Wheels aerodynamics and impact on passenger vehicles drag coefficient

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Abstract. The effort of developing a vehicle engages all automotive engineering branches, including aerodynamics. To fulfil the CO_2 requirements, the body should be as streamlined as possible. This paper aims to analyse the influence the body shape in the wheels area has on the global CdA parameter, which measures aerodynamic performance. Due to the difficulties encountered in lowering this parameter by conventional means, the paper summarizes a study performed on enclosing the rear wheels opening in a progressive way. Due to accessibility and relative small error between simulation and physical test, the method of computational fluid dynamics (CFD) was used to obtain the results. The main conclusion is that enclosing the rear wheel has an important aerodynamic benefit and does not affect other functions of the vehicle. Careful design of wheel area from an aerodynamic point of view and not only for visual considerations may lead to significant reduction in drag and improvements of vehicle drag coefficient. Based on the positive results, the work will be continued by adapting this idea on commercial vehicles. Although CFD is a good method for developing and optimizing aerodynamic solutions, the results should be validated by physical tests.

1. Paper purpose

Reducing the vehicles' emission level implies improvement of energy efficiency. As such, extensive research is done mainly on engine and exhaust systems. The difficulties met in reaching the ambitious targets impose a multiple approach. Aerodynamic resistance is an important factor that needs to be considered. By optimizing the vehicle's shape, the engine power output could be decreased thus simplifying the emissions issue.
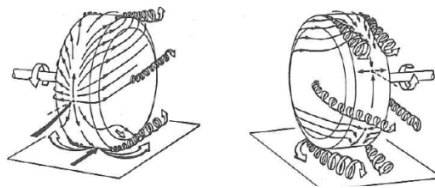
Modifying design theme or adding new parts can minimize the drag coefficient, a measure of aerodynamic performance. This paper studies the possible benefits brought by using (i) an enclosed rear wheel arch opening and (ii) alternative shapes of rear wheel front deflector. Basic wheel aerodynamic notions are summarized in the next chapter.

2. Theory of wheel aerodynamics

An aerodynamic "streamlined" body refers to a relative reduced variation of air speed, pressure, direction and friction parameters. To obtain the desired shape, while observing the rules imposed by law, design, client comfort and needs, every part in contact with the exterior airflow has to be optimized in detail, in close connection to all linked engineering departments.

When studying the wheel aerodynamics, the next main constraints have to be considered: it has a rotating movement, for passenger vehicles it is enclosed in the body and it is in permanent contact with the road. The studies performed on this topic showed that, in front of the wheel, a stagnation point appears (pressure coefficient "Cp" >2) due to viscous pumping effect given by the rotating motion [1]. The swirling airflow reaches the rear shoulders of the wheel where the high-speed lateral currents are detaching, as seen in figure 1. This leads to a low-pressure area placed behind the wheel. Associated drag can be optimized by reducing wheel thickness (low projected area) and using tires with curved shoulders (it prevents separation in front and rear).

Figure 1. Airflow around a rotating simplified wheel [2].

The wheel housing, surrounding more than half of the wheel geometry, can be formed from few complex parts or by multiple parts reduced in size. While front wheels are linked to more systems, imposing a higher porosity of the housing, the relative simplified role of rear wheels allows the use of a full housing. This latter type is preferred because it isolates the flow near the wheel thus allowing a better control. The housing has to be designed and exteriorized as much as needed so the low pressure point behind the wheel could be enclosed. Close related to housing design, the rear bumper from lateral extremity has to be aerodynamically optimized (minimum radius) that allows a clean detachment.

The exterior face of the wheel represented by the wheel cap or the rim itself (depending on the technical definition) also has a significant influence on the airflow. The general aerodynamic purpose is to mask the wheels as much as possible. To create the desired uniform surface between the wheel and the vehicle body, the distance between the tire and the wing has to be minimum. If these main guidelines are followed, the source of the drag is minimized and the total aerodynamic resistance is reduced.

