Proceedings of the ASME 2010 3rd Joint US-European Fluids Engineering Summer Meeting and 8th International Conference on Nanochannels, Microchannels, and Minichannels
FEDSM-ICNMM2010
August 1-5, 2010, Montreal, Canada

FEDSM-ICNMM2010-30321

AERODYNAMIC FORCES ON A SIMPLIFIED CAR BODY – TOWARDS INNOVATIVE DESIGNS FOR CAR DRAG REDUCTION

Mahmoud Khaled
Thermofluids, Complex Flows and Energy Research Group – Laboratoire de Thermocinétique, CNRS-UMR 6607, Ecole Polytechnique
University of Nantes
Nantes, France

Fabien Harambat
Aerodynamic and Aeroacoustic Research and Development Department – PSA Peugeot Citroen
Vélizy, France

Anthony Yammine
Testing system and Turbocharging Department – Kratzer Automation
Villebon-sur-Yvette, France

Hassan Peerhossaini
Thermofluids, Complex Flows and Energy Research Group – Laboratoire de Thermocinétique, CNRS-UMR 6607, Ecole Polytechnique
University of Nantes
Nantes, France

ABSTRACT
The present paper exposes the study of the cooling system circulation effect on the external aerodynamic forces. We report here aerodynamic force measurements carried out on a simplified vehicle model in wind tunnel. Tests are performed for different airflow configurations in order to detect the parameters that can affect the aerodynamic torsor and to confirm others previously suspected, especially the air inlets localization, the air outlet distributions and the underhood geometry. The simplified model has flat and flexible air inlets and several types of air outlet, and includes in its body a real cooling system and a simplified engine block that can move in the longitudinal and lateral directions. The results of this research are generic and can be applied to any new car design. Results show configurations in which, with respect to the most commonly adopted underhood geometries, the overall drag coefficient can be decreased by 2%, the aerodynamic cooling drag coefficient by more than 50% and the lift coefficient by 5%. Finally, new designs of aerodynamic drag reduction, based on the combined effects of the different investigated parameters, are proposed.

Keywords: Aerodynamic, Drag reduction, Simplified vehicle body, Aerodynamic drag, Cooling drag, Aerodynamic Lift, Torsor.

INTRODUCTION
Reducing aerodynamic forces, particularly drag, is of major interest in several applications [1-5], particularly in automotive industries. The aerodynamic torsor of a vehicle is among the most important parameters in new car development. Over the years, the torsor was decreased by more than 50% before further improvement became difficult [6-13]. Therefore, any improvement in this domain rapidly became a challenge to car manufacturers.

Assessment of the impact of different parameters on the aerodynamic torsor is the basis for launching second-stage improvements (further reducing the aerodynamic torsor of a vehicle). These studies are commonly carried out on different types of vehicles to assess the influence of various parameters on the aerodynamic torsor quantification, and the ways they can be improved.

Often, there are two key elements that prevent the launch of improvements. The first is the specificity of the solution, i.e. often good findings are made for certain types of vehicles that cannot be applied to other types. The second element is the compromises necessary: in some cases promising solutions for the reduction of aerodynamic torsor can be found rather easily, but they have a negative impact on other car aspects, especially the underhood thermal situation. These compromises are usually made according to design priorities.

This work is motivated by an interest in the effects and the hierarchy of various parameters on the aerodynamic torsor of simplified vehicle models. Measurement of aerodynamic forces on these models is a way to find underhood geometrical configurations that reduce the aerodynamic torsor. Here we present a parametric analysis of the different factors that influence the aerodynamic torsor on a simplified vehicle model. The simplified model has flat and flexible air inlets and several types of air outlet, and includes in its body a real cooling system and a simplified engine block that can move in the *X* (longitudinal) and *Y* (lateral) directions. We attempt to provide generic results and to avoid specificities in the resulting solutions. At the same time, the effective solutions found in this study can be tested on real cars.

The rest of this paper is organized as follows. The next section focuses on the basic definitions of vehicle aerodynamic forces. Then, the experimental setup is described in detail. The following section presents results and analysis of the parametric study on the trends of aerodynamic forces. The last section proposes new designs for car drag and pitch momentum reduction.

VEHICLE AERODYNAMIC TORSOR

The aerodynamic torsor *T* of a vehicle (Figure 1) is defined as the following torsor of six components:

$$T = \left(F_x; F_y; F_z; M_x; M_y; M_z\right) \quad (1)$$

where:

- F_x is the drag: the force in the longitudinal flow direction (in the flow direction of the wind tunnel), opposite to the vehicle movement;
- F_y is the lateral force: horizontal force directed at the right-hand side of the vehicle;
- F_z is the lift: upward vertical force;
- M_x the rolling momentum: momentum of the aerodynamic forces with respect to the vehicle *x* axis ;
- M_y the pitching momentum: momentum of the aerodynamic forces with respect to the vehicle *y* axis;
- M_z the yawing momentum: momentum of the aerodynamic forces with respect to the vehicle *z* axis;

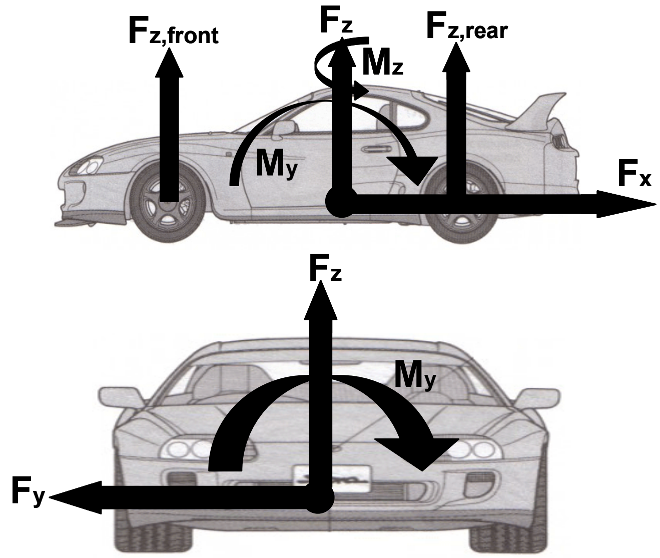

Figure 1: Aerodynamic torsor components for a vehicle.

