolling resistance is constant if we do not take into account the change in driving conditions. The dependence of rolling resistance and air drag of the vehicle (Fig. 2) shows the significance of the increasing resistance caused by the aerodynamic properties of the vehicle. The air drag increases with the square of the vehicle speed, so at speeds above 100 km/h (speed may vary depending on the specific vehicle) it becomes dominant [22, 23].

Aerodynamics deals not only with external flow, but also with problems of internal flow systems. Because the outer and inner current fields are interconnected, and both must be considered at the same time.

According to the laws of fluid mechanics, motor vehicles are considered to be surface objects located in close proximity to the road. Their detailed geometry is very complex, provided by a number of holes and cavities, such as the engine

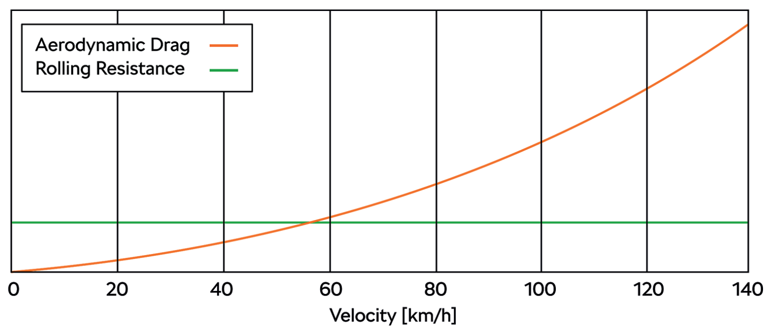

Fig. 2. Air drag compared to rolling resistance.

compartment or the vehicle fairing, which are connected to the external airflow and, together with the rotating wheels, increase the complexity of the airflow. The airflow around the vehicle is fully three-dimensional. Turbulent flow is created at vehicle surfaces. Large turbulent flow is created in the rear of the vehicle and in many cases contains large end air vortices.

Another equally important task that aerodynamics provides is engine cooling. The direction of air flow to the radiator is determined by the air flow at the front of the vehicle. The grille must be designed to direct the air into the radiator, while maintaining the least possible pressure loss. The flow in the area of the hood and windscreen can be used for heating and ventilation system. Therefore, most vehicles have a fresh air supply in this area.

BASIC PRINCIPLES OF CAR AERODYNAMICS

External airflow affects vehicles. Forces and moments are created here that affect the performance and stability of the vehicle. Until recently, vehicle aerodynamics have only focused on these two effects, and only recently has it focused on the need to prevent pollution of windows and lights, noise reduction, brake cooling, oil pan cooling, etc. In Fig. 3 we can see an example of the air flow, where some factors can be identified, such as the tear-off of the air flow at the rear of the vehicle in Figure 6.

The aerodynamic drag D of the vehicle increases with the square of the vehicle speed. It can be calculated as follows

$$D = \frac{1}{2} A_x c_D \rho v_F^2 \tag{1}$$

where: A_x is the reference (cross sectional) area of the vehicle,
c_D is the air drag coefficient,
ρ is the air density,
v_F is the cruising speed.

In general, the reference area depends on the design requirements of the vehicle body type and is determined by the projection of the vehicle in the direction of travel (Fig. 4). The air drag coefficient is a number used to describe all the complex dependencies of shape, slope, and flow conditions on drag. This coefficient is influenced not only by the car body but also by the chassis, wheels, tires, and rear-view mirrors. Therefore, if a larger SUV has better aerodynamics and therefore a lower air drag coefficient, it may not have lower drag than a smaller car due to its larger frontal area. Efforts to reduce air drag are focused on reducing the air drag coefficient. For currently manufactured cars, the values of the air drag coefficient of cars range somewhere between 0.2 and 0.4 [1].

The air drag of a European mid-size vehicle is almost 75 to 80% of the total resistance of the vehicle at a speed of 100 km/h. This creates scope to improve fuel consumption by improving the aerodynamics of the vehicle. In essence, this is a direct reduction in the air drag of the vehicle by modification its external parts. However, the aim may also be to improve dynamics, as better aerodynamics of the vehicle will reduce the power required to overcome air drag.

