Does an active adjustment of aerodynamic drag make sense?

Marek Maciejewski
Politechnika Poznańska, Instytut Maszyn Roboczych i Pojazdów Samochodowych, 60-965 Poznań, ul. Piotrowo 3
E-mail: marek.maciejewski@put.poznan.pl

Abstract. The article concerns evaluation of the possible impact of the gap between the tractor and semitrailer on the aerodynamic drag coefficient. The aim here is not to adjust this distance depending on the geometrical shape of the tractor and trailer, but depending solely on the speed of articulated vehicle. All the tests have form of numerical simulations. The method of simulation is briefly explained in the article. It considers various issues such as the range and objects of tests as well as the test conditions. The initial (pre-adaptive) and final (after adaptation process) computational meshes have been presented as illustrations. Some of the results have been presented in the form of run chart showing the change of value of aerodynamic drag coefficients in time, for different geometric configurations defined by a clearance gap between the tractor and semitrailer. The basis for a detailed analysis and conclusions were the averaged (in time) aerodynamic drag coefficients as a function of the clearance gap.

1. Introduction
A characteristic feature of articulated vehicles, unlike conventional trucks, is additional free space between the rear wall of the cab and the front wall of the trailer. In the case of a small clearance gap between both units, it can be assumed that the aerodynamic effect will not be significant. It appears that in this situation the pressure acting on the rearward-facing surface of the tractor and the forward-facing surface of the trailer are more or less similar, and therefore will not lead to a significant change in the aggregated drag. On the other hand, in case of a large distance between the vehicle units, the pressure difference on both surfaces may become large enough to result in clear increase of the aerodynamic drag for the entire vehicle. Therefore, it can be assumed that increasing the distance between the vehicle units will increase the aerodynamic drag. This finding is consistent with the principle that the drag coefficient of the tractor-trailer system depends solely on the geometry of individual units and the distance between them.

Recently, the author of this publication made a contact with a company engaged in transport operations involving articulated vehicles. The company representative observed that their drivers report a noticeable dependency of aerodynamic drag on the vehicle speed and the distance between units. We confirmed this observation and explained that in general:

- aerodynamic drag coefficient depends only on the relative position of the two units of the articulated vehicle, and is speed independent,
- aerodynamic drag of the vehicle (with given geometric configuration, i.e. with specific drag coefficient) depends solely on speed.
The above statements have been confirmed by many aerodynamic tests and simulations that can be found in literature relating to the aerodynamics of articulated vehicles and the available ways to reduce their aerodynamic drag forces [1, 2, 3, 4, 5, 6, 7, 8, 9].

The company representative did not agree with above statements and was convinced that speed also affects the drag coefficient. He believed, that in order to minimize the aerodynamic drag, the gap between the tractor and the trailer should be adjusted during the drive according to the current speed of the vehicle. This difference of opinion led the company to turn to the author of the publication with the proposal to carry out fast numerical simulations to finally resolve the matter. Thus, the subject of carried out simulations was not only finding a certain optimum amount of space between the tractor and trailer, but also to examine whether the optimal value of the gap depends on the speed. Although the dependence of the drag coefficient on speed seemed doubtful due to the aerodynamic interference phenomena occurring in the space between the vehicle units, it was considered to be worth checking. If it turned out to be true, an active adjustment of the gap magnitude depending on the speed would be a simple and convenient method to reduce aerodynamic drag.

2. Method of the numerical simulation

The numerical simulations of aerodynamic phenomena around the articulated vehicle were carried out on the basis of the Navier–Stokes equations for incompressible fluid, because for typical speeds for road vehicles, relative errors made due to the assumption of flow incompressibility are negligibly small. For incompressible formulation, in the continuity equation is missing an evolutionary term, and this equation should be treated as divergence-free (solenoidal) condition for velocity field. To circumvent this limitation, an additional term containing the time derivative of pressure has been introduced into the continuity equation. This introduced artificial compressibility, that ensured a sufficient coupling between the continuity and momentum equations.

For computational simulations, it is necessary to replace the initial continuous problem with its discrete counterpart. The discretization process consists in replacing a continuous system (with infinite degrees of freedom) by its discrete representation (with a finite number of degrees of freedom) expressed through nodal points defined usually on a computational mesh. This requires a simultaneous definition of behaviour of the points lying inside each mesh cell, depending on behaviour of nodal points of given cell. For this purpose, the polynomial approximation methods are used most often. The polynomials are simultaneously applied to reconstruct the effect of operators included in mathematical description. Such form of discretization (in combination with appropriate approximation) is applied to both, space and time, in our case, sequentially.