The front and rear lift forces are those induced at each rolling train (vehicle part):

$$F_z = F_{z,front} + F_{z,rear} \quad (2)$$

Taking as the reference surface the vehicle's front surface, dimensionless coefficients of the different components of the aerodynamic torsor can be defined as follows:

$$C_x = \frac{2F_x}{\rho.S.V^2}; C_y = \frac{2F_y}{\rho.S.V^2}; C_z = \frac{2F_z}{\rho.S.V^2} \quad (3)$$

$$C_l = \frac{2.M_x}{\rho.S.l.V^2}; C_m = \frac{2.M_y}{\rho.S.l.V^2}; C_n = \frac{2.M_z}{\rho.S.l.V^2} \quad (4)$$

EXPERIMENTAL SETUP

Here we describe wind tunnel S4 of Saint-Cyr l'Ecole (France), the simplified vehicle body, the test facilities and the test configurations.

S4 Wind Tunnel

Wind tunnel S4 of the Aerotechnical Institute of Saint-Cyr l'Ecole is a wind tunnel designed for automotive testing at scale 1. The test section is 5 m wide and 3 m high. The maximum air speed in the tunnel is 40 m/s. There is no moving belt device in the wind tunnel.

Given the car size (scale 1), the wind tunnel walls affect the flow around the model. To limit wall effects, wind tunnel S4 has a ventilated-test section type with longitudinal slots permitting a flow closer to the real flow around the vehicle. The wind tunnel has a six-component balance to measure the vehicle aerodynamic torsor.

Simplified vehicle body

The simplified body is a representative form of a vehicle front block (Figure 2a).

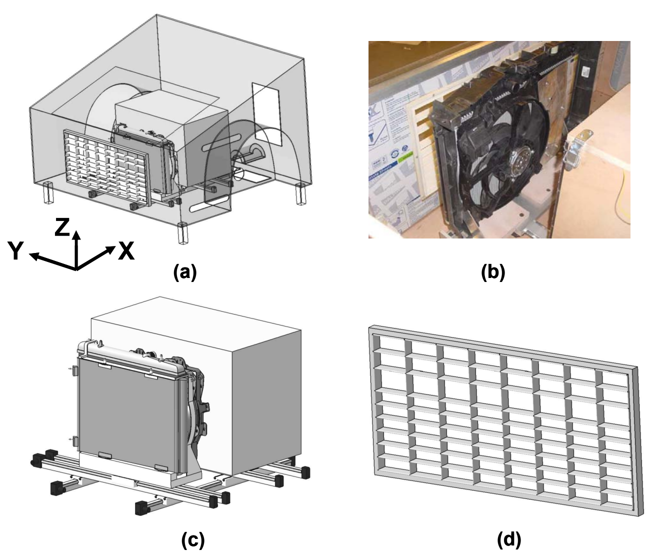

Figure 2: (a) Vehicle simplified body, (b) real cooling module and simplified engine block inside simplified body, (c) XY displacement mechanism, (d) modular air inlet of simplified body.

The front end dimensions (projected in a plane normal to the direction of car movement) are the same as those of a real vehicle. The simplified experimental model is 1.7 m wide and 1.3 m long. Its height varies from 0.6 m at the front face to 1 m at the rear face (which represents the apron and cowl of a real vehicle). Its internal body includes a real cooling system (radiator, condenser, and fan) and a simplified engine block (Figure 2b). These two elements are placed on traversing mechanism that allow their displacement in the *X* (direction of vehicle movement) and *Y* (lateral direction) directions (Figure 2c). The initial configuration represents that of a Peugeot 207 car where the cooling system is shifted to the right (on the *Y* axis) and the engine block is centered with respect to the vehicle axis (*Y*) and located 6 cm behind the cooling system. In this simplified body, the engine block can move from –6 cm to +6 cm in the *Y* direction (in 2-cm steps) and from 6 cm to 20 cm from the cooling system in the *X* direction (also in 2-cm steps).

The air inlet opening of the simplified body (Figure 2d) is plane and modular: with a fixed frame and several windows, one can generate different air-inlet geometries and dimensions by opening and closing a given and well defined number of windows.

The simplified body is equipped with several types of air outlets: a vertical opening, a tunnel outlet (representing the air outlet in the space around the exhaust tunnel of a real vehicle), and openings in the wheel arches and in the body bottom (Figure 3).