Forces and moments acting on the car

Using the basic coordinate system of the vehicle, starting at its center of gravity, it is possible to define the forces and moments acting on the car while driving. The most dominant is the aerodynamic drag force (marked as D) acting against the direction of the vehicle. The second is the lift force (marked as L) acting upwards. This force negatively affects the stability and manoeuvrability of the vehicle, as it reduces the pressure of the tires on the road. The third is the side force (marked as Y) acting in the direction of the Y-axis,

Fig. 3. Streamlines in the longitudinal midsection of a car

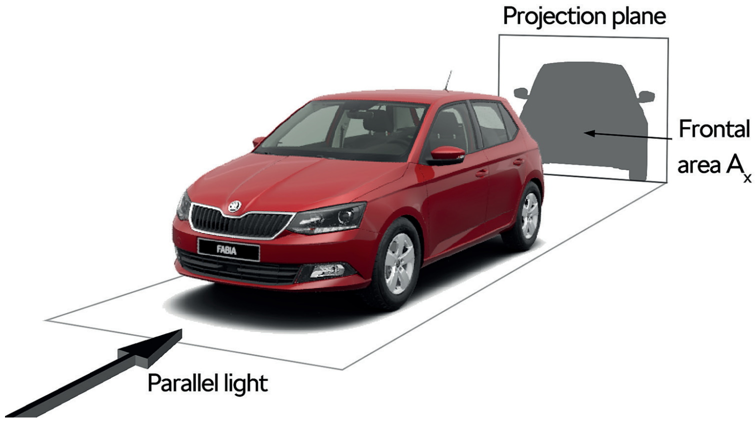

Fig. 4. Definition of the reference frontal area A_x of the vehicle

which causes the vehicle to deviate from its direction of travel. The resulting vector of the action of the force of the air is formed by the given forces (Fig. 5) [1].

These three acting forces are behind the formation of three moments. The first of these is the pitching moment (marked as M) acting around the Y axis. This moment causes a change in the distribution of forces between the front and rear axles, e.g. during acceleration and braking. The second is the rolling moment (marked as R) acting around the X-axis. It is created by driving in curves or on a road that is inclined at a certain angle. The last moment is the yawing moment (marked as N) acting around the Z axis [1].

To simplify the numerical equations, we consider the so-called "symmetric airflow", which is defined without crosswinds. This means that the angle $\beta = 0°$. Assuming symmetrical vehicle geometry, the forces Y and the moments, R, N are also zero [1].

The components of the resultant force and moment are determined on a specific vehicle by measurements in wind tunnels. In cases where, for economic or other reasons, it is not possible to carry out measurements on 1:1 scale models, the aerodynamic properties shall be measured on scale models. Relevant results can be obtained thanks to Reynolds' law of similarity and finding the Reynolds number. The equation for the Reynolds number is as follows [1]

$$Re_l = \frac{V_\infty l}{\nu} \tag{2}$$

where: V_∞ is the flow speed,
ν is the kinematic viscosity of the air,
l is the characteristic linear dimension (vehicle length).

It is thus possible to find out other required dimensionless coefficients listed in Table 1. All these coefficients are based on the dynamic free-stream pressure $\frac{\rho V_\infty^2}{2}$ and the largest cross-sectional area A_x of the vehicle. For the moments, forces and coefficients, a specific quantity of the car length l is used (Table 2) [1].

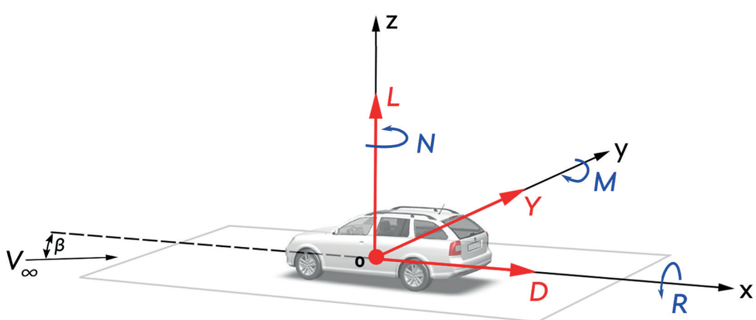

Fig. 5. Forces and moments acting on a vehicle.

Working methods

Initially, aerodynamic modifications of vehicles were carried out only on the basis of experimental approaches. Shape changes were performed on scale models or full-scale models. Cogotti in [24] describes measurements on full-size models in the process of developing new cars in the wind tunnel of the Pininfarina research centre, including the development of a methodology for such measurements in the tunnel. Experimental measurements for various body modifications have been performed by Altinisik [25]. The aim was to fine-tune the aerodynamic properties while preserving the original design as much as possible.

Nowadays, CFD calculation programs are often used in vehicle design together with experimental wind tunnel measurements. CFD computational programs make it possible to analyse multiple models and thus achieve the optimum vehicle body shape relatively quickly and at low cost. Increased fuel prices and stricter legislative requirements to reduce exhaust emissions increase the importance of aerodynamic properties in the vehicle design process [1]. In addition, virtual CFD methods accelerate and increase the efficiency of vehicle aerodynamics. Using virtual predictions obtained by CFD simulation, problems can be identified faster and cheaper. An example is the static pressure distribution in Fig. 6, which can be used to identify areas to modify the airflow by changing the shape of the vehicle body.