The space discretization of the problem is realised with the use of approximation corresponding to the finite volume method, where the solution change (in a time step) for single computational cell is resulted from current balance conditions on the cell walls, i.e. from the flux balance established on the basis of the Riemann problem solution for reconstructed fields of primitive variables. In this resolving, the upwind numerical scheme referred to the signs of local eigenvalues is used. Determination of numerical fluxes through the cell walls is the basis to carry out a time integration (the explicit Runge–Kutta method) and determine variable values inside particular cells in next time step of automatically selected length.

Due to the significant impact of computational mesh configuration (the resolution and form) on the accuracy of the achieved results, and inability to predict a priori the appropriate mesh arrangement, the computational program was developed in the adaptive version to ensure required accuracy of simulations. It carries out standard computations on initial mesh and then, on the basis of assessment of the solution quality, determines subdomains where the solution is not sufficiently accurate. The mesh density gets appropriately increased in indicated subdomains. The cyclical procedure for successive mesh refinement is continued until assumed
criteria for the accuracy have been fulfilled. The adaptive program that has been used includes, unlike the standard one, two new elements: a procedure to estimate the solution quality (on the basis of solution error estimation, or estimation of the intercellular variable gradients) in particular cells, and a procedure for the computational mesh refinement based on increasing the local mesh density as a result of successive bisection of the longest cell edges in chosen mesh subdomain.

3. Range and conditions of simulations

The scope of considerations was to determine the aerodynamic properties of articulated vehicles depending on following two factors: the clearance gap between the tractor and semitrailer, and the vehicle speed. These properties are determined mainly by the aerodynamic drag coefficient, and to the lesser degree by distributions of pressure and velocity components.

All numerical simulations have been performed in the two-dimensional (2D) space. Admittedly, for precise reconstruction of aerodynamic phenomena around vehicles, it would be appropriate to use 3D simulations, but for comparative studies of vehicles with similar outlines, the 2D simulations are sufficient. It is even more justified when comparing aggregate properties, e.g. drag coefficients. Other reasons for 2D simulations were:

- the easier identification of main factors influencing the aerodynamic drag,
- simpler and clearer forms of aerodynamic phenomena,
- the simpler and faster creation of vehicle models,
- far shorter times of simulations.

Conducted simulations tried to reconstruct typical traffic conditions, i.e. the vehicles moving in open space, without artificial, physical or computational, limitations related to insufficient size of computational domain. This size was equal for all simulations. It is worth noting that assumed boundary conditions did not reconstruct aerodynamic circumstances from wind-tunnels, but reflected real, windless conditions from road traffic.

Objects of aerodynamic simulation were the articulated vehicle models with simplified bodywork forms achieved by straightening out the bodywork lines and omission of local curvatures. This had an undoubted impact on the increase of aerodynamic drag but, at the same time, caused their greater diversity. The simplification of bodywork forms had no impact on simulation processes, but enabled much more to emphasize some forms of aerodynamic phenomena, in comparison to more streamlined models.

Figure 1 presents an exemplary articulated vehicle model with the clearance gap indicated by the letter B. The total number of considered tractor-trailer gap sizes is equal to 16: from 0.0 m (a one-body or ‘monospace’ form) to 1.5 m, with a step of 0.1 m. The geometrical shape and position of the tractor are the same in all of computational models. The trailer shape and sizes (the length: 15 m, the height: 4 m, and the ground clearance: 0.4 m) are identical, but the trailer position is variable, appropriate to the gap size B.

All the created vehicle models were placed in the duly geometrically defined outer outline of assumed flow domain. The height of computational domains was always equal to 24 metres and the length was equal to 72 meters (from -12 m to 60 m). Such defined flow domains were used to generate the initial computational meshes for all considered models. A sample initial mesh, created for the gap size B equal to 1 m, is presented in figure 2.

The boundary conditions for each computational domain have been defined according to the following scheme:

- on the vehicle profile: the motionless solid boundary,
- on the left- and right-side of the ‘tunnel’: inflow and outflow boundaries, respectively,
- at the top of flow domains: the symmetric boundary conditions,
The considered vehicle speeds, or the air inlet velocities, have been assumed as 15, 20, 25
and 30 m/s. The control parameters for each of computational processes were identical.

For description of the computational domain configurations, the uniform notation has been
introduced according to the following pattern:

AB-C

where particular symbols (A, B and C) denote:

A – v (always), as distinctive sign of all the simulations considered,
B – the clearance gap (in decimetres) between the tractor and semitrailer,
C – the vehicle speed (in metres per second).