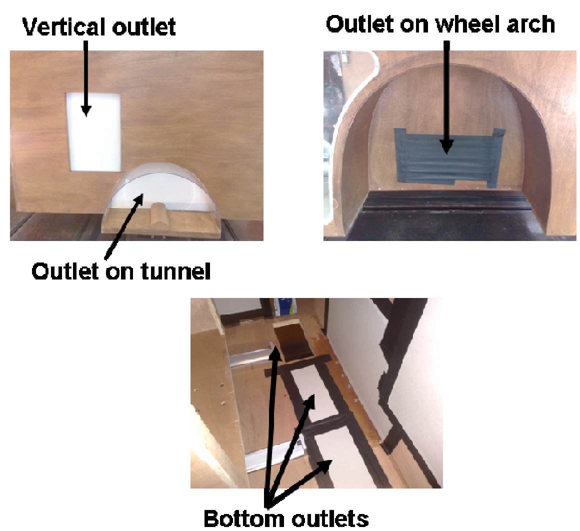

Figure 3: Air outlets in the vehicle simplified body.

In the experiments, not all outlets are open at the same time; combinations of different types of these openings permit simulation of the air exits of different vehicle series: for example, by closing the vertical outlet and the one in the bottom, and by keeping the outlets in the wheel arches and the tunnel open, one can simulate the configurations of conventional PSA Peugeot-Citroen vehicles series. On the other hand, by keeping open only the air outlet in the model tunnel, one can simulate typical air flow configurations of BMW vehicles.

Test facilities and configurations

The aerodynamic force measurements are carried out at a wind speed of 30 m/s. The simplified experimental model is fixed on the wind tunnel balance by four attachments. The resolution of the force coefficients measurements is of the order of ± 0.001.

Forty-nine different aerodynamic configurations were tested:

- 4 configurations to test the effects of different outlet types in single-outlet design;
- 6 configurations to test the effects of different combinations of two outlet types;
- 9 configurations to test the effects of outlet positioning in single-outlet design;
- 8 configurations to test the effects of the ratio between the inlet and outlet sections in classical air outlet design (outlets in the wheel arches and the tunnel);
- 8 configurations to test the effects of engine-block positioning with respect to the cooling system in the longitudinal direction for classical air-outlet design;
- 8 configurations to test the effects of engine-block positioning with respect to the cooling system in the lateral direction for classical air-outlet design;
- 6 configurations to test the effects of air-inlet positioning in the front end for classical air-outlet design.

RESULTS AND ANALYSIS

In this section, the aerodynamic force measurements for the different configurations above are analyzed.

Air outlet type effects in single air-outlet design

To study the effect of different air-outlet types on the aerodynamic torsor, four configurations were tested corresponding to the different outlet types in Figure 3. The front-end air inlet, conserved in the different configurations, has area 970 cm². Each of the different air outlets (Figure 3) has cross-sectional area 1350 cm². In each test, only the outlet of interest is opened (other outlets being closed with scotch).

Figure 4 shows the different torsor coefficients (aerodynamic drag, lift and pitching momentum coefficients) for the different types of outlet.

It is observed that the vertical outlet is the dominant outlet in the drag coefficient *Cx* (0.778). Then the outlets in decreasing order of drag reduction are, respectively, the tunnel exit (0.797), the outlet in the simplified body bottom (0.807), and the wheel-arch outlet (0.831). Indeed, in the vertical outlet and in the tunnel exit, the air stream leaves the simplified body more horizontally than in the bottom exit and the wheel arches. Thus, the departing air stream retains most of its initial momentum in the *X*-direction in the vertical exit, so that the drag is reduced in these cases compared to others.

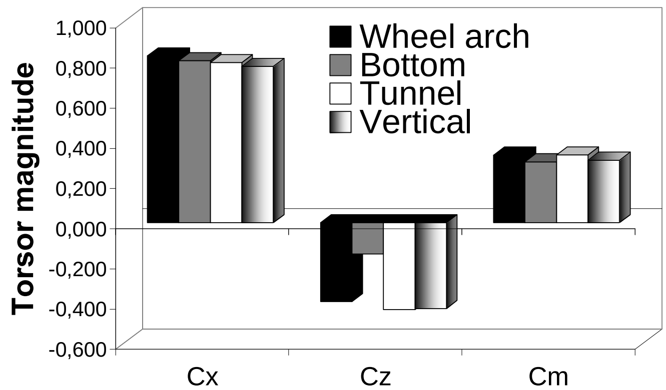

Figure 4: Aerodynamic torsor for the different air outlet types in single air outlet design.

Unlike the drag coefficient, the lift coefficient *Cz* is larger in absolute value in the vertical exits than in the other cases, because the air cannot leave the simplified body as vertically as in the bottom outlet. For this outlet type, the air stream leaves the model as vertically as possible, thus reducing the aerodynamic lift. This feature is very clear in Figure 4: the *Cz* coefficient is -0.155 for the bottom outlet, -0.393 for the wheel arch outlets, -0.433 for the tunnel exit and -0.427 for the vertical outlet.

From the aerodynamic point of view, the bottom and wheel arch outlets are more efficient for the lift coefficient *Cz*. However, in terms of a real automobile, one cannot keep only these two types of outlets, since other constraints must also be satisfied, especially the underhood cooling. Therefore, in new-car design the two vertical outlets are retained in the first assessment, before returning to the analysis of the aerodynamic drag.

In analyzing the drag, the same approach to selecting the optimal outlet solutions is used. Although the vertical air outlet is advantageous in terms of drag reduction, it does not exist in the real configurations of current vehicles (unless this type of outlet will be used in future vehicles). Finally, from the automotive aerodynamic point of view, the tunnel air outlet is the most promising in the single-outlet design.