All the theoretical phenomena mentioned above promoted the integration of parts that have the purpose of controlling airflow's behavior.
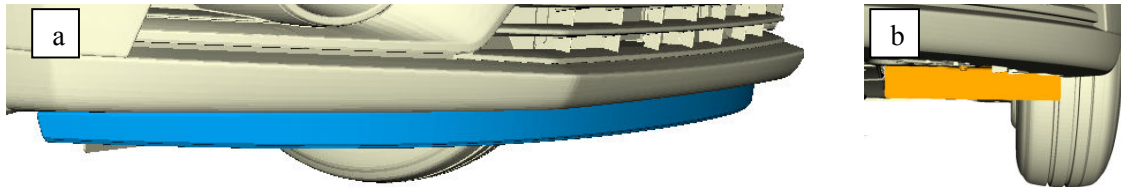
3. Experimental study using CFD

The air taming aerodynamic elements can be added on the body (front dam, wheel deflector et al) or integrated in the vehicle design theme (air curtain, front bumpers lateral curvature et al). Another classification is done by means of control - passive elements (fix, without movement) and active elements (controlled based on vehicle speed, they can modify position for maximum effect). The passive elements are most common, but the active ones are reaching the mass segment due to harsh pollution laws.

The main aerodynamic add-on elements are:

- Front dam (figure 2a) – directs the air towards the floor. In most cases, it is made of plastic and has a fixed height. For a better performance, the height can be varied as a function of vehicle speed. At lower speed, the exposed height is minimum so the air is directed towards the cooling pack and brake system. At high speed, the element has a maximum exposed height for maximum aerodynamic effect. An intermediate position can exist for maximized aerodynamic gain.

- Front wheel deflector (figure 2b) – reduces pressure value in front of the tire. The shape and size may vary depending on wheel dimensions and front-end shape and length. The front dam and front wheel deflector can form one single item with a compromise between aerodynamics gain and associated costs.

Figure 2. Aerodynamic elements: front dam (a), front wheel deflector (b).
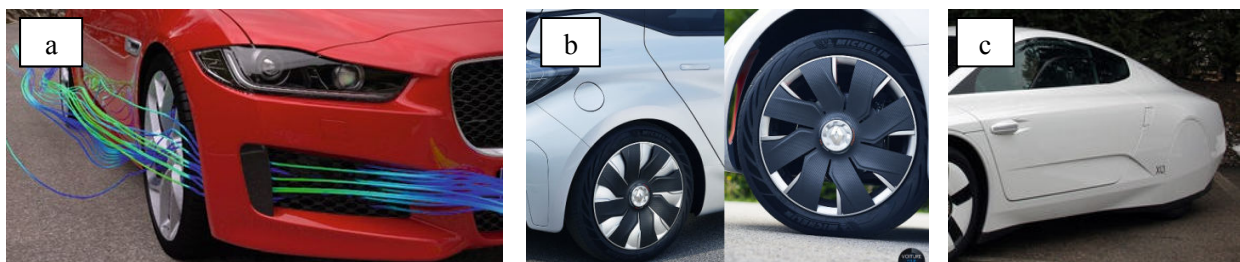
The more advanced aerodynamic elements are:

- Air curtain (figure 3a) - in the lateral extremities of the front bumper, a well-defined space is created thus allowing air to pass from the front of the bumper towards the wheel housing. The passing airflow from the engine compartment towards the exterior of the wheel, which increases drag, is optimized by the high velocity air stream that flushes the exterior of the wheel. An extension of this solution is to add air curtains after the wheel, allowing an easier evacuation of engine compartment flow for a better equilibrium of pressures.

- Wheel cap (figure 3b) – performed studies showed that minimum Cd value is reached for full enclosed cap. For maximum efficiency and the lowest impact on brake cooling, active wheel caps should be used.

For safety reasons, the tire thread surface cannot be made uniform (slick tire), but the turbulence can be reduced by working on the shoulder's radius and by erasing the 3D imprints on the exterior side.

An unusual solution is to enclose completely the rear wheels in the vehicle body, as seen in figure 3c. Since the rear wheels are not directional, or have just small directional angles for rear active direction systems, the solution is feasible and does not imply developing of a complex system. As for other aerodynamic body shapes, this solution is not widely applied due to customer desire for a classical shape.

Figure 3. Advanced aerodynamic elements: air curtain (a) [3],
active wheel cap (b) [3], enclosed rear wheels(c) [5].