Total number of computational simulations was 64.

4. Direct results of simulations

Results of carried out numerical simulations of articulated vehicle aerodynamics may take one
of two forms: direct or indirect. Direct results of aerodynamic simulations are relevant to:

• temporary distributions of variables (i.e. pressure, and horizontal and vertical components
  of velocity) in each flow domain, for predefined points in simulation time,
Figure 3. Exemplary final mesh for the computational configuration v10-25 and 20\textsuperscript{th} second of simulation.

- temporary configurations of adaptive computational meshes (for predefined time points), indicating the different forms of aerodynamic phenomena around vehicle.

Direct results of simulations, and in particular those referring to variable distributions, tell a lot about aerodynamic phenomena around road vehicles. The consideration of variable distribution in a flow field is justified only if we want to explain certain specific questions related to local flow forms. Such analysis of direct results is not too effective in the context of overall and concise evaluation of the aerodynamic properties of vehicles.

The exemplary post-adaptive mesh form, from the final time point (20 s) of the simulation, for the model v10-25 (the gap is equal to 1 m, and the velocity – 25 m/s), is presented in figure 3. The distributions of pressure and both components (horizontal and vertical) of velocity, for the time point equal to 20 s, can be found in figure 4.

5. Aggregate indirect results

Unlike presentation of direct results, which always concerns only one specific case of computational configurations and only one of primitive variables (pressure or velocity components) distributed over a computational mesh, the presentation of indirect results, understood as overall aerodynamic properties, may refer simultaneously to one or many different computational configurations dynamically, in a function of time. Typical indirect and comprehensive measures with regard to description of aerodynamic features of vehicles are the aggregate aerodynamic drag and lift forces. These quantities are however inconvenient to compare the aerodynamics of different vehicles. For this purpose the dimensionless drag and lift coefficients are more suitable. Therefore, in our comparative studies on aerodynamic resistance, we mainly use the aerodynamic drag coefficient determined typically on the assumption that the overall aerodynamic drag has a fully convective (non-diffusive) character.

For a specific aerodynamic simulation, the aerodynamic drag coefficient is not a fixed value; it changes in time according to temporary distributions of primitive variables. Moreover, the temporary changes in the drag coefficient can be directly compared to other ones from different vehicles. It allows comparing many such coefficients on a single timeline chart. Examples of the drag coefficient comparisons can be found in figures 5 and 6. The first one shows temporary changes of drag coefficients for exemplary clearance gaps between the tractor and semitrailer (for constant vehicle speed), and the second one presents temporary changes of drag coefficients for exemplary vehicle speeds at a constant gap between the vehicle units.

As already noted above, the aerodynamic drag coefficient usually evolves in time, which is related to variable forms of aerodynamic phenomena around the vehicle. It is usually not
Figure 4. Exemplary variable distributions for the model v10-25 (20\textsuperscript{th} second): (a) pressure, (b) horizontal velocity, and (c) vertical velocity, where the field values are locally defined by colours (red – maximum, blue – minimum).

noticeable in wind-tunnel tests because of a high inertia of vehicles, and also, to a limited extent, an elasticity of the weighting system with force-measuring transducers. Because it is widely accepted that the aerodynamic drag coefficient is defined as a constant value, the averaging of that coefficient was carried out based on the values obtained for various time steps. Due to the fact, that the first few seconds of each simulation are characterised by dissimilarity or fluctuation of results, the averaging was carried out in relation to the recurrent and stable part of results. These large fluctuations result from assumption of approximate, and in general spurious, initial conditions for the flow domain. Hence, the averaging was carried out for the results from the second half of the time steps, which was sufficient enough to achieve a reliable value of the constant drag coefficient.

Moreover, observing the velocity component distributions at different vehicle speeds, it can be noted that the aerodynamic phenomena, e.g. detaching air vortices behind a vehicle, occur at a rate dependent on the vehicle speed. The greater the running speed, the greater the vortices
Figure 5. Drag coefficients as a function of time, for some computational configurations with various gap sizes (in dm) and the constant speed (25 m/s).

Figure 6. Drag coefficients as a function of time, for some computational configurations with various running speeds and the constant gap size (10 dm, i.e. 1 m).

creation rate behind a vehicle. Consequences of this can be noticed in relationships between an aerodynamic drag coefficient and a vehicle speed, e.g. in figure 6. At higher vehicle speeds, the correct periodic forms of aerodynamic phenomena are achieved in less time. Stabilization of these phenomena normally takes place after a certain number of time steps, i.e. after propagation of boundary conditions to the whole flow domain.