Effects of combinations of air outlets in double air-outlet design

Here the aim is to verify the effect on the aerodynamic torsor of different combinations of two outlets. For this purpose, the aerodynamic torsor is measured for six different combinations of the different outlet types, two by two: vertical + tunnel (V + T), bottom + vertical (B + V), bottom + tunnel (B + T), vertical

+ wheel arches (V + WA), tunnel + wheel arches (T + WA), and bottom + wheel arches (B + WA).

The ratio between the inlet and outlet cross-section areas is maintained at 0.72 among the different configurations. Similarly, the air inlet surface is conserved in the different air-outlet combinations with cross-section area 1940 cm². For each configuration, the total air-outlet area is 2700 cm ² and is split equally between the two air outlets.

Figure 5 shows the *Cx* drag coefficient for the different air-outlet combinations.

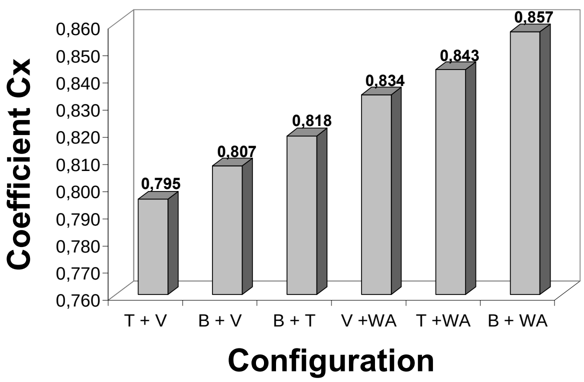

Figure 5: Cx coefficients for the different air outlet combinations tested.

We see that for most outlet combinations, especially those for which the vertical outlet is present, the drag coefficient *Cx* is below that of the most common classical configuration of wheel arches and tunnel outlets. Then, keeping in mind that the vertical outlet is not applicable to real vehicles, the option “bottom + tunnel” combination is retained as optimal in the double-outlet design vis-à-vis vehicle drag reduction.

By comparing the real outlet configurations used on current vehicles, we note that the solution “tunnel alone” remains the best tions for aerodynamic drag reduction among the three real options “single tunnel”, “tunnel + wheel arches” and “tunnel + bottom”.

Figure 6 shows respectively the lift *Cz* and the pitching momentum *Cm* coefficients.

It is observed that the best outlet combination for lift coefficient reduction is “bottom + wheel arches”. However, as already mentioned, this solution cannot be adopted on real vehicles, nor can the “vertical + bottom” configuration. Therefore, the "tunnel + bottom" combination is the best realistic combination for lift coefficient reduction. Similarly, we note that the “tunnel + bottom” combination is the most advantageous for moment (*Cm*) reduction.

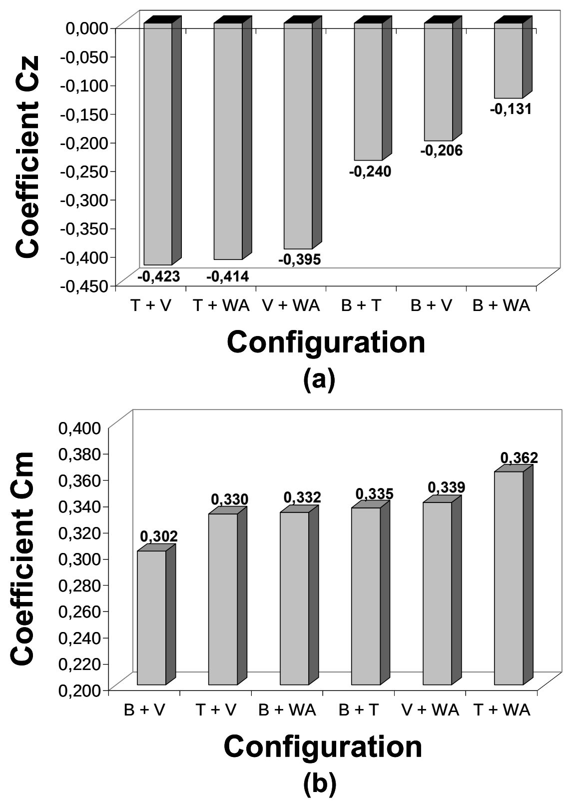

Figure 6: (a) Lift coefficient Cz and (b) pitching momentum coefficient Cm for the different air-outlet combinations.

Finally, from the automotive aerodynamic point of view, the combination “tunnel + bottom” is the best solution for the double-outlet design.

Air outlet position in single-outlet design

Here we study the effects of the position of the air outlet type on the aerodynamic torsor. For this purpose, the aerodynamic forces were measured for nine different air-outlet position configurations: left bottom (L – B), central bottom (C – B), right bottom (R – B), high vertical (H – V), central vertical (C – V), bottom vertical (B – V), front wheel arch (F- WA), central wheel arch (C - WA), and rear wheel arch (R – WA).

The ratio between the inlet and outlet cross-sectional area is maintained at 0.72 among the different configurations. Similarly, the air-inlet surface of 325 cm² is maintained for the various air-outlet combinations. For each configuration, the surface area of the air outlet is 450 cm².

Figure 7 shows the *Cx* drag coefficient for the different air-outlet positions examined here.