Development trends

The trend in car aerodynamics is to reduce the air drag of the vehicle. The air drag coefficient c_D has thus been reduced from 0.8 for vehicles of the 1920s to an average of 0.45 for vehicles of the 1970s. This improvement occurred in two phases. In the first phase, between the two world wars, the vehicles were lengthened and rounded, while retaining the characteristic design features of the time, such as the bulging fenders and lights. In the second phase, the vehicles had fenders and headlights built into the body, which greatly improved the airflow around the vehicle. The concept vehicles still created opportunities for future improvements in aerodynamics. The GM Aero 2002 and Ford Probe IV prototypes designed in the 1980s achieved air drag coefficients of 0.14 and 0.15, respectively. In the case of today's commercially produced vehicles, it is between 0.25 and 0.35. In the long term, it can be assumed that the lower limit will be reduced to 0.2 [2].

Aerodynamics of the rear body of a hatchback

The rear of the vehicle is specific in that each body variant (sedan, combi, hatchback) requires an individual shape geometry solution to achieve the desired flow. Hatchback bodies often achieve the least favourable results. For this body type, it is important to tune the trailing edge of the rear of the vehicle to eliminate turbulence behind the vehicle. The turbulent flow generated in the

Table 1. Summary of equations of dimensionless coefficients

$c_D = \dfrac{D}{\dfrac{\rho}{2} V_\infty^2 A_x}$	$c_L = \dfrac{L}{\dfrac{\rho}{2} V_\infty^2 A_x}$	$c_Y = \dfrac{Y}{\dfrac{\rho}{2} V_\infty^2 A_x}$
Drag coefficient	Lift coefficient	Side coefficient

Table 2. Equations for calculating acting forces and moments

$D = \dfrac{1}{2} c_D \rho v_F^2 A_x$	$L = \dfrac{1}{2} c_L \rho v_F^2 A_x$	$Y = \dfrac{1}{2} c_Y \rho v_F^2 A_x$
Drag force	Lift force	Side force
$M_M = \dfrac{1}{2} c_M \rho v_F^2 A_x l$	$M_R = \dfrac{1}{2} c_R \rho v_F^2 A_x l$	$M_N = \dfrac{1}{2} c_N \rho v_F^2 A_x l$
Pitching moment	Rolling moment	Yawing moment

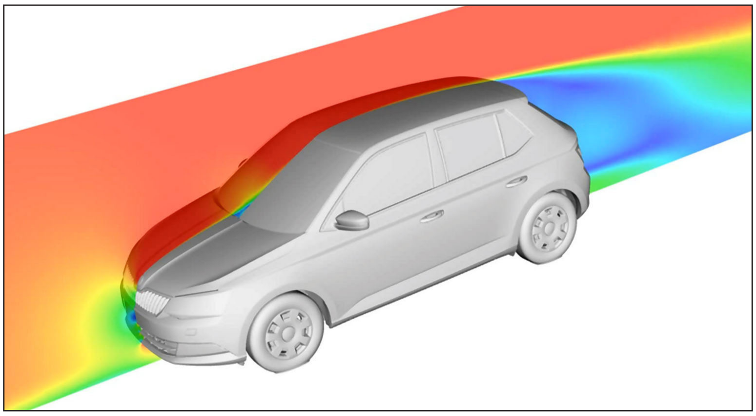

Fig. 6. General visual demonstration of the static pressure around the hatchback vehicle body obtained by CFD simulation

wake region (low pressure region) contributes the formation of pressure drag, which is eventually reduces the vehicle performance and causes rear window fouling as well as aerodynamic noise. The fouling is caused by swirling dust particles and water droplets from the wheels. As can be seen in Fig. 7, these are dispersed over a larger region in the case of the hatchback.

CAD MODEL CREATION

Baseline – original model

The initial state of the upper part of the tailgate consists of a simply shaped plastic spoiler (Fig. 8). The angle between the roof line and the trailing edge is approximately 150°. This angle is based on the conceptual design of the vehicle, which depends on the dimensional requirements of the interior and luggage compartment. The individual radii and chamfers are also based on the manufacturing conditions of the component. A brake light is integrated in the spoiler.

Spoiler and finlet

The tailgate spoiler (Fig. 9) is installed in the roof section in the rear window area as an additional element to improve the flow behind the vehicle. Its function is to optimize the instantaneous separation of the airflow from the rear, to improve the overall aerodynamics and also to increase the driving stability by increasing the downforce. The spoiler is usually manufactured as a plastic component due to the need to achieve an optimum shape.