This paper aims to analyze the possible benefit of rear-enclosed wheels by means of an add-on mask on a generic hatchback shape followed by wheel deflector optimization. Showing that CO_2 reduction is possible by using just a low-cost mask add-on together with perspectives on improved driving range, it can bring this nonconformist solution towards masses and not only to experimental vehicles. A small emission gain on a vehicle sold in high volumes will have a bigger impact than few green vehicles sold in a small number due to their high price.

4. Interpretation of CFD results

The computational fluid dynamic (CFD) method, which is based on mathematical models, represents an alternative method for wind tunnel tests that are expensive. The mathematical approach is getting very popular based on representative results and reduced costs. Due to the calculation error, a final physical test is still required.
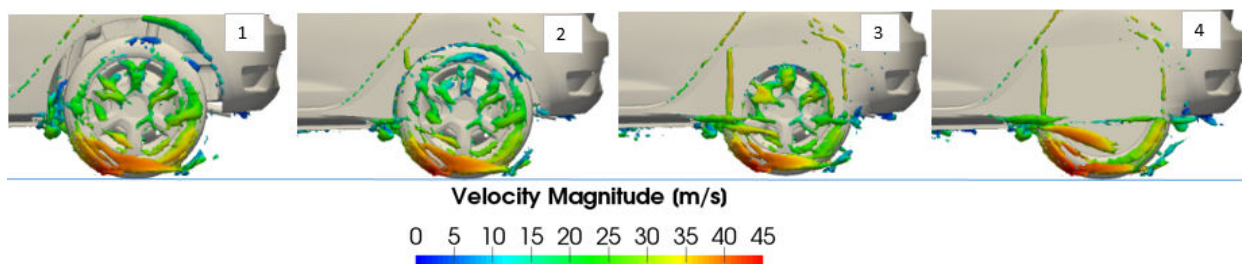
For the current study, the used CFD software uses the Lattice Boltzman simplified microscopic mathematical method. This method considers a typical volume element of fluid to be composed of a collection of particles that are represented by a particle velocity distribution function for each fluid component at each grid point. The time is measured in discrete time steps and the fluid particles can collide with each other as they move, possibly under applied forces. The rules governing the collisions are designed so that the time-average motion of the particles is consistent with the Navier-Stokes equation. This method is considered an optimal choice for current study due to its characteristics and extensive use in automotive and aeronautical engineering

The CFD simulations are based on a standard setup. The base vehicle has a hatchback type body and 195/55/R16 tires. The first step of the study aims to evaluate the mask dimension. Results are summarized in table 1. The best Cd result is obtained for the fully enclosed wheel arch with a delta of 0.024 in comparison with a standard configuration. Case 2 and 3 show the tendency of a decreasing Cd with wheel arch mask increase.
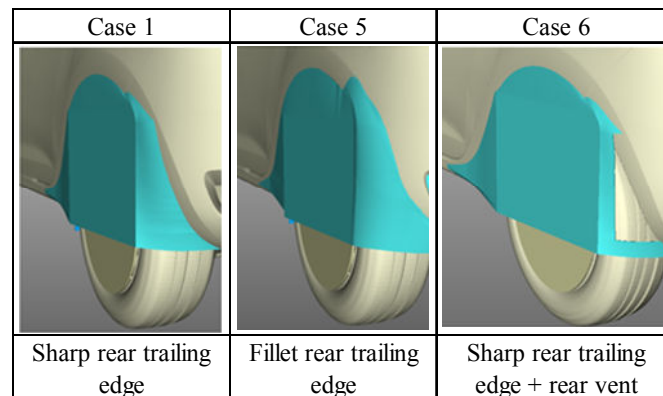
Table 1. CFD results of gradually enclosed wheel arch.