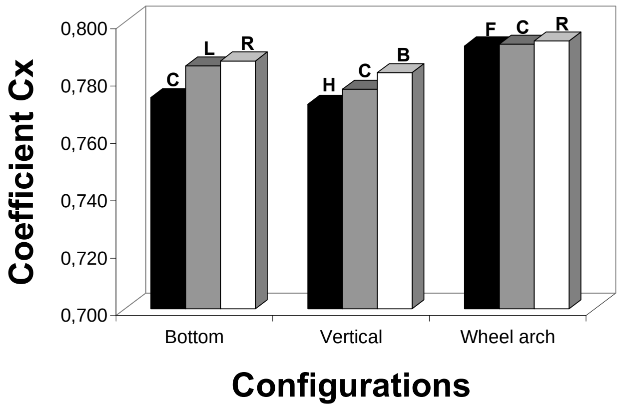

Figure 7: Drag coefficient Cx for the different air-outlet position configurations.

We note that:

- the aerodynamic drag is smaller when the bottom outlet is centered on the vehicle width (Y). When positioned on the left or the right, the bottom air outlet induces almost the same drag;
- the higher the vertical outlet, the lower the induced aerodynamic drag;
- the wheel arch air-outlet position has no impact on the aerodynamic drag.

Figure 8 shows the lift coefficient Cz for the different air outlet position configurations. We note that

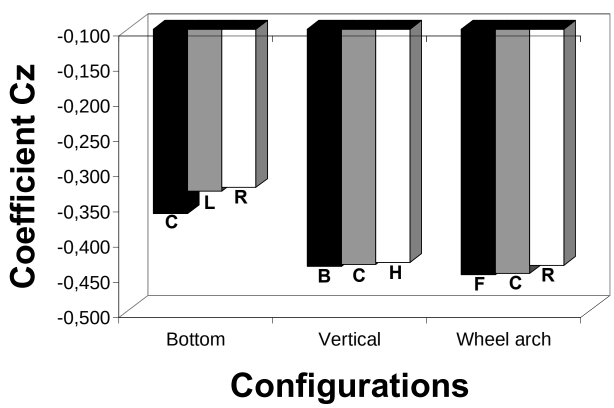

Figure 8: Lift coefficient Cz for the different air-outlet position configurations.

- the lift is greater when the bottom outlet is centered with respect to vehicle width. Whether positioned on the left or the right, the bottom outlet induces the same aerodynamic lift;
- the lower the vertical outlet, the greater the aerodynamic lift;
- the wheel arch air-outlet positioned at the rear decreases aerodynamic lift.

It should be emphasized that the effect of air-outlet position on the other elements of the aerodynamic torsor is negligible. Finally, for the vertical and bottom air outlets, the trends of the variations in drag and lift are always in opposite directions, suggesting the adoption of compromises from the aerodynamic point of view. On the other hand, the air outlet in the wheel arch should be placed as far as possible towards the rear of the wheel arch.

Effect of the inlet and outlet sections ratio in classical air outlets design

The purpose of this section is to investigate the effect on the aerodynamic torsor of the ratio of the air inlet and outlet cross-sectional areas. To this end, the aerodynamic forces were measured for eight different inlet/outlet ratios ranging from 0.2 to 0.9 in 0.1 steps. The air outlets are the ones most commonly used in current car designs (especially in PSA Peugeot Citroen cars) in the tunnel and the wheel arches, and are maintained over the different configurations. The total air-outlet surface in each case is 2700 cm².

Figure 9 shows the variation of the relative *Cx*, *Cz* and *Cm* as a function of the inlet/outlet cross-sectional ratio. The relative coefficients are determined by dividing the absolute coefficients by the maximum absolute value obtained for the different inlet/outlet cross-sectional ratio. The lift coefficient is represented in absolute value.

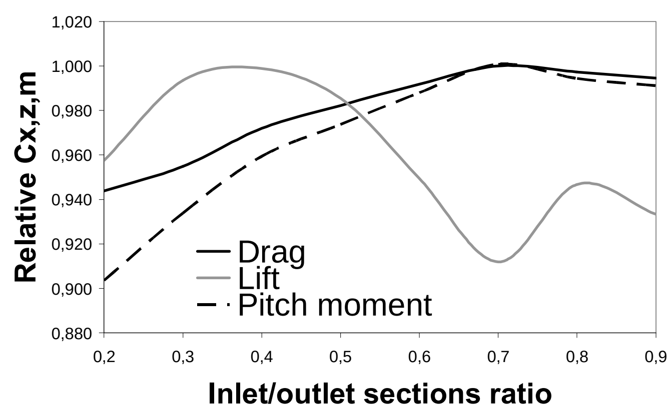

Figure 9: Variations in torsor relative coefficients as a function of inlet/outlet cross-sectional area ratio.

Figure 9 shows that:

- the *Cx* drag coefficient as well as the pitching moment *Cm* increase when the inlet/outlet cross-sectional ratio increases up to 0.7, beyond which they become almost constant;
- the *Cz* lift coefficient decreases in absolute value when the inlet/outlet cross-sectional ratio increases up to 0.7, beyond which *Cz* undergoes slight variations.

Indeed, the inlet/outlet cross-sectional ratio is essentially a parameter imposed by underhood aerothermal constraints. It can be concluded from the above findings that, after a ratio of 0.7, the greater this ratio, the greater the improvement in the underhood cooling, while retaining the aerodynamic situation unchanged. Therefore, the optimum design of real vehicles from an aerothermal point of view is to have an air inlet cross-sectional area equal to that of the air outlet.

