DOI: 10.24352/UB.OVGU-2019-006 TECHNISCHE MECHANIK, 31, 1, (2019), 51-63
submitted: January 6, 2019

Prediction of Aerodynamic Coefficients of Road Vehicles on Bridge Deck with and without Wind Protection by Means of CFD for Crosswind Stability Investigations

V. Krämer, B. Pritz, E. Tempfli, M. Gabi

While planning a new bridge construction the risk of traffic accidents due to critical wind conditions should be carefully considered. The determination of aerodynamic forces and moments on vehicles is indispensable for stability investigations. However, the aerodynamic coefficients of vehicle-bridge systems depend on many factors which make it difficult to generalise the procedure. This paper is focusing on analysing a particular bridge geometry whereby aerodynamic coefficients were predicted by means of CFD. The accuracy of the numerical model was validated with the aid of experimental data from wind tunnel tests. Specifically, this work was conducted to investigate the effect of the wind barrier considering various wind flow angles and vehicle speeds. Mean forces and moments on the vehicle were analysed depending on both absolute and relative wind flows. The impact of performing relative motion between vehicle and bridge deck was investigated. Simulation results without wind barrier are qualitatively in good agreement with results found in literature. Nevertheless, the flow situation with wind barrier and relative motion is significantly more complex. Thus, CFD modelling has dominating advantages over wind tunnel tests in terms of both parameter variation and model accuracy. In this particular case CFD modelling is indeed essential in order to represent all possible wind flow angles and the relative motion between the vehicle and the bridge deck which remains difficult or rather hardly possible to perform in the wind tunnel.

1 Introduction

When starting to plan a new bridge construction the study and the analysis of the effects of crosswinds on road vehicles are indispensables in order to reduce the risk of wind-induced accidents. For stability analysis, force and moment coefficients are required as input parameters as shown by Baker at al. (2009) and Proppe et al. (2010). Such stability investigations serve to determine the probability of road accidents due to overturning, sideslip or rotation of the vehicle under various conditions. Thereby, the final goal is to identify the maximum safe vehicle speed on the bridge deck for a specific wind situation and for a certain vehicle type. As a result, the traffic on the bridge could be easily regulated if necessary.

Also for the newly planned bridge construction on the Kiel Canal in the north of Germany this procedure is essential. Especially lightweight high-sided vehicles and vehicles with a trailer represent critical cases being situated on a bridge in such a wind prone region. Consequently, this is an important safety and economic issue, as such accidents can cause life-threatening situations as well as traffic and infrastructure disruptions. In the past, many experimental as well as numerical studies have already been conducted concerning similar problems with vehicles in crosswinds in order to identify the aerodynamic characteristics.

Baker et al. (1991, 1996) carried out the mean aerodynamic force and moment coefficients of several ground vehicles in high crosswinds. According to Baker (1991), to all six aerodynamic forces and moments should be paid attention when considering a vehicle. The influence of the relative motion between the bridge deck and the vehicle needs to be assessed as well. Baker and Humphreys (1996) came to the conclusion that the relative motion must have a strong effect on some of the aerodynamic coefficients. Wang et al. (2013) showed, however, that this has only small influence on the aerodynamic results considering bridge geometry without wind barrier. In fact, the difference between simulations with and without relative motion in the case with an existing impermeable wind barrier was not tested in his study. Furthermore, Zhu et al. (2012) demonstrated that there is a significant difference between the aerodynamic characteristics of a vehicle over a bridge deck compared to a vehicle on a ground. In particular, different vehicle types, different wind directions as well as several vehicle positions were investigated in wind tunnel tests and partly strong variations in results were found. Dorigatti et al. (2012) proved the high impact of the bridge deck geometry on the aerodynamics. Some more various essential factors are mentioned and investigated by Malviya and Mishra (2014), such as acceleration and braking conditions, inclined ground planes, road surface curvature, centrifugal cornering effects and surrounding environment. Bettle et al. (2003) conducted numerical simulations which showed that vehicle speed and vehicle position (windward lane vs. leeward lane) have especially a large impact on the side force and roll moment coefficients. In addition, Coleman et al. (1992) showed that at least the variation of the side force and lift force coefficients with yaw angle is quite different with wind barriers than without. Thereby, it was confirmed that on the one hand the solidity and on the other hand the height of the wind barrier are decisive factors for the reduction of forces and moments on the vehicle. This fact was also ascertained by Guo et al. (2015). By conducting wind tunnel tests, Chen et al. (2015) demonstrated that wind barriers generally have a positive impact on the vehicle stability. Still the investigated wind barriers were permeable and had a low height ratio relative to the vehicle.

Regarding all the mentioned studies it can be concluded that the results actually cannot be compared with each other. There are too many aspects having a significant impact on the results, for instance bridge geometry, wind barrier type, vehicle types, vehicle position and speed, vehicle manoeuvring, reference dimensions etc. Consequently, determination of the force and moment coefficients should definitely be conducted for every specific bridge construction. Nevertheless, there is a number of assumptions that have to be studied in order to standardise the analysis.