Setup	Case 1	Case 2	Case 3	Case 4
Cd	0.377	0.367	0.364	0.353
ΔCd	/	0.011	0.013	0.024
Description				
	Standard wheel arch opening	Wheel arch enclosed to outer tire limit	Wheel arch enclosed to outer cap limit	Wheel arch completely enclosed

The results can be understood by studying the Lambda parameter. As it can be observed in figure 4, the mask acts mainly on vorticity formed in the wheel housing and rim area with small impact on the front of the tire. Case 2 shows an improvement of the drag associated to the distance between the wheel arch and the tire, while case 3 shows a small gain on rim flow. The full mask minimizes wheel arch and rim flow. Based on these results, the study is continued with the 4th case configuration.
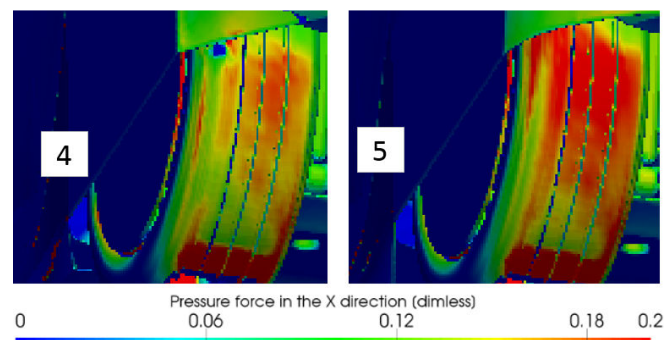

Figure 4. Lambda parameter for mask size variation.

The second step of the study consists in comparing three different full mask configurations – straight rear trailing edge (case 4), curved rear trailing edge (case 5) and straight rear trailing edge plus cut area (case 6), as seen in figure 5.

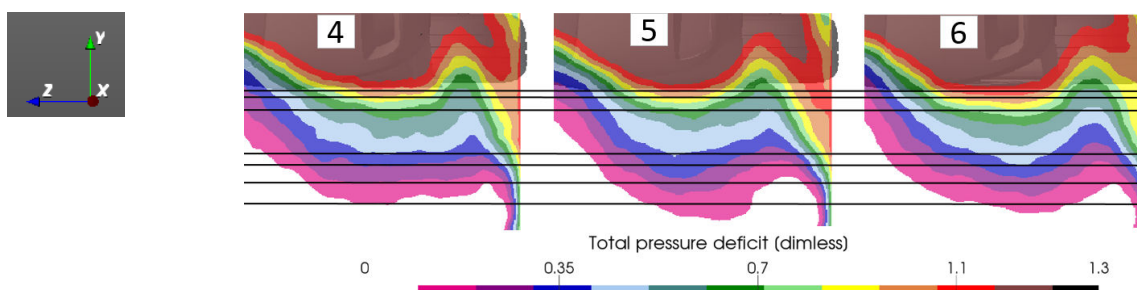| Case 1	Case 5	Case 6
Sharp rear trailing edge	Fillet rear trailing edge	Sharp rear trailing edge + rear vent

Figure 5. Mask configuration of case 4, 5 and 6.

CFD simulations indicate that case 4 is more aerodynamic favorable than case 5 due to a smaller pressure value behind the wheels, as seen in figure 6 (comparison of red imprints).

Pressure force in the X direction (dimless)

0   0.06   0.12   0.18   0.2

Figure 6. Pressure force in X direction behind rear wheels.

The best configuration can be chosen by studying the pressure values behind the rear wheel (+50 mm on X with reference to rear bumper extremity). As seen in figure 7, the size of the trail is reduced for case 4, while cases 5 and 6 are more exteriorized in shape. Based on figure 6 and figure 7, case 4 is the optimal solution.

Total pressure deficit (dimless)

0   0,35   0,7   1,1   1,3

Figure 7. Total pressure deficit at rear bumper extremity + 50mm on X.

The third step of the research consists in identifying a better shape for the front deflector. The straight deflector is replaced with a bigger shape. The optimal dimensions are sought with the help of three different configurations described in table 2, together with the associated Cd results, in reference to case 4.

Table 2. Wheel deflector results.

Setup	Case 4	Case 7	Case 8	Case 9
Cd	0.355	0.349	0.348	0.349
ΔCd	/	0.006	0.007	0.005
Description	Standard wheel deflector	Volumetric shape, base = 0mm	Volumetric shape, base = 10mm	Volumetric shape, base = 15mm

The first important conclusion is that an optimal height of the wheel deflector exists and this does not match the maximum height. In addition, it may be observed that the wheel deflector brings a smaller gain than the wheel arch mask. The different results will be explained using the CFD parameters, as follows:

Figure 8 describes the high drag area visualized with air speed. Due to the relative small difference between the four analyzed configurations, the images will show only slight changes. The drag has two main components: one component found behind the rear wheels and one component in the front area of the wheels. The latter is the main one that gives the deflector performances. If compared in detail, the most reduced vein is for the 8th case.

