On the impact of size and position of semi-trailer on the aerodynamic drag of an articulated vehicle

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Abstract. The paper relates to the numerical aerodynamic simulation of an articulated vehicle. All simulations were comparative, where variables were only three geometric parameters: the height and length of the semi-trailer, and the gap between the tractor and semi-trailer. Simulation results have been investigated and compared in terms of observed values of aerodynamic drag coefficients. These coefficients have been presented in time (for example only), but above all, as constant, averaged magnitudes which are more suitable for comparisons. Total number of simulations and thereby geometrical configurations was 125, i.e. for 5 sizes of the height and length of trailer, and 5 clearance gaps between the tractor and trailer. Results have been presented graphically and discussed.

1. Introduction
In the conventional meaning, reducing the aerodynamic drag is associated with appropriate shaping of the front and rear of a vehicle, in conjunction with change of the bluff bodied shapes to streamlined ones. In case of a truck, where a cargo box is located directly behind the cab, there is only one overpressure zone covering the front face of the cab and an upper part (above the cab) of the cargo box, and only one zone of underpressure located behind the truck rear face. In case of an articulated vehicle there is an additional free clearance gap between the rear face of tractor and the front face of semi-trailer, resulting in underpressure at rear face of the tractor, and overpressure at front face of the trailer. The pressure levels cannot be determined without carrying out relevant studies [1, 2, 3, 4, 5], and in our case – without numerical simulations. In these simulations the main focus was put on determining the effect of aerodynamic interference processes taking place between tractor and semi-trailer, and on the aerodynamic drag level (as a function of the clearance gap between both units of an articulated vehicle). Moreover, the impact of characteristic trailer parameters, i.e. height and width, on the results was investigated.

In this study, only primary, rectilinear geometric forms of the tractor and trailer were considered. The models did not have any roundings or aerodynamic drag reduction devices. The study was concerned, above all, with estimating the impact on aggregated level of aerodynamic drag coefficient for an articulated vehicle, depending on two primary covariates, i.e. trailer height and length, under different conditions defined by the clearance gap between the tractor and trailer. Determining the most advantageous geometric parameters of trailer as a gap function, will allow to continue studies on developing more complex geometric forms of trailers in order to further reduce the aerodynamic drag by rounding of corners and edges, and introducing other, more complex geometric forms, to be realised in future studies.
The results presented here are focused mainly on changes in aerodynamic drag coefficients as a function of the trailer height and length, for different tractor-trailer gaps.

2. The adaptive solution method
Numerical simulations of aerodynamic processes around moving vehicles were carried out on the basis of the incompressible Navier–Stokes equations. The lack of an evolutionary term in the continuity equations made such a description of a problem less convenient, as the equation could only be taken as a divergence-free constraint for velocity. The simple solution which allows to circumvent the difficulties connected therewith and which has been used in these simulations, is an introduction to the continuity equation of a new term comprising a time derivative of pressure. This means an introduction of artificial compressibility, which causes convenient, in computational context, coupling of the continuity equation and momentum equations.

The idea of the theoretical description of air (as a fluid) behaviour presented above relates to the problem description on the continuous level. In order to solve this problem with the use of a computer, the continuous level of description should be replaced with the discrete one. The discretization process consists in replacing an infinite number of material points by a certain finite number of ‘nodal’ points, usually characteristic points of a computational mesh. Through these nodal points and related flow parameters, it is possible to describe the state of flow at any point in the domain under consideration. The (usually polynomial) approximation is also used to express the effect of differential operators from our problem description.

The discretization process applies to both, the space and time. This may take place simultaneously for both dimensions, or sequentially (alternately). For the vehicle aerodynamics, i.e. for a subsonic problem, it is natural to assume the sequential approach. The space discretization may be in general implemented through the finite differences, finite elements or finite volumes. Here, the last approach has been applied, while the time discretization is based on finite differences and the explicit integration is used. The solution in individual cells is determined from temporary equilibrium conditions for fluxes on local cell boundaries, in the basis of an solution of the Riemann problem. The calculated values of numerical fluxes are used to integrate with respect to time, and to determine the primitive variables in cells on the next time step.

The flow around any vehicle can be categorised as a laminar or turbulent, but if the flow is turbulent only in a subdomain, the entire flow is already considered as turbulent. For typical vehicle speeds, the flow at the rear of a vehicle is always turbulent – superimposed on the main flow. The turbulence is difficult to define in a universal way. It can be characterised by the irregularity, distinct and effective mixing, the dissipation, high Reynolds numbers, and the wide range of length and time scales. It is assumed that the largest eddies present in the flow are of the same order as the characteristic flow size. Besides that, there is also the whole spectrum of eddies with much smaller sizes, dissipated due to the viscosity.