Concerning the mentioned investigations CFD offers a number of advantages over the wind tunnel tests. The major advantage is the possibility to simulate a moving vehicle-bridge deck system which is rather difficult to perform in a wind tunnel. Furthermore, the determination of forces and moments is more precise given the fact that they are calculated over the complete surface of the vehicle. Even though this can also be achieved by conducting experiments with a special balance, this procedure is quite expensive and has to be extremely accurate. Consequently, in wind tunnel tests forces and moments usually are carried out by measuring pressure in several local positions on the vehicle surface which results in a very coarse integration. Further, the Reynolds number for a situation with real bridge dimensions differs significantly from a scaled model usually used for wind tunnel tests. Therefore, the accuracy of wind tunnel investigations can be doubted. Sterling et al. (2009) carried out full-scale experiments on a high-sided lorry and compared the results with wind tunnel tests and CFD simulations. Thereby, especially for the rolling moment coefficient, the full-scale measurements and CFD values were in very good agreement, whereas wind tunnel tests provided discrepant results. Nevertheless, a wider range of yaw angles can be considered by performing numerical simulations. Indeed, because of the finite model length the influence of the cut-off ends of the bridge model increases when positioned parallel to the wind tunnel.
Concerning numerical calculation, Krajnovic et al. (2012) proved that despite fine computational grid and unrealistically small wind velocities, RANS models show better results compared to LES simulation because of the wall treatment. Finally, Alonzo-Estébanez et al. (2017) showed that steady state approach instead of unsteady analysis guarantee sufficiently accurate results without require high computational effort.

The present study deals with determination of mean force and moment coefficients for a specific bridge deck geometry. Further, the general effect of wind barriers and the importance of the relative motion of the vehicle-bridge system were investigated. The established numerical model was successfully validated. The main focus of the study lies on the illustration of advantages and partly even indispensability of CFD regarding studies on this issue.

2 Model Geometry

The simplified horizontal bridge deck geometry, the wind barrier as well as the vehicle position are depicted in Figure 1. In the current study, this vehicle position on the outside road lane on the windward side of the bridge deck (hard shoulder being quite large in this case) was chosen for a better comparison with literature results as this was the most frequently investigated position. The cross section of the bridge was analysed first as a two-dimensional geometry (see Figure 2).

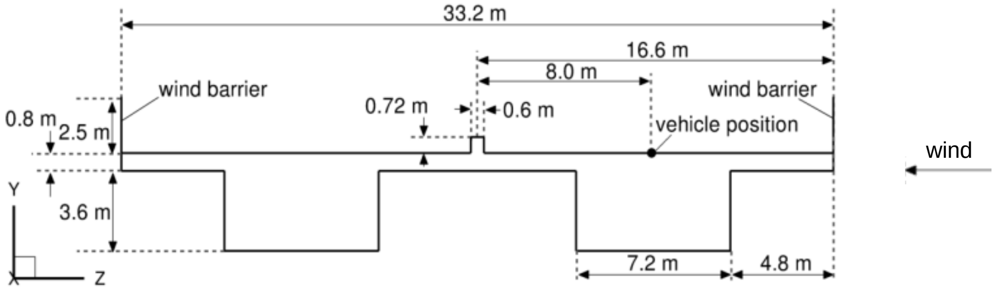

Figure 1. Cross section of the modelled bridge deck, vehicle position and overall dimensions

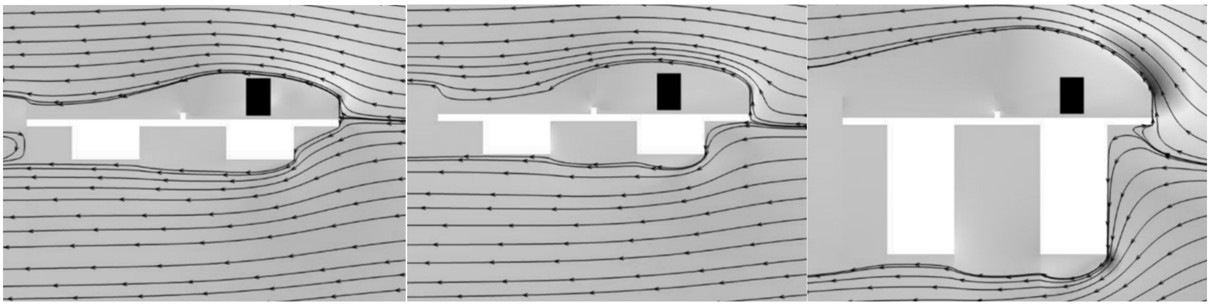

Figure 2. Effect of the bridge deck and wind barrier heights (left: 4 *m* high bridge deck and 2 *m* high wind barrier; middle: 4.4 *m* high bridge deck and 2.5 *m* high wind barrier; right: 15 *m* high bridge deck and 2.5 *m* high wind barrier). The truck geometry of 4 *m* height is not included in the simulation; it is depicted only for comparison purpose. The wind velocity is thereby 20 m/s.