The finlet is installed as an accessory that mates with the spoiler and the side edges of the tailgate window. They are used as a pair in two pieces. The purpose of this component is to create a trailing edge located outside the rear window of the vehicle and prevent turbulent flow near the glass. In addition to improving aerodynamics, another benefit is the reduction of fouling. In practice, the finlet is manufactured as a plastic component and care must be taken in its connection to the spoiler and other body parts.

Modifications to the shape of the rear of the hatchback

In order to optimise airflow and improve aerodynamic performance, three modifications to the spoiler with fins were designed. The aim was to achieve as little swirl as possible at the rear and thus reduce the overall air drag of the body.

Design A

It is a one-piece spoiler (Fig. 9 to Fig. 11) with an integrated brake light. The design takes into account the view zone, but also the continuity of the connection between the roof and the spoiler. From the point of view of aesthetic quality, this part has been designed so as not to detract from the appearance of the vehicle and to follow the shape of the body seamlessly. The proposed spoiler is considered to be a one-piece component. It partially extends into the side walls of the vehicle, thus combining the advantages of a roof spoiler and side finlets.

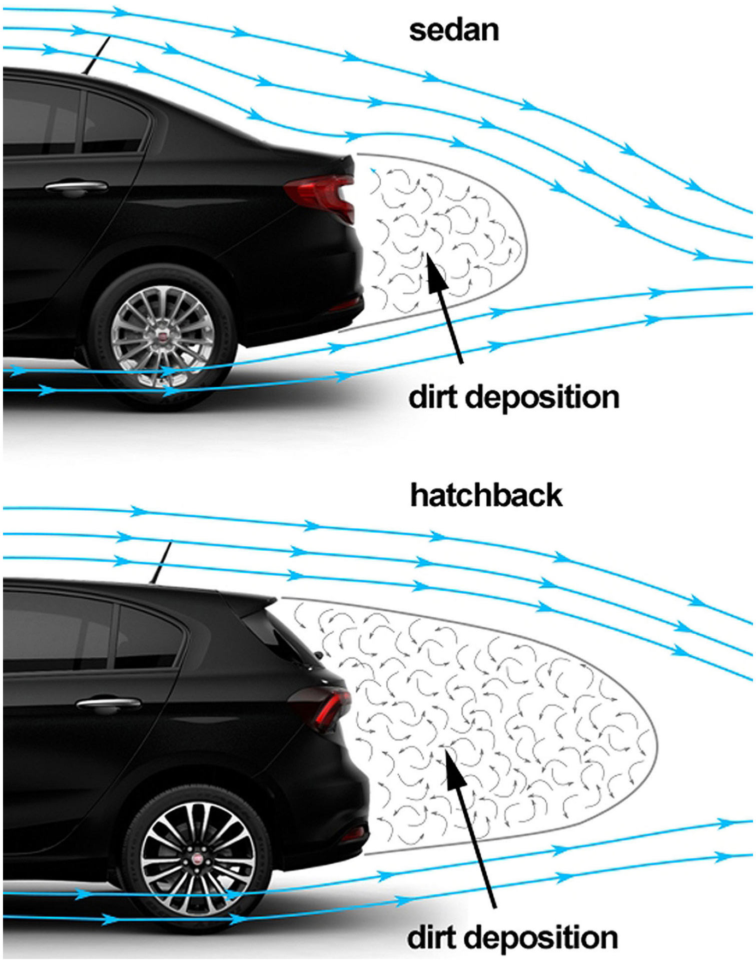

Fig. 7. Wake region behind the vehicle and deposition of dirt.

Design B

It is a one-piece spoiler (Fig. 12 to Fig. 14) without brake light. Aesthetics and continuity with the original body design are also taken into account in this case. The roof spoiler, as in design A, partly extends into the side walls of the vehicle, thus combining the advantages of the roof spoiler and the finlets. At the same time, it takes on the relief of the main upper window line and further develops this shape. However, this modification suppresses the rearward view of the vehicle due to the narrowing at the top of the spoiler adjacent to the body.

Design C

It is a two-piece spoiler (Fig. 15 to Fig. 17) that contemplates the incorporation of a rear brake light. The second part of the spoiler consists of a pair of side ribs fixed along the entire height of the rear window. The design takes into account the continuity of the connection between the roof, the spoiler and the finlets. This design

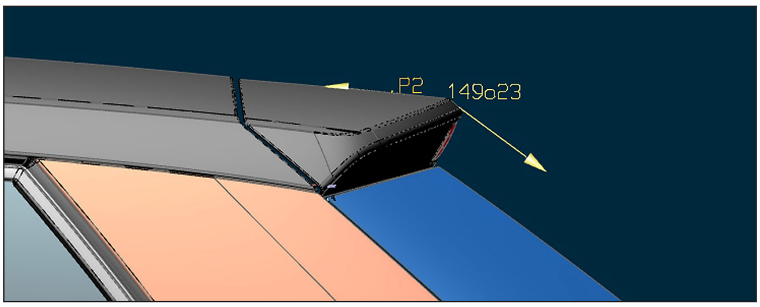

Fig. 8. Spoiler of the production vehicle.