Each flow around a vehicle, regardless of whether it is laminar or turbulent, is correctly described using the Navier–Stokes equations. In order to take these small scales of turbulent flow into account, an adequate spatial resolution (density) of the computational mesh should be ensured. This may, however, result in a huge number of degrees of freedom (unknowns) in solved problem, and can make a direct solution of the Navier–Stokes equations a very demanding and challenging task, even for parallel computing. As a remedy, a turbulence modelling can be used, i.e. an eddy parametrization, either all or only those with the smallest sizes. This makes sense especially when the purpose of the simulation is to determine the forms of phenomena, their effects and parameters characterizing them, such as the drag coefficient. The turbulence modelling consists essentially in modification of the Navier–Stokes equations through direct reference only to the averaged flow and simultaneous parametrization of mixing processes. Three general approaches to compute turbulent flows can be distinguished:
• the Reynolds-averaged Navier–Stokes equations (RANS), where almost all of the eddies are subject to modelling,
• the large eddy simulation (LES), where the parametrization concerns only the smallest eddies (due to mesh resolution),
• the direct numerical simulation (DNS), where no parametrization is carried out.

To explain the classification above, it should be noted that the eddy parametrization is not related to any real reconstruction of aerodynamic phenomena on a computational mesh, but rather only with the description of their effects, mainly the smallest ones.

In case of comparative studies, the purpose is to estimate the effects of modifications introduced to the original computational configuration, or just to compare similar geometric forms of vehicle body to search for the optimal solution. In such cases, it can be possible and perfectly reasonable to ignore the reconstruction of small eddy effects because they are characterised by rather large homogeneity, and this means that committed errors in the flow simulations, for geometrically similar objects, are almost equal, and thus it does not affect the correctness of comparative simulations.

The proper local resolution (density) of computational mesh is always of primary importance for correct reconstruction of aerodynamic phenomena. Generally, the smaller the specific phenomenon (e.g. an eddy) is, the finer the mesh should be. Users are not able to properly arrange the unstructured mesh, according to the temporary flow conditions. It requires a criterion to indicate a mesh subdomain, and a procedure to carry out the suitable modification of this mesh subdomain. Such an algorithm is build into the program used to realise all simulations. The software was written by the author under a grant from the European Commission: Highly efficient parallel 3D codes for industrial applications (CP-94-01239). The version of the program used for our aerodynamic simulations is marked with the identification code ll2-35.

3. Scope of simulations
The purpose of simulations was to determine the impact of geometric parameters characterising the trailer, on the aerodynamics of an articulated vehicle. The study concerned a simple shape of the tractor and trailer, without any roundings and additional geometric forms which are usually made to reduce aerodynamic drag, such as side skirts, boat tails, gap reducers, vortex generators and so on. The reason for such an assumption was to focus on two fundamental trailer parameters: the length and height. The simple shape of tractor remained identical in all simulations. The determination of the most profitable length–height relationships will be the basis for further studies in the near future, taking more sophisticated geometric trailer shapes into consideration.

Moreover, due to a significant impact of the tractor-trailer gap size on the aerodynamic drag, the simulations were carried out for different clearance gaps. This allows to show the impact of aerodynamic interference between the tractor and trailer on aerodynamic properties of the entire vehicle. Thus, our studies included 125 independent simulations carried out for 5 different trailer heights, 5 different trailer lengths, and 5 tractor-trailer gaps.

Although the direct simulation results allow to observe changes in the flow field and its parameters, i.e. the pressure and velocity components, further analyses have been mainly related to the aerodynamic drag coefficient as a consolidated gauge allowing the unambiguous and convenient evaluation of the tractor-trailer system. However, rather than using real, varying in time, values of drag coefficients, the analyses were conducted based on the averaged values characteristic for particular computational configurations. The values of these coefficients, due to the simple and austere shape of vehicle models, will be very high in relation to real vehicles, but at the same time their diversity will be greater.
Figure 1. The articulated vehicle models: (a) p36-5-120, where B=3.6 m, C=0.5 m and D=12 m, and (b) p40-9-160, where B=4.0 m, C=0.9 m and D=16 m.

All of 125 numerical simulations were performed in the two-dimensional (2D) space. Admittedly, for precise reconstruction of aerodynamic phenomena around vehicles, it would be appropriate to use the 3D simulations, but for comparative studies of vehicles with similar outlines, the 2D simulations are sufficient. It is even more justified when aggregate properties (e.g. the drag coefficient) are compared. 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, and far shorter times of simulations.

Numerical simulations use the opposite flow conditions, i.e. with the stationary vehicle and the moving road and air. It is an analogy with the situation encountered in wind-tunnels, however without any physical restriction for the flow. The introduced limitations for computational flow domains had no effect on the results, and assumed forms of boundary conditions did not reconstruct those from wind-tunnels.