Thereby, as shown in Figure 2, it was confirmed that the lower the bridge geometry or the wind barrier the more critical in the stability situation of the vehicle. In the present study a commonly used wind barrier of 2.5 *m* height was investigated which offers enough protection also for higher truck geometries (Figure 2, middle) and which has already been in a parametric study for a similar vehicle-bridge system (Ingenieurgesellschaft Niemann & Partner GbR, 2007). For the entire analysis three different vehicle types were examined: van, truck with a trailer and passenger car with a trailer. However, in this paper only the van geometry is exemplarily discussed, which is shown in Figure 3. The real geometry was approximated with rectangular block shape in order to cover all of the critical vehicle shapes (e.g. vehicles with nearly sharp edges).
In the further part of the present paper the results of the study of the three-dimensional configuration of the van at the position shown in Figure 1 will be presented.

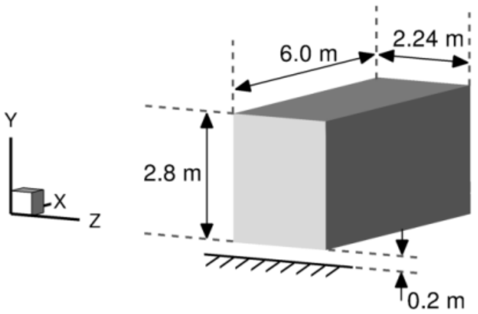

Figure 3. Van model

3 Flow Conditions

The vehicle is moving on bridge deck with the constant speed u whereas the wind is blowing at an absolute angle α with velocity c. Consequently, the relative wind velocity w at the angle β, which is acting on the vehicle, results from the velocity triangle shown in Figure 4.

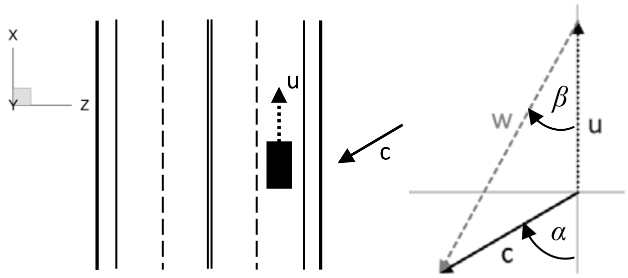

Figure 4. Velocity triangle

The cases computed in the present investigation are listed in Table 1. A key aspect was to achieve a wide range of relative angles *β* (see cases 1 to 9). As confirmed later in Section 7, the force and moment coefficients are described more universally in function of this angle rather than of the absolute angle *α*. Thereby, the evaluated relative angles remain between 0° and 90° as driving against the wind are the most critical configurations for the stability investigations. Especially in cases with a wind barrier, the relative wind angles of attack between 0° and 60° generally show higher values of aerodynamic coefficients (see Figure 12). In cases 3.1 to 3.3 and 4.1 to 4.3 (see Table 1) the variation of the absolute angle *α* was examined while the relative angle *β* remained constant. The variation of the relative angle *β* with the absolute angle *α* being constant could be analysed as well when considering cases 2, 3.2, 4.2, cases 3.1, 4.1, 5, 6 and cases 3.3, 4.3, 7, 8, 9, respectively (see Table 1). Cases marked with an asterisk represent calculations without relative motion between the vehicle and the bridge deck (*u* = 0 *m/s*). This corresponds to an usual wind tunnel test when the vehicle is fixed on the bridge deck. For these calculations either an absolute (**, vehicle speed completely neglected) or relative (*, hypothetical vehicle speed according to velocity triangle from Figure 4) angle of attack was defined.

Table 1. Investigated configuration cases: *α*, *β* in [°] and *c*, *u*, *w* in [*m/s*]

	absolute system			**relative system**	
case	***α***	***c***	***u***	***β***	***w***
1	30	20	130	**11**	54
2	60	20	130	**21**	49
3.1	90	20	130	**29**	41
3.2	60	34	130	**29**	61
3.3	120	18	130	**29**	31
4.1	90	14	60	**40**	22
4.2	60	31	60	**40**	42
4.3	120	11	60	**40**	15
5	90	23	80	**45**	32
6	90	30	60	**61**	34
7	120	21	60	**70**	19
8	120	26	60	**81**	23
9	120	20	60	**94**	10
3.1*	-	-	0	29	41
3.1**	90	20	0	-	-
3.2*	-	-	0	29	61
5*	-	-	0	45	32
6*	-	-	0	61	34

4 Aerodynamic Coefficients

For the safety analysis the mean forces and moments in each coordinate direction must be determined over all surfaces of the vehicle. Figure 5 illustrates all forces and moments on the vehicle model as well as the wind and vehicle movement directions. Thereby, F_D, F_L and F_S are the drag force, the lift force and the side force, respectively, and M_R, M_Y and M_P are the rolling moment, the yawing moment and the pitching moment, respectively.