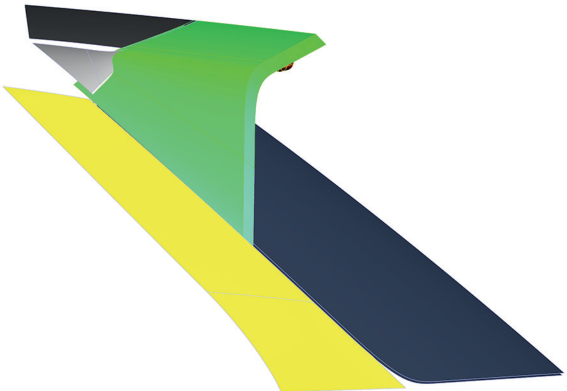

Fig. 9. Design A – spoiler side profile

also provides a good view from the rear of the vehicle. From an aesthetic point of view, it follows the line of the roof and the tailgate. The shape of the finlets is widened at the top for a better connection to the roof spoiler.

Comparison of designs

The proposed designs represent three different options for modifying the rear of the hatchback. By confronting each model with the component's production requirements and its price, the most suitable design was selected.

Design A, after checking manufacturability, requires two directions of moulding, which increases both the difficulty and cost of its production. Therefore, this design will not be refined to prototype quality.

Design B was aesthetically pleasing, most consistent with the shape of the tailgate and the rest of the vehicle, but did not meet the requirements for rearward visibility, particularly at the top of the rear window. In this case, a brake light was not incorporated. Its incorporation would have resulted in a further narrowing of the view.

For this reason, design C was selected as the most appropriate and was subjected to further investigation.

CFD ANALYSIS OF THE SELECTED DESIGN

Figure 18 shows the difference in air drag coefficient along the length of the vehicle for two different rear body modifications compared to the original (production) vehicle. The differences were determined by simulation at a speed of 140 km/h. The red curve in the figure corresponds to spoiler C without finlets, the green curve to spoiler with finlets. From the result of the difference plot, it can be seen that the design of the rear of the vehicle not only has a local effect on the affected area, but also has an effect on the front of the vehicle, which is consistent with the theoretical knowledge of aerodynamic forces. While the drag coefficient increases slightly in the front wheel area, it decreases in the modified area. In the case of a spoiler without finlets, the coefficient decreases locally by approximately -0.003, in the case with finlets the decrease is up to twice as large.

For a better understanding of the effect of the rear design modification on the aerodynamic performance of the vehicle, the normalized fields of some other flow characteristics are shown in

Fig. 10. Design A – rear spoiler profile

Fig. 11. Design A – full vehicle model

Fig. 19 to Fig. 29. All are determined at a speed of 140 km/h. In addition to the version with the modified spoiler with and without finlets, the results for the original (production) vehicle as well as for the vehicle in the sport version are also shown for comparison.

Figures 19 and 20 shows the drag distribution on the vehicle surface. The variant with the spoiler without finlets shows a lower drag on the rear window of the vehicle compared to the original vehicle. A slight decrease in value can also be seen at the bottom of the tailgate. An even greater decrease in drag on the rear window is achieved for the variant with finlets.

Fig. 21 and Fig. 22 show the distribution of the total pressure coefficient in the section x=3400 mm, which is located in the near wake region. This plane was chosen because the wake is largest at this location. Among all the versions compared, the most significant reduction in the pressure coefficient can be observed for the vehicle with the modified spoiler with finlets.

Fig. 12. Design B – spoiler side profile

From the comparison of the normalized velocity magnitude fields shown in Fig. 23 and Fig. 24, it is evident that the modified spoiler without finlets has no significant effect on the change in the distribution and magnitude of the flow velocity in space compared to the production version. The changes are more pronounced for the sport version and the vehicle with the modified spoiler with finlets. As can be seen, the low-speed region becomes smaller with increasing spoiler length. Figures 25 and 26 shows the velocity streamlines at 140km/h. Both vehicle models with the modified spoiler show a reduction in the flow velocity behind the vehicle.