Effects of engine-block/cooling-system *X* and *Y* spacing in classical outlet design

This section discusses the effects of longitudinal and lateral spacing between the cooling system (radiator, condenser and fan) and the engine block on the aerodynamic torsor of a vehicle, especially on the drag and the cooling drag. For this purpose, the aerodynamic forces were measured for eight different configurations of engine-block/cooling-system spacing *X* = 6, 8, 10, 12, 14, 16, 18 and 20 cm and eight other configurations of cooling-system position in the lateral direction *Y* = 0, 2, 4, 6, 8, 10, 12 and 14 cm with respect to the engine block. It should be noticed that *X* = 6 cm and *Y* = 0 corresponds to a real Peugeot 207 configuration in which the cooling system is right-shifted from the vehicle center and shifted by 6 cm in the longitudinal direction from the vehicle center. The inlet/outlet cross-sectional ratio is maintained constant at 0.72 among the different configurations. The air inlet cross-sectional area is also kept constant at 1940 cm^2 among the different configurations. Air outlets for all the configurations are those of conventional PSA Peugeot Citroen vehicles (tunnel and wheel arches). The total air outlets area in each case is 2700 cm².

Figure 10 shows the variations in the relative *Cx*, *Cz*, *Cm* and *Cc* as functions of the longitudinal spacing *X* between the cooling system and the engine block. The relative coefficients are determined by dividing the absolute coefficients by the coefficient corresponding to the reference configuration *X* = 6 cm. We note that:

- the absolute values of the aerodynamic drag coefficient *Cx*, the cooling drag coefficient *Cc* and the lift coefficient *Cz* decrease when the spacing between the cooling- system and the engine block increases;
- the pitching moment coefficient *Cm* also decreases when the spacing *X* increases, but with a smaller slope.

Therefore, among the parameters investigated, the spacing *X* between the cooling module and the engine block is the first one for which the two coefficients *Cx* and *Cz* vary in the same direction. Consider now the improvement (reduction) percentage of the drag coefficient *Cx*, the cooling drag coefficient *Cc* and the lift coefficient *Cz*. These percentages are calculated each time with respect to the reference spacing 6 cm between the cooling system and the engine block. Increasing the spacing *d* between the cooling system and the engine block from 6 to 20 cm decreases the drag coefficient by 1.44%, the cooling drag coefficient by 17.36 % and the lift coefficient by 1.83%.

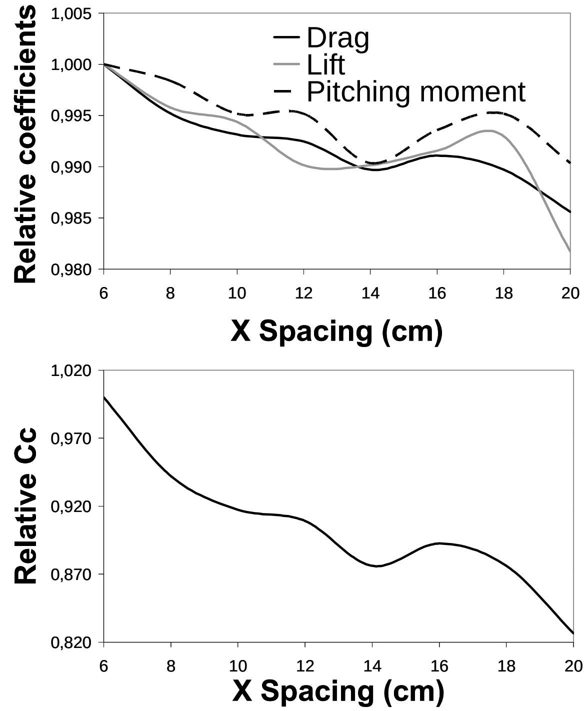

Figure 10: Variations of aerodynamic torsor relative coefficients as a function of the spacing d.

Figure 11 shows variations in the drag *Cx*, the lift *Cz* and the pitching moment *Cm* coefficients as a functions of the lateral position *Y* of the cooling system with respect to the engine block. It can be seen that:

- the drag coefficient *Cx* as well as the pitching moment *Cm* decrease when the position *Y* of the cooling system increases, in other words when the cooling system is shifted more to the right side of the engine block (with respect to the vehicle driver seat);
- the lift coefficient *Cz* remains almost constant when the position *Y* of the cooling system varies.

Therefore, of the different parameters investigated, the distance *d* between the cooling system and the engine block is the second parameter for which the aerodynamic torsor coefficients vary in the same direction.

Now consider the improvement (reduction) percentage in the drag coefficient *Cx*, the cooling drag coefficient *Cc* and the pitching moment coefficient *Cm*. These percentages are calculated each time for the central *Y* = 0 position of the cooling system with respect to the engine block. It is noted that shifting the cooling system to the right of the engine-block, i.e. by varying the *Y* position from 0 to 14 cm, decreases the drag coefficient by 1.1%, the cooling drag coefficient by 12.75% and the pitching moment *Cm* by 1.45%.

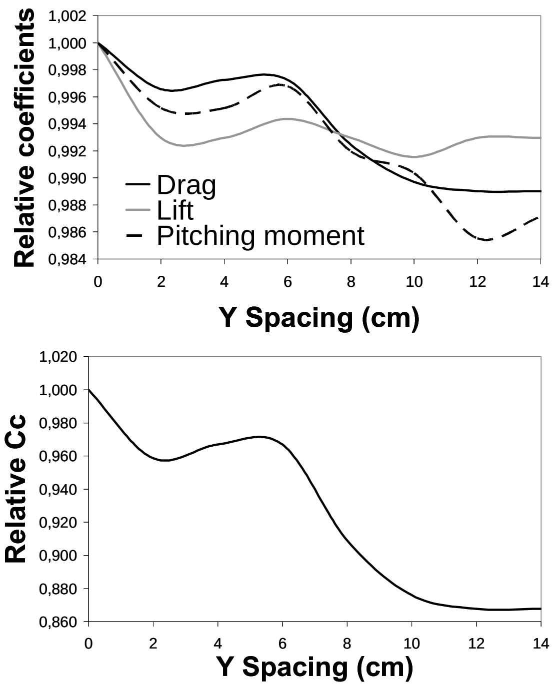

Figure 11: Variations of aerodynamic torsor relative coefficients as a function of the spacing Y.