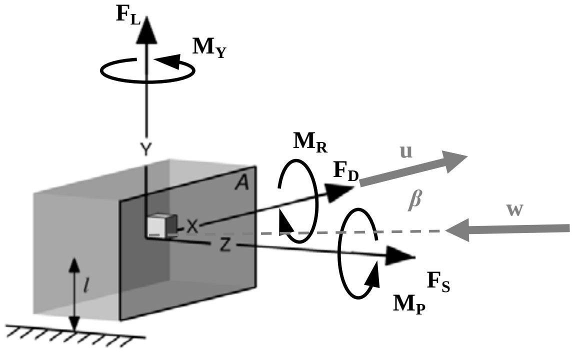

Figure 5. Aerodynamic forces and moments on a vehicle

All six aerodynamic forces and moments refer to the geometric centre point of the vehicle. With air density ρ_{air}, relative velocity of the wind *w*, reference area *A*, reference length *l* and the calculated forces and moments the six non-dimensional aerodynamic force and moment coefficients are defined as:

$$c_i = \frac{F_i}{\frac{\rho}{2} w^2 A} \tag{1}$$

$$c_{M_i} = \frac{M_i}{\frac{\rho}{2} w^2 A l} \tag{2}$$

Concerning the reference area *A* as well as the reference length *l* there are widely varying specifications given in the literature (front surface of the vehicle or some arbitrary reference area, vehicle length, vehicle height or some arbitrary length, respectively). For all of the calculations in the present study the side surface of the vehicle was chosen as reference area *A* (see Figure 5). Given the fact that the wind direction varies considerably (see β in Table 1), the side surface is the largest possible windward surface of the vehicle. Particularly with regard to the side load being the most critical one. As reference length *l* the distance between the geometrical centre of the vehicle and the bridge deck was considered (see Figure 5).

5 Numerical Model

Steady-state numerical simulations have been performed using the commercial software ANSYS CFX© which is based on finite volume method. The block-structured numerical grid was generated using ANSYS ICEM-CFD©. The calculations were carried out with air under normal conditions at ambient temperature of 25 *°C* and pressure of 1 bar. Consequently, the density of the air ρ_{air} was equal to 1,185 kg/m^3 for the present study.

The computational domain consists of three independently meshed subdomains as shown in Figure 6: the first domain in close proximity to the vehicle, the second domain around the bridge and the third domain representing the farfield. The subdomains are connected by interfaces.
As mentioned in Section 1, the cut-off ends of the bridge geometry can have a significant impact on the flow dynamics on the bridge deck and on the aerodynamic coefficients on vehicle surface when $\beta \neq 90°$. In contrast to wind tunnel tests, CFD allows to avoid this problem by using periodic boundary conditions in driving direction. The computational domain is thus virtually ordered periodically along the x-axis in order to design a quasi-infinitely long bridge with vehicles at a fixed distance to each other on it. The vehicle is situated in the first area in the middle of the entire domain along the x-axis. The length of one periodic section of 325 *m* was carefully examined. Thus, it could be guaranteed that the flow fields of two running vehicles do not significantly influence each other, even for small values of β. The height and the length of the computational domain were both set in such a way that the boundary conditions (BCs) do not affect the flow field around the bridge deck.

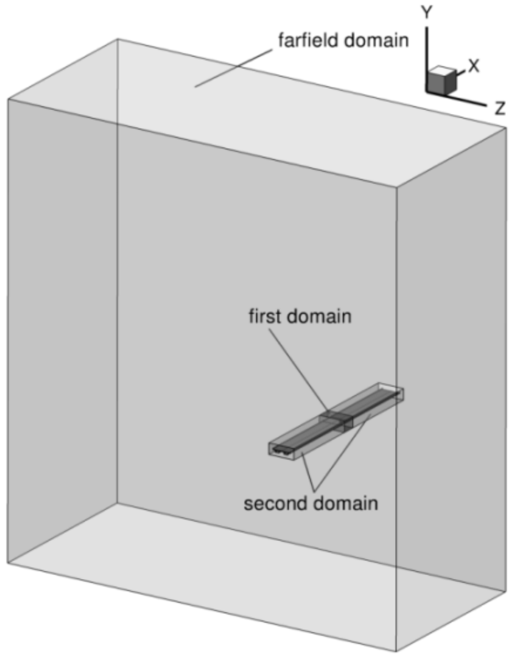

Figure 6. Computational domains

In order to prove that the accuracy of the solution is not dependent on the grid resolution, four different grid sizes were tested for the case 3.1: with 600 000, 3 million, 20 million and 34 million cells. Figure 7 presents all six force and moment coefficients as a function of the grid size. As it can be seen, there is still a significant difference between the results of the 3 million and the 20 million cells meshes. On the other hand, the slight deviation between the results of the 20 million and the 34 million cells meshes is negligibly small. Thus, to guarantee both accurate results and reasonable computing time the final mesh comprised approximately 20 million cells.