The resulting air drag coefficient values for all vehicle models analysed are shown in Table 3. CFD simulation results show that the air drag coefficient is reduced by 0.0025 for the vehicle with the modified spoiler without finlets, which leads to a saving of approximately 0.2 litres of fuel per 100 km and theoretically reduces CO_2 emissions by 0.8 g. In the case of a spoiler with finlets, the reduction is up to 0.0062. The estimated reduction in fuel consumption is about 0.4 l/100 km and the reduction in CO_2 is about 1.6 g (under ideal conditions). In terms of aerodynamics, the newly proposed design of the rear of the hatchback can be considered to be an improvement compared to the production version. Note that the calculation of the fuel consumption and CO_2 emission reduction values was performed based on the vehicle parameters for the WLTP cycle.

Fig. 13. Design B – rear spoiler profile

Fig. 14. Design B – full vehicle model

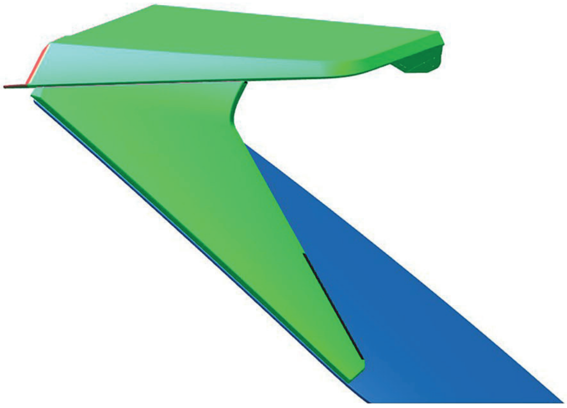

Fig. 15. Design C – spoiler side profile

DESIGN PROCESSING INTO PROTOTYPE QUALITY

Based on the results of the CFD analysis, which clearly demonstrated the advantages of the new spoiler designs, the CAD model C of the modified spoiler with finlets was refined to prototype quality. The result of this processing is the so-called Class-A surface model (also referred to as STRAK), which takes into account detailed requirements for manufacturability, aesthetics and aerodynamic performance retention. It achieves a premium level of surface quality for visible

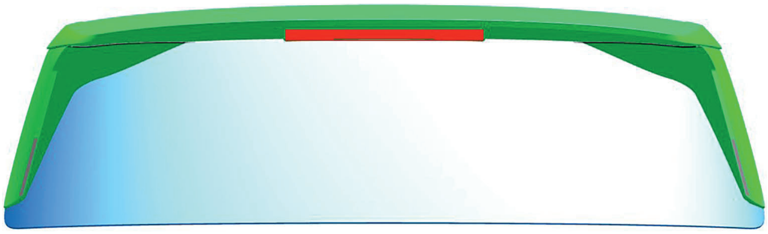

Fig. 16. Design C – rear spoiler profile

Fig. 17. Design C – Full vehicle model

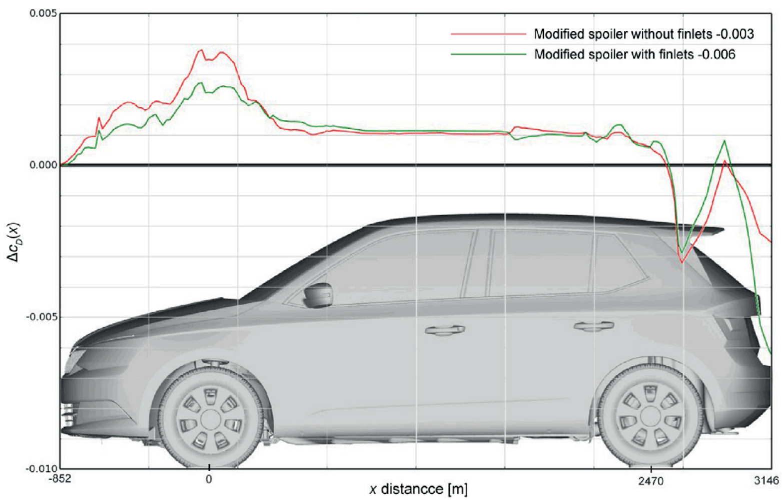

Fig. 18. Difference in drag coefficients along the vehicle with the modified spoiler compared to the original (production) vehicle

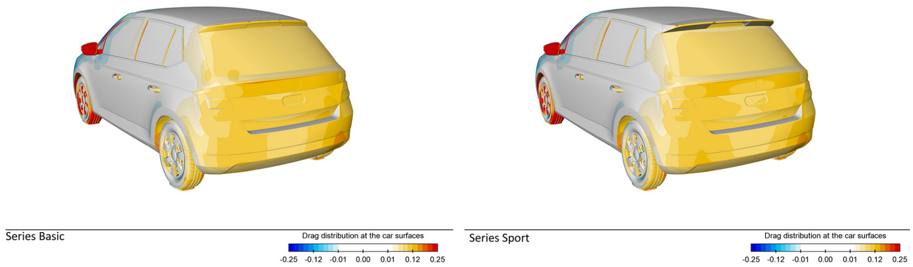

Fig. 19. Drag distribution map on the surface of the production vehicle (left) and the sports version vehicle (right) at a speed of 140 km/h