Effect of air inlet position in tunnel air-outlet design

In this section, the effect on the aerodynamic torsor of the lateral (*Y*) and vertical (vehicle height, *Z*) positioning of the air-inlet opening in the vehicle front end is investigated. For this purpose, the aerodynamic forces were measured for six different air-inlet positions: left air inlet (L-AI), Y central air inlet (YC – AI), right air inlet (R – AI), upper air inlet (U – AI), Z-central air inlet (ZC – AI) and bottom air inlet (B – AI). The inlet/outlet cross-sectional ratio is maintained constant and equal to 0.72 among the different configurations. The air inlet surface area also remains constant at 970 cm² in all configurations. Only the air outlet in the tunnel is open; it too is constant among the different configurations and equal to 1350 cm².

Figure 12 shows the variations in the drag coefficient *Cx*, the cooling drag coefficient *Cc*, the lift coefficient *Cz* and the pitching moment coefficient *Cm* for the six air-inlet configurations as well as for the classical configuration (current on several series vehicles and consisting of two separate air inlets, upper and lower) in order to characterize the different effects. Data corresponding to the classical air-inlet position are shown in solid black in the different columns of Figure 12.

It is noticed that the central position in *Z* of the air-inlet opening is best for aerodynamic torsor reduction. Also, given other constraints, the central *Z* position and the classical position are the most advantageous solutions. Here again, of the different parameters investigated, the air-inlet position is another parameter for which the different coefficients of the aerodynamic torsor vary in the same direction.

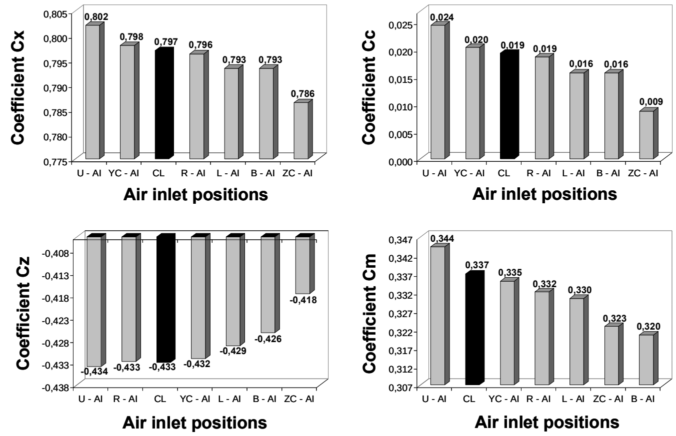

Figure 12: Aerodynamic torsor different coefficients as functions of the air-inlet positions.

Consider now the improvement (reduction) percentages in the aerodynamic drag coefficient *Cx*, the cooling drag coefficient *Cc*, the lift coefficient *Cz* and the pitching moment *Cm*. These percentages are calculated for each configuration relative to that for the classical air-inlet position. We see that, with respect to the classical air inlet position, the *Z* central position reduces the drag coefficient by 1.3%, the cooling drag coefficient by 56.4 %, the lift coefficient by 4.9% and the pitching momentum coefficient by 3.6%.

DRAG REDUCTION DESIGNS

Let us consider a Peugeot 207 passenger car as an example series vehicle. On this vehicle, the air outlets are in the exhaust tunnel and in the wheel arches, and the mean spacings in the *X* and *Y* directions of the cooling system and the engine block are respectively about 6 cm and 0 cm in the configurations of the simplified vehicle body tested above.

Now we consider a hypothetical Peugeot 207 car on which the cooling system is shifted by 14 cm to the right with respect to the engine block and by 20 cm in the *X* direction, away from the cooling system. In addition, let its air inlet opening be centered in the *Z* direction and let there be only one air outlet in the exhaust tunnel.

Now one can gain the following percentages in aerodynamic drag coefficient reduction with respect to actual Peugeot 207 vehicles:

- 3% in tunnel outlet with respect to the classical Peugeot 207 outlets;

- 1.4% with X position 20 cm with respect to the 6 cm of the reference case;
- 1.1% in Y position of 14 cm with respect to the 0 cm of the reference case;
- 1.3% in Z centered air inlet with respect to the classical inlet (double openings).

By combining the different percentages above and by repeating the same procedure for the lift and pitch moment coefficients, we find that we can gain a 7% drag coefficient reduction and a 5% pitch moment coefficient reduction, while the lift coefficient remains almost constant. This design thus permits reducing the aerodynamic drag of a real Peugeot 207 passenger car to 93% of its actual value and the pitching moment to 95% of its actual value while keeping the lift force almost unchanged.

It should be emphasized that the gain determined above is the maximum that can be obtained by applying all the improvements investigated here. Various combinations of the different configurations investigated above provide intermediate improvements over the reference case. Therefore, by two air-outlet configurations ("tunnel" or "tunnel + bottom") and respectively almost 7 and 5 cooling-system/engine-block X and Y positioning configurations which permit aerodynamic drag reduction, one can find 70 (2×5×7) conceptual combinations that could reduce the aerodynamic drag up to 5%. As an example, Figure 13 gives orders-of-magnitude reductions for six of the 70 intermediate designs, as detailed in Table 1.