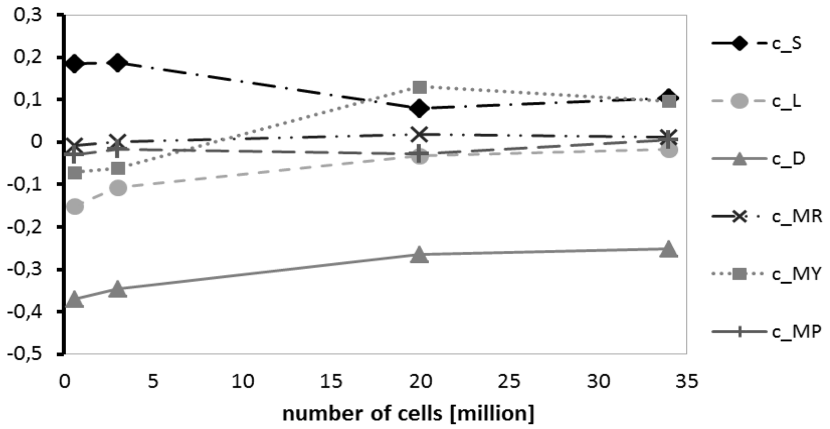

Figure 7. Grid dependence, case 3.1

The reference frame for CFD calculations was attached to the vehicle. Thus, the vehicle surface was defined as no-slip wall. Whereas a moving wall BC was chosen for the bridge deck, considering the motion between the bridge deck and the vehicle. The overview of boundary conditions for the current study is presented in Figure 8.

The relative wind velocity *w* under the angle β was specified at the inlet with a turbulence intensity of 5*%*. It should be noted that the atmospheric boundary layer was neglected in the current study as the bridge deck is placed approximately 40 *m* above the ground. Thus, a homogeneous inflow was realised. At the outlet static pressure was defined. The top and the bottom faces of the domain were set as a free slip wall. As mentioned previously, for the faces at the ends of the bridge section periodic BCs were chosen.

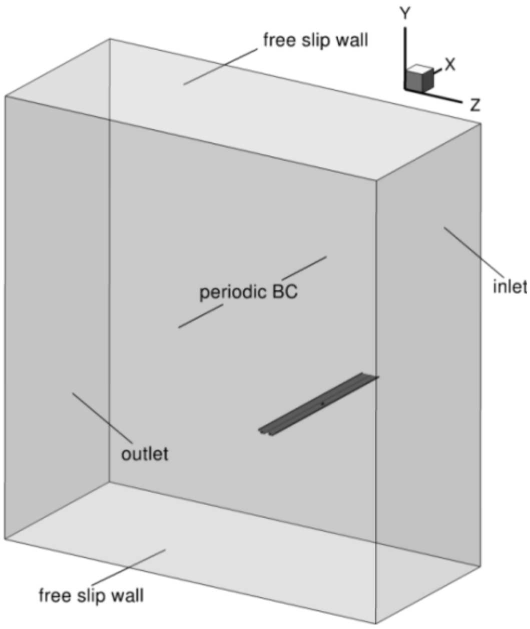

Figure 8. Boundary conditions

All calculations were based on RANS equations and were carried out using the eddy viscosity transport equation turbulence model according to Menter (ANSYS CFX-Solver Theory Guide, 2011). Thereby, scalable wall functions were used in order to make the solution in the near-wall regions independent of the refinement of the grid. The size of the first cell near the wall was kept at $y^+ < 50$ for regions around the vehicle and the road surface. In the present study, the high resolution scheme (a second order upwind scheme) implemented in ANSYS CFX© was used for the advection terms and the turbulence (ANSYS CFX-Solver Theory Guide, 2011).

6 Validation

For the validation of the designed numerical model against experimental results, wind tunnel tests were performed at the Institute of Fluid Machinery at KIT. The tests were carried out in a closed return wind tunnel which can produce air speeds up to 60 *m/s*. The diameter of the outlet nozzle is 1.8 *m* and thus limited the scaling of the examined model. Therefore, the geometric scale for the wind tunnel vehicle-bridge model was set 1:40. The average air speed was set to 20 *m/s*. Local pressure measurements were carried out in the measuring positions defined in Figure 9.

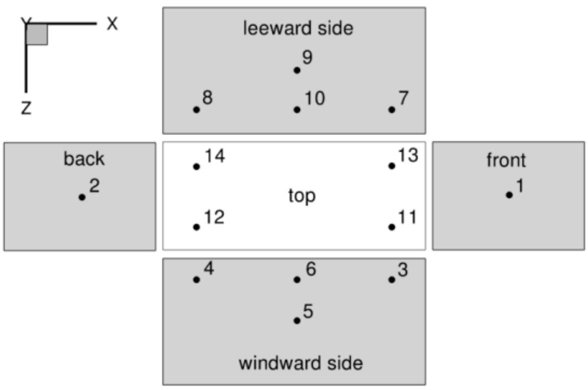

Figure 9. Wind tunnel test measuring positions on surface of the van model (the coordinate axes are valid for the top side)

As already discussed, the possibilities to vary the model settings in wind tunnel tests are rather limited. Consequently, to compare numerical with experimental results, an equally scaled vehicle-bridge system without

relative motion and with the yaw angle of 90° had to be simulated. Finally, pressure values on vehicle surface were extracted from simulation results for the same positions as shown in Figure 9.
In order to analyse the results the non-dimensional pressure coefficient using the density of air ρ_{air}, the freestream velocity U_∞ and the static freestream pressure p_∞ was determined as follows:

$$c_p = \frac{p - p_\infty}{\frac{1}{2}\rho_{air} {U_\infty}^2} \tag{3}$$

Figure 10 shows both pressure coefficients from the wind tunnel tests and CFD in each of the measuring positions. The results are presented in each case with and without wind barrier.