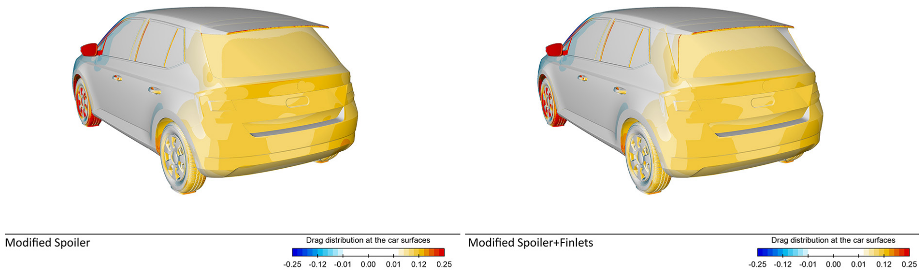

Fig. 20. Drag distribution map on the surface of the vehicle with modified spoiler without finlets (left) and with finlets (right) at a speed of 140 km/h

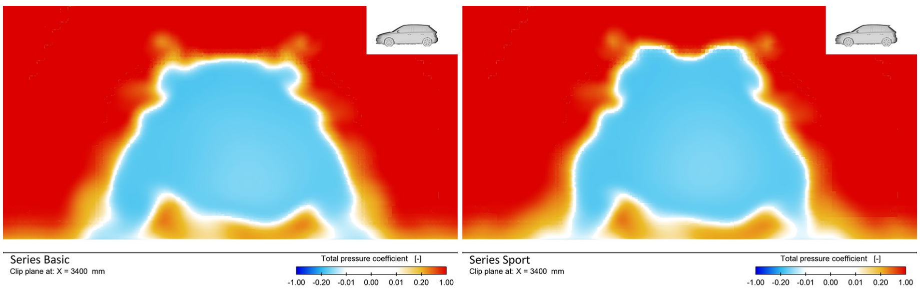

Fig. 21. Distribution map of the total pressure coefficient in the section x=3400 mm of the production vehicle (left) and the sports version vehicle (right) at a speed of 140 km/h

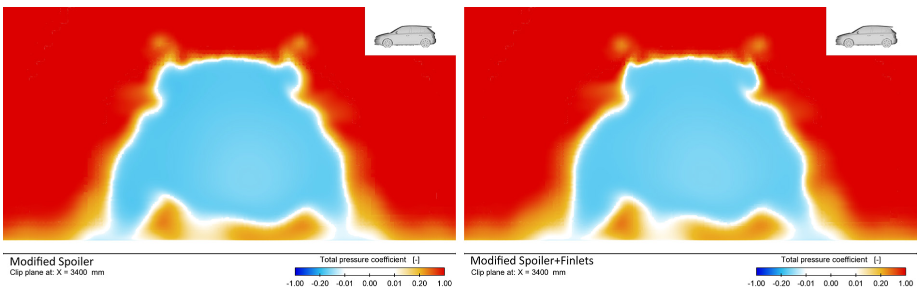

Fig. 22. Distribution map of the total pressure coefficient in the section x=3400 mm of the vehicle with modified spoiler without finlets (left) and with finlets (right) at a speed of 140 km/h.

shapes, which requires a high level of automotive design knowledge, technical regulations and surface modelling skills. By modifying, smoothing and offsetting individual surfaces in both the spoiler and rib areas, further improvements have been made to the view through the rear window of the vehicle. The final surface model of the spoiler is shown in Fig. 27. Figure 28 presents what the standard bodywork of a Škoda Fabia would look like with the proposed spoiler. The designed part is coloured in the same way as the roof and the A-pillars of the vehicle.