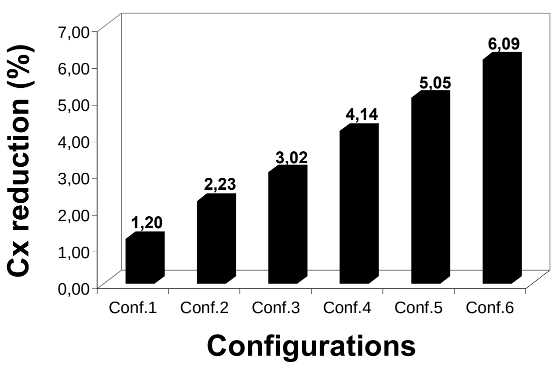

Figure 13: Percentages of Cx reduction for different proposed designs.

	Air inlet	Air outlet	X spacing	Y spacing
Conf. 1	Classical	Classical	8 cm	2 cm
Conf. 2	Classical	Classical	14 cm	8 cm
Conf. 3	Z centered	Classical	14 cm	8 cm
Conf. 4	Classical	Tunnel	8 cm	2 cm
Conf. 5	Z centered	Tunnel	8 cm	2 cm
Conf. 6	Z centered	Tunnel	16 cm	10 cm

Table 1: Geometrical details of the different proposed designs.

CONCLUSIONS

This paper reports the results of aerodynamic force measurements carried out on a simplified vehicle model in a wind tunnel. The purpose is to establish a parametric analysis of the different parameters that influence the aerodynamic torsor of a vehicle. Specifically, it was found that:

- The drag coefficient as well as the pitch moment coefficient increase with the inlet/outlet cross-sectional ratio up to 0.7, beyond which they become almost constant. The lift coefficient decreases with this ratio also up to a value of 0.7, above which it varies slightly.

- Increasing the longitudinal distance between the cooling system and the engine block from 6 to 20 cm reduces the drag coefficient by 1.4%, the cooling drag coefficient by 17.4% and the lift coefficient by 1.83%.

- Shifting the cooling system to the right with respect to the engine block reduces the drag coefficient by 1.1%, the cooling drag coefficient by 12.8% and the pitching moment coefficient by 1.5%.

- With an air inlet opening centered in the Z direction, it is possible to reduce, with respect to classical air inlet position, the drag coefficient by 1.3%, the cooling drag coefficient by 56.4% and the pitching moment coefficient by 3.6%.

Finally, from the improvements found for the different parameters investigated, new designs for reducing the vehicle aerodynamic torsor are proposed.

REFERENCES

[1] N. Kikuchi, Y. Matsuzaki, T. Yukino and H. Ishida, Aerodynamic drag of new-design electric power wire in a heavy rainfall and wind, Journal of Wind Engineering and Industrial Aerodynamics 91 (2003) 41-51

[2] X. Liu, M. Levitan and D. Nikitopoulos, Wind tunnel tests for mean drag and lift coefficients on multiple circular cylinders arranged in-line, Journal of Wind Engineering and Industrial Aerodynamics 96 (2008) 831-839

[3] F. Cheli, F. Ripamonti, D. Rocchi and G. Tomasini, Aerodynamic behaviour investigation of the new EMUV250 train to cross wind, Journal of Wind Engineering and Industrial Aerodynamics, in press

[4] S. Watkins and G. Vino, The effect of vehicle spacing on the aerodynamics of a representative car shape, Journal of Wind Engineering and Industrial Aerodynamics 96 (2008) 1232-1239

[5] J.H.G. Macdonald and G.L. Larose, A unified approach to aerodynamic damping and drag/lift instabilities, and its application to dry inclined cable galloping, Journal of Fluids and Structures 22 (2006) 229-252

[6] R.M. Wood and S.X.S. Bawer, Simple and Low-cost Aerodynamic Drag Reduction Devices for Tractor-Trailer Trucks, SAE Paper 2003-01-3377, 2003

[7] I. Bayraktar, D. Landman, C. Hunter, R. Wood and J. Flamm, An Assessment of Drag Reduction Devices for Heavy Trucks Using Design of Experiments and Computational Fluid Dynamics, SAE Paper 2005-01-3526, 2005

[8] R.E. Schoon, Practical Devices for Heavy Truck Aerodynamic Drag Reduction, SAE Paper 2007-01-1781, 2007

[9] R.M. Wood, Operationally-Practical and Aerodynamically-Robust Heavy Truck Trailer Drag Reduction Technology, SAE Paper 2008-01-2603, 2008

[10] J.D. Kee, M.S. Kim and B.C. Lee, The Coanda Flow Control and Newtonian Concept Approach to Achieve Drag Reduction of Passager Vehicle, SAE Paper 2001-01-1267, 2001

[11] W.R. Lanser, J.C. Ross and A.E. Kaufman, Aerodynamic Performance of a Drag Reduction Device on a Full-Scale Tractor/Trailer, SAE Paper 912125, 1991

[12] A. Gupta and S.M. Ruffin, Aerothermodynamic Design of Supersonic Channel Airfoils for Drag Reduction, SAE Paper 975572, 1997

[13] K. Rokhsaz, A. Brief Survey of Wing Tip Devices for Drag Reduction, SAE Paper 932574, 1993