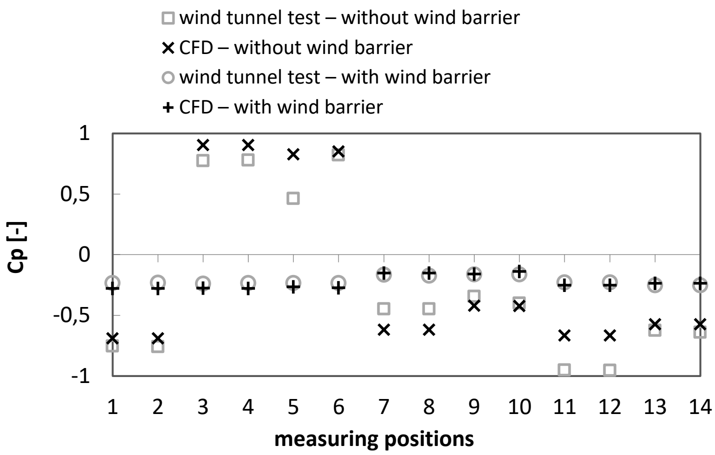

Figure 10. Comparison between results obtained from CFD and from wind tunnel tests

It can be seen that in the absence of the wind barrier the pressure coefficient values are considerably higher than in the case with wind barrier. This proves that a wind protection of 2.5 *m* height generally leads to an improvement in stability situation of the vehicle. Generally, wind tunnel and CFD results are in very good agreement for the case with wind barrier. However, also without wind barrier there are only few measuring positions with larger deviations between numerical and experimental pressure coefficient values (see positions 5, 11 and 12 in Figure 10). This is due to the high flow gradients because of the flow separation on sharp edges as there is no wind protection. Measuring positions 11 and 12 are situated near the separation edge on the windward side and thus are directly in the separation zone. Position 5 is strongly influenced by the separation on the bridge edge. Consequently, already small deviations between simulation and experiment referring to the size of the separation bubbles can cause major discrepancies in results.

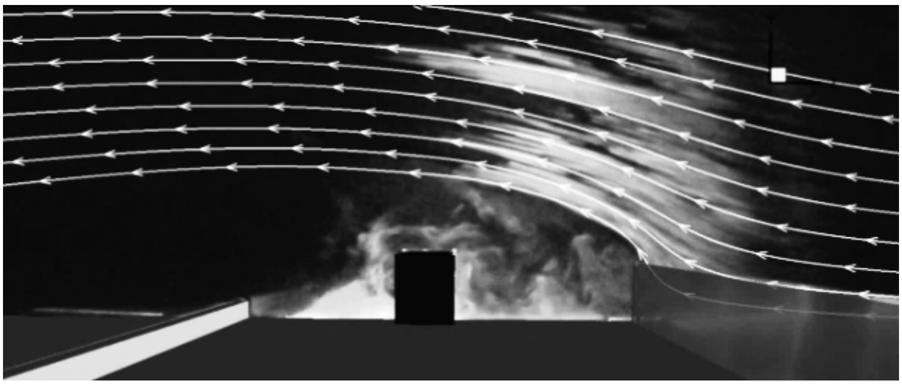

Figure 11. Comparison between results obtained from CFD and from wind tunnel tests

Further, also the overall flow fields from numerical and experimental results are in good agreement. According to Figure 11, streamlines visualized in the wind tunnel are quite similar to computed streamlines. The flow separation on wind barrier is in very good agreement.

7 Results

The results of the study are summarised in Figures 12 to 14. In Figure 12, calculations considering the relative motion between vehicle and bridge deck with wind barrier as well as without wind barrier are presented. The force and moment coefficients are plotted over both the relative wind angle β and the absolute wind angle α. Figures 13 to 14 outline the comparison between vehicle-bridge systems with and without relative motion. However, the causes for the particular distribution of the coefficients are not the focus of the present paper.

Figure 12 illustrates the six force and moment coefficients in function of relative wind angle β (left column) and absolute wind angle α (right column). For the same angle α there is almost always a large variation of results depending on vehicle velocity as well as on wind speed. In particular, in the case without wind barrier the scattering of results is stronger than in the case with wind barrier. This is due to the fact that wind barrier significantly influences the flow field on the bridge deck und thus more or less equalizes it for different configurations. Conversely, the dependence on the relative angle β presents a clear curve shape despite various vehicle velocities and wind speeds (see $\beta = 29°$ and $\beta = 40°$ with wind barrier). It could be ascertained that the aerodynamic coefficients show a meaningful dependency on the relative angle β obtained from the velocity triangle (Figure 4).