4. Vehicle models, flow conditions and meshes
In accordance with the purpose of this work and reasons already given, the objects of aerodynamic simulation were two-dimensional models of articulated vehicles with simplified bodywork forms achieved by straightening out the bodywork lines and omission of local curvatures. Two extreme (with the smallest and largest trailer and clearance gap) examples of these vehicle models are presented in the figure 1. The trailer height, trailer length and clearance gap are denoted by the capital letters B, D and C, respectively. Each of these quantities includes 5 specific values:

- the height B: 3.6, 3.7, 3.8, 3.9 and 4.0 metres,
- the gap C: 0.5, 0.6, 0.7, 0.8 and 0.9 metres, and
- the length D: 12, 13, 14, 15 i 16 metres.

All created vehicle models were placed in duly geometrically defined outer outline of assumed flow domain. The height of computational domains was always equal to 24 metres and the length
Figure 2. The sample initial meshes for the models: (a) p36-5-120 and (b) p40-9-160 (the coordinates are scaled in metres).

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 concerned models. The sample initial meshes, created for the smallest and largest values of the geometric parameters B, C and D, are presented in figure 2.

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

- on the vehicle outline: the motionless solid boundary,
- on the left- and right-side of the pseudo-tunnel: inflow and outflow boundaries, respectively,
- at the top of flow domains: the symmetric boundary conditions, and
- at the bottom of wind-tunnel: the moving (with inflow speed) solid boundary.

The vehicle speed, or the air inlet velocity, was always equal to 20 m/s. The physical parameters, like the air density and kinematic viscosity, were equal in each computational case. The control parameters for each of computational and adaptive processes were identical. The simulation time was always equal to 15 s.

The names of particular computational configurations has been defined in accordance with the following scheme:

\[ \text{AB-C-D} \]

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

A – the letter ‘p’, as the distinctive sign for carried out simulations,
B – the trailer height (in decimetres),
Figure 3. The sample final meshes for the models: (a) p36-5-120 and (b) p40-9-160, in 15th second of simulation.

C – the clearance gap (in decimetres),
D – the trailer length (in decimetres).

5. Aerodynamic drag coefficients
As previously mentioned, the presentation of simulation results is limited only to aerodynamic drag coefficients, because issues related to forming the flow field described among others through distributions of pressure and velocity components, are not subject to these considerations. However, to illustrate the outcome of adaptation processes, the figure 3 presents sample final forms of computational meshes, which had the forms as in figure 2 at the beginning of computations.

In general, for unsteady problems such as the vehicle aerodynamics, the magnitude of drag coefficient is variable in time. For the sample forms of computational configurations: p36-5-120 and p40-9-160 (in the figures 2 and 3), the temporal variation of drag coefficients is presented in the figure 4. Such form of aerodynamic drag coefficients is, however, unsuitable for comparisons. Therefore for further considerations on obtained results, the constant, consolidated values of these coefficients were defined for each computational configuration. The constant drag coefficients have been determined based on the results from second half of time steps because the initial results (from the first seconds) were disturbed by the inadequate form of initial conditions. Thus the determined (constant) values of drag coefficients are reliable.

In order to illustrate the formation of aerodynamic drag coefficients depending on varying parameters characterised by the tractor-trailer gap, the trailer height and the trailer length, for each clearance gap following have been determined:

- the dependence of the drag coefficient on the trailer length, in figure 5, and
- the dependence of the drag coefficient on the trailer height, in figure 6.
Figure 4. The drag coefficients as a function of time, for the models p36-5-120 and p40-9-160.

Moreover, for each tractor-trailer gap all drag coefficients have been averaged, and percentage differences in relation to these average values have been determined. These percentage differences have been shown in the figure 7, where the coordinates are the trailer length (D) and the trailer height (B). The last three figures have given rise to conclusions.

6. Conclusions
Based on the analysis of the aerodynamic drag coefficient levels presented in the figures 5, 6 and 7, the following can be concluded.

1. There is a general correlation between the drag coefficient magnitude and the trailer length: the longer trailer, the higher drag coefficient.
2. There is no clear correlation between the drag coefficient and the trailer height. Nevertheless, for smaller trailer heights, the scatter in the drag coefficients is larger.
3. Because of the aerodynamic interference between the tractor and the trailer, some combinations of the trailer height and length can cause particular (beneficial or negative) consequences for the drag coefficient magnitude. For such cases it is recommended to carry out the 3D simulations, which can describe the aerodynamic interference and determine the aerodynamic drag coefficient in more reliable way.

References
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Figure 5. The averaged drag coefficients in a function of the trailer length, for different tractor-trailer gaps: (a) $C=0.5\, m$, (b) $C=0.6\, m$, (c) $C=0.7\, m$, (d) $C=0.8\, m$ and (e) $C=0.9\, m$. 
Figure 6. The averaged drag coefficients in a function of the trailer height, for different tractor-trailer gaps: (a) C=0.5 m, (b) C=0.6 m, (c) C=0.7 m, (d) C=0.8 m and (e) C=0.9 m.
Figure 7. Percentage differences of particular drag coefficients in relation to their mean value, for the gaps: (a) $C=0.5$ m, (b) $C=0.6$ m, (c) $C=0.7$ m, (d) $C=0.8$ m and (e) $C=0.9$ m.