Because of automatic adjustment of size of each time step, its length depends on maximal, local flow velocities from all computational cells. With some approximation it can be claimed that the time step size is inversely proportionate to a vehicle speed. This dependence may be distorted by process of automatic computational mesh adaptation, but all parameters of that process were uniform for all simulations.

Because the end time of simulations for each vehicle speed was equal to 20 s, and the sizes of time steps are different and dependent on vehicle speeds, the resulting numbers of time steps are accordingly different. At high speeds, the number of short time steps was large, and at low
After calculating the constant, aggregated aerodynamic drag coefficients for each of carried out simulations, it was possible to determine general relationships for aerodynamic drag coefficients in terms of the clearance gap between tractor and trailer, and the speed of articulated vehicle. Figure 7 presents the curves of drag coefficients versus gap size, for all considered vehicle speeds: 15, 20, 25 and 30 m/s. These relationships are the basis for the answer to the question from article title: Does an active adjustment of aerodynamic drag make sense?

6. Conclusions

Fundamental conclusions from the carried out simulations have been outlined in the following two points.

(1) In the range of studied gaps between tractor and semitrailer (from 0.0 m to 1.5 m, with the step 0.1 m), it was found that the lowest values of aerodynamic drag coefficient took place in the case of no gap and for the gaps equal to 0.7 and 1.1 m, regardless of the vehicle speed.

(2) There is no need to control a tractor-trailer gap size depending on vehicle speed in order to actively reduce the aerodynamic drag, because the value of the drag coefficient is not influenced by vehicle speed. This conclusion is consistent with our initial assumption presented in the introduction to this article.

Finally, it would be advisable to draw the attention to two other issues. The first concerns little diversity of results, i.e. different values of drag coefficients for different speeds. That issue does not apply to zero gap, i.e. a one-body or ‘monospace’ case, but to the cases with real (from 0.1 m to 1.5 m) gaps between the tractor and semitrailer. In these cases, some,
considerably insignificant, differences in the level of drag coefficient can be noticed. This is due to the differences in aerodynamic interference at different speeds.

The second issue raises the question: why the aerodynamic drag coefficient does not grow successively with the increase of the clearance gap? In fact, it stems from the nature of 2D simulations, where the exchange of air between the tractor and trailer occurs only vertically, whereas in reality and 3D simulations, this exchange occurs in both horizontal and vertical directions. It does not affect, in any way, the above presented conclusion regarding no effect of running speed on the level of aerodynamic drag coefficient for each considered configuration of articulated vehicles.

References
[1] Hammache M and Browand F 2004 On the aerodynamics of tractor-trailers Lecture Notes in Applied and Computational Mechanics 19 (Berlin: Springer) pp 185–205
[2] Roy C, Payne J, McWherter-Payne M and Salari K 2004 RANS simulations of a simplified tractor/trailer geometry Lecture Notes in Applied and Computational Mechanics 19 (Berlin: Springer) pp 207–18
[3] Nayeri C N, Haff J, Greenblatt D, Loefsdahl L and Paschereit C O 2009 Drag reduction on a generic tractor-trailer using active flow control in combination with solid flaps Lecture Notes in Applied and Computational Mechanics 41 (Berlin: Springer) pp 179–91
[4] Leuschen J and Cooper K R 2009 Summary of full-scale wind tunnel tests of aerodynamic drag-reducing devices for tractor-trailers Lecture Notes in Applied and Computational Mechanics 41 (Berlin: Springer) pp 451–462
[5] van Raemdonck G M R and van Tooren M J L 2016 Numerical and wind tunnel analysis together with road test of aerodynamic add-ons for trailers Lecture Notes in Applied and Computational Mechanics 79 (Switzerland: Springer International) pp 237–52
[6] El-Alti M, Chernoray V, Kjellgren P, Hjelm L and Davidson L 2016 Computations and full-scale tests of active flow control applied on a VOLVO truck-trailer Lecture Notes in Applied and Computational Mechanics 79 (Switzerland: Springer International) pp 253–67
[7] Devesa A and Indinger T 2012 Fuel consumption reduction by geometry variations on a generic tractor-trailer configuration SAE Int. J. Commer. Veh. 5 18–28
[8] Hirz M and Stadler S 2013 A new approach for the reduction of aerodynamic drag of long-distance transportation vehicles SAE Int. J. Commer. Veh. 6 453–8
[9] Anbarci K, Acikgoz B, Aslan R A, Arslan O and Icke R O 2013 Development of an aerodynamic analysis methodology for tractor-trailer class heavy commercial vehicles SAE Int. J. Commer. Veh. 6 441–52