As can clearly be seen and was already detected in validation results (Figure 10), the force coefficients as well as moment coefficients are significantly higher in the case without wind barrier (cf. Figure 12 (a) and (c), (e) and (g)). The side force is the highest one if there is no wind protection. Due to the presence of the wind barrier its magnitude not only decreases up to approximately 75%, but also changes its direction. Thus, the vehicle is rather pushed towards the wind barrier. The lift force coefficient has very small values compared to the two other ones. The values of the drag force coefficient do not change much by adding wind protection, as expected. Concerning the moments, the most critical one for the stability analysis is usually the roll moment. As it can be observed in Figure 12 (e) and (g), with the presence of the wind barrier this coefficient could be reduced considerably.

The cases marked with * and ** in Table 1 omit relative motion between the bridge deck and the vehicle which correspond the most common configurations in wind tunnel tests. In the wind tunnel test either the relative angle β (*) or the absolute angle α (**) can be realised between flow direction and the bridge model. From Figure 13 it can be seen that in the case without wind barrier the relative motion between the vehicle and the bridge deck has a negligible effect on the results when relative wind flow is set at the inlet (case 3.1*). However, when the vehicle speed is neglected and the absolute angle is defined at the inlet (case 3.1**), significant deviations can be detected.

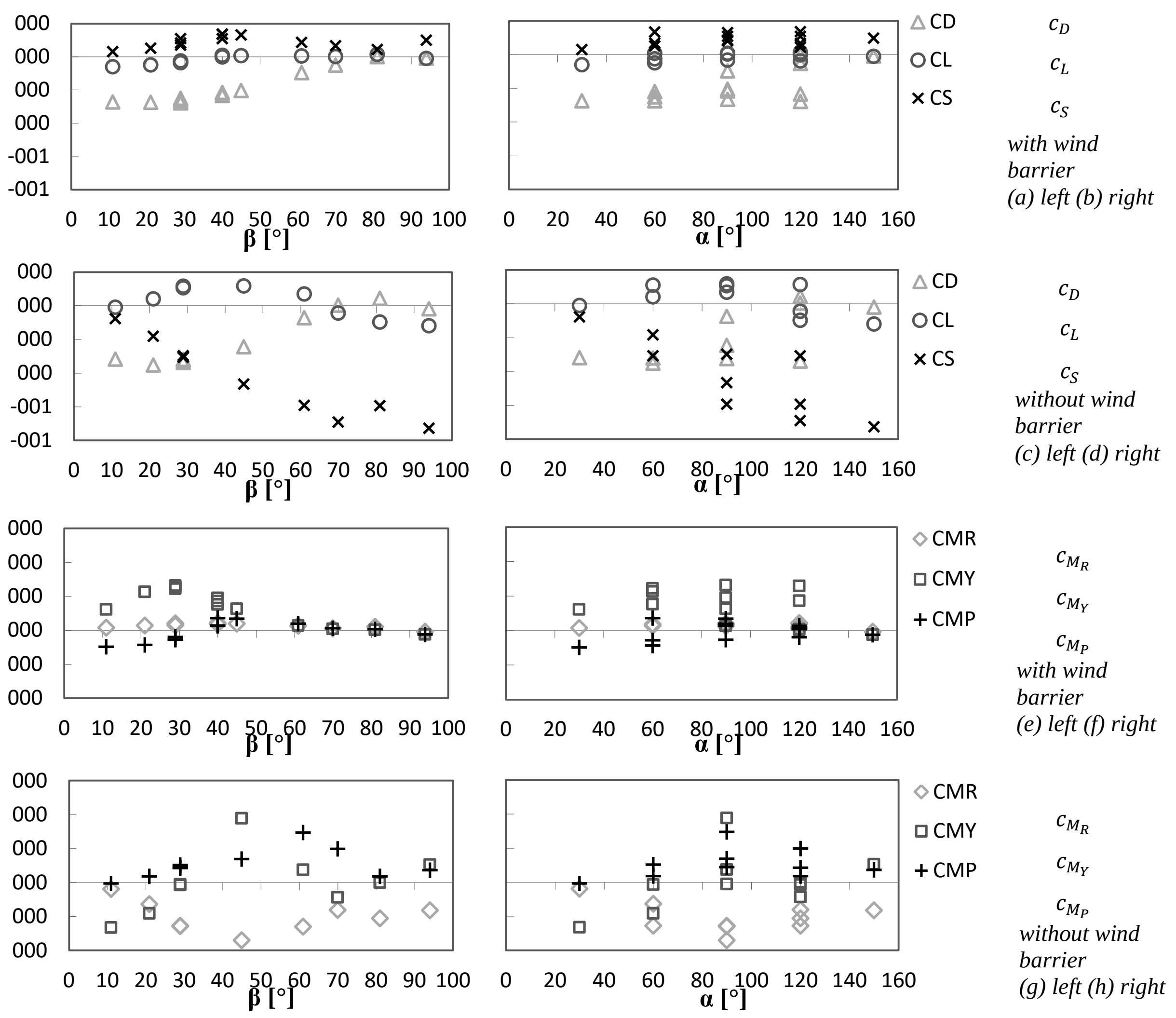

Figure 12. Computed force and moment coefficients on the vehicle on a bridge deck with and without wind barrier; plotted over the relative angle β (left) and the absolute angle α (right)

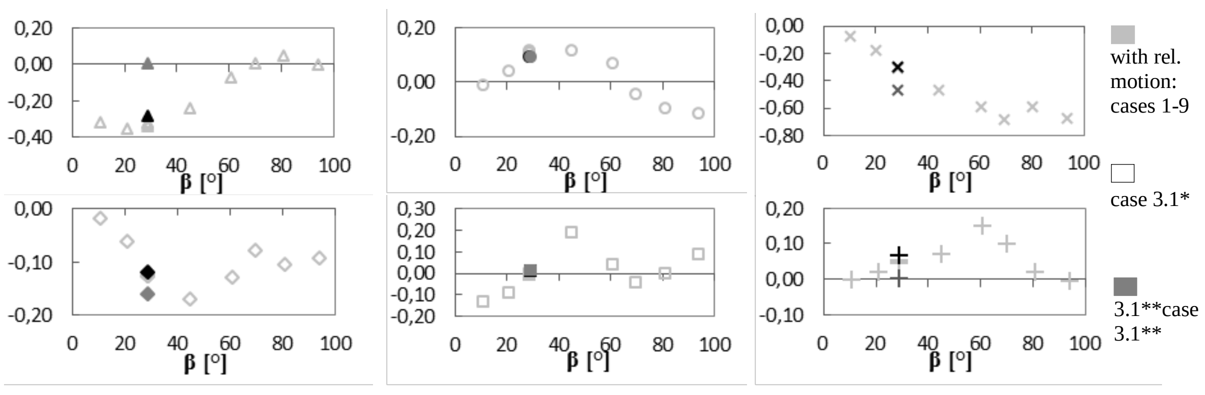

Figure 13. Results with and without relative motion (without wind barrier)

On the contrary, according to Figure 14 the relative motion has a stronger impact on the results when wind barrier is present. Case 3.1** shows large discrepancies here as well. Additionally the deviations for all cases with asterisks are significant. In particular, the distributions of the side force as well as for the roll moment coefficients are substantially different (c_S and c_{M_R} in Figure 14). These two coefficients are particularly important for the stability analysis.

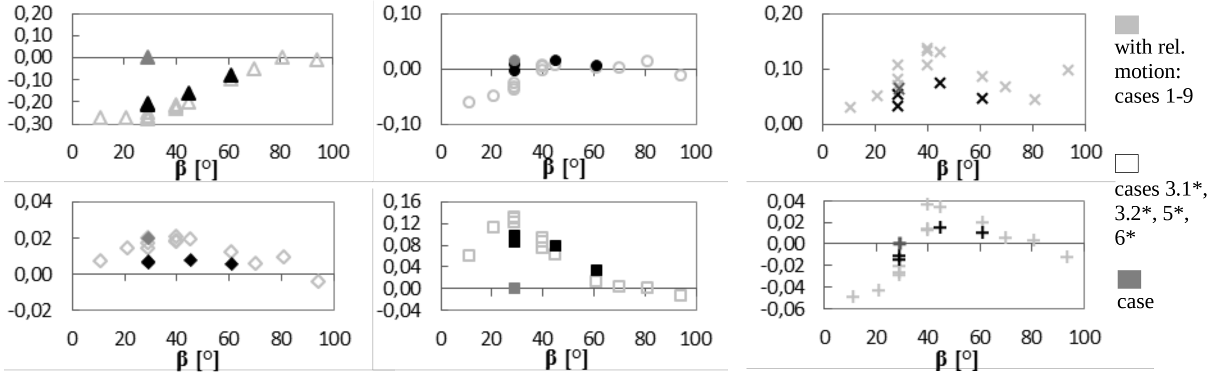

Figure 14. Results with and without relative motion (with wind barrier)

To sum up, if a wind barrier exists and accurate results are required, the relative motion is indispensable.

8 Conclusions and Outlook

Six aerodynamic coefficients under different wind conditions were determined for a van model on a bridge deck with and without wind barrier by means of CFD. The numerical model was first validated through wind tunnel tests. Furthermore, the effect of wind barrier was evaluated and the impact of relative motion between the vehicle and the bridge deck was investigated. Finally, following conclusions could be obtained:

(1) Force and moment coefficients show clearly defined characteristic curves if plotted over the relative angle of attack β which represents the relative wind flow acting on the vehicle.
(2) Wind barrier of 2.5 m height significantly reduces force as well as moment coefficients on the vehicle surface.
(3) Modelling the relative motion of the vehicle-bridge system has only slight influence on aerodynamic coefficients of the vehicle on a bridge deck without wind barrier