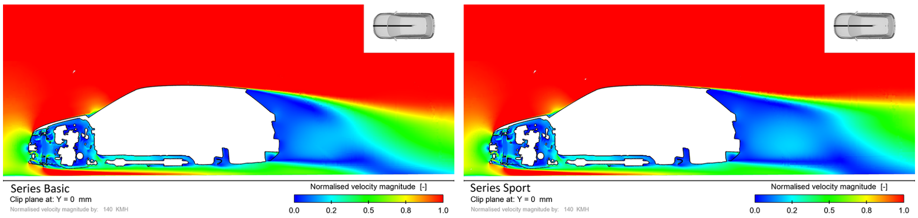

Fig. 23. Normalized velocity magnitude distribution in the section y=0 of the production vehicle (left) and the sports version vehicle (right) at a speed of 140 km/h

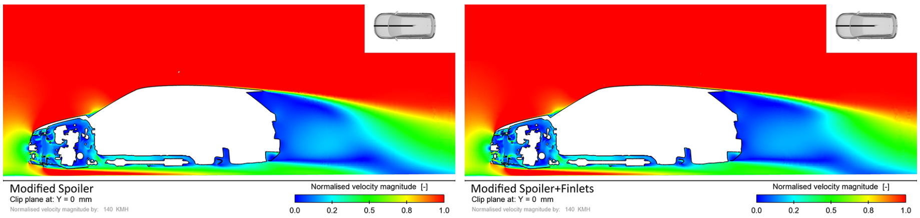

Fig. 24. Normalized velocity magnitude distribution in the section y=0 of the vehicle with modified spoiler without finlets (left) and with finlets (right) at a speed of 140 km/h

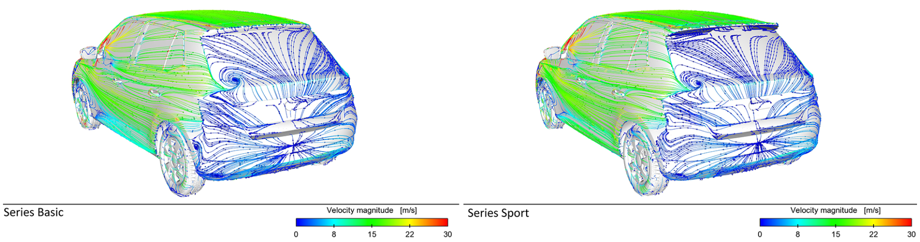

Fig. 25. Velocity streamlines on the body of the production vehicle (left) and the sports version vehicle (right) at a speed of 140 km/h

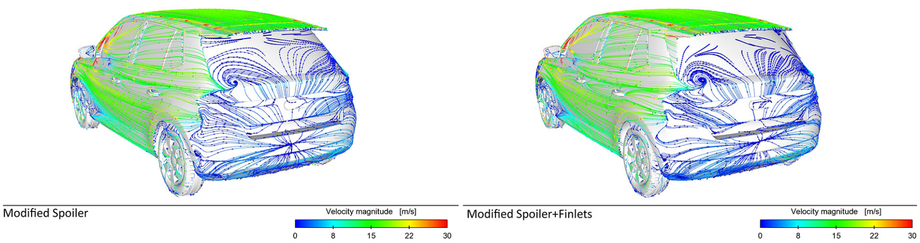

Fig. 26. Velocity streamlines on the body of the vehicle with modified spoiler without finlets (left) and with finlets (right) at a speed of 140 km/h

Table 3. Summary of simulation results

Vehicle model	c_D $[-]$	A $[\mathrm{m}^2]$	$c_D A$ $[\mathrm{m}^2]$	Δc_D
Production vehicle (reference)	0.3110	2.0805	0.64710	
Sports vehicle	0.3130	2.0805	0.65125	+0.0020
Modified spoiler without finlets	0.3085	2.0805	0.64188	-0.0025
Modified spoiler with finlets	0.3048	2.0805	0.63422	-0.0062

Fig. 27. Final Class-A surface model of the modified spoiler with finlets

Fig. 28. Visualization of the Škoda Fabia III with the resulting spoiler design

CONCLUSIONS

The aim of this paper was to investigate the effect of the aerodynamic features of the hatchback tailgate on the aerodynamic drag of a mass-produced passenger car, the Škoda Fabia III. The main attention was paid to the spoiler and side finlets. A total of three designs were proposed, of which Design C was selected as the most suitable based on an objective evaluation. This design was subjected to CFD analysis to assess the aerodynamic response of the vehicle model at a speed of 140 km/h. The parameters monitored were the aerodynamic drag, the velocity and nature of the flow, the total pressure coefficient, and the wake region. A modified spoiler model with and without finlets was analysed. The simulation results were compared with those obtained for the vehicle model in standard production version, and in the sports version. In the case of the proposed design of the modified spoiler with finlets, an improvement was obtained in all the parameters studied. The coefficient of aerodynamic drag has been reduced by 0.0062, resulting in an expected fuel saving of 0.4 l/100 km and a reduction in CO_2 emissions of 1.6 g/km under ideal conditions according to the WLTP driving cycle. The resulting CAD model of the spoiler, taking into account the technological requirements for the production of plastic parts, was converted to prototype quality.

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