Velocity Magnitude (m/s)
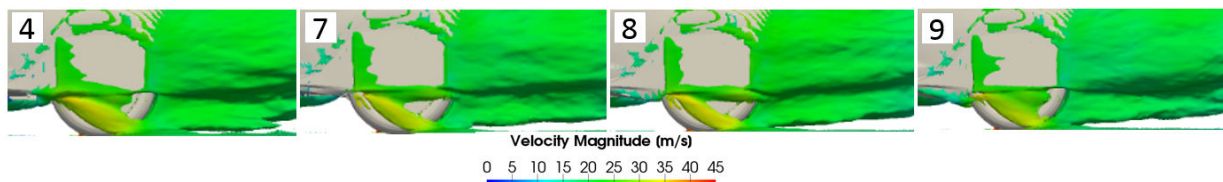0 5 10 15 20 25 30 35 40 45

Figure 8. Wheel deflector assessed by drag magnitude.

The airflow pattern can be also plotted by using the total pressure deficit, as seen in figure 9. Even if the red trail in case 4 is longer than the other ones, the result can be explained by a smaller deficit area in the extremity of the wheel (brown trail). It can be concluded that for the used hatchback body the wheel deflector brings a relative reduced gain in comparison with the full wheel arch mask.
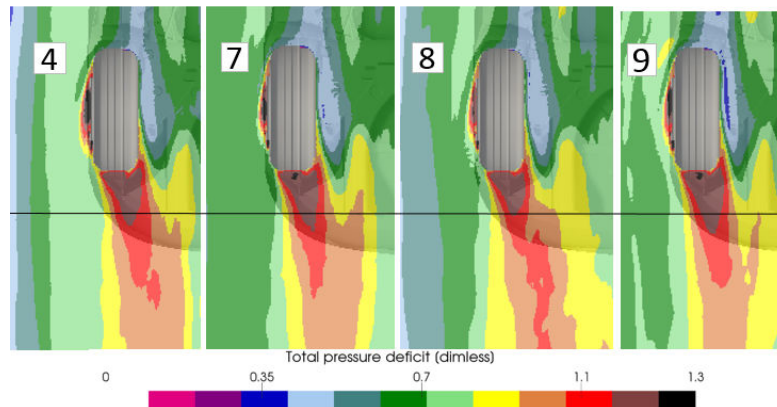
Figure 9. Total Pressure deficit depending on deflector height.

5. Conclusions and future work

The decrease of vehicle emissions can be done by improving the efficiency of engine and exhaust systems, reducing total mass and improving aerodynamic performance. This paper is focused, in three steps, on the influence of the rear wheel arch mask and front deflector shape on a hatchback body drag.

The first step of the research concluded that between different size masks, the biggest in size has the best performances with a gain of 0.024. In the second step, the full mask shape with a straight rear trailing edge is compared with a rear curved mask and another one that has a rear perforation. The analysis of the results obtained showed that the new proposed shapes brought a degradation of drag coefficient. As consequence, the study was continued with the third step during which the full mask with a straight trailing edge was used as base. In the final step, the influence of four different wheel deflectors was studied, comparing the standard straight deflector with other three different sizes. While the impact of deflectors was reduced compared to the full mask, the detailed study revealed that the profiled deflector having the same height as the straight one brought the biggest gain.

The results in the present study showed that an important reduction of drag coefficient is possible if the wheel geometry is carefully optimized. An important observation is that results cannot be generalized because the behavior of airflow is very sensitive to the smallest difference in vehicles parameters. For a maximum gain, each aerodynamic element has to be adapted to the destined vehicle shape. Even if the CFD tool is robust, with a relative small error, a wind tunnel session is still recommended for validating the results.

Based on the results obtained, the work will be continued by applying and adapting the tested elements on medium and heavy class utility commercial vehicles. For this type of vehicles, a significant gain is expected to be identified, as these are more exposed to airflow due to the significant dimensions of wheels.

6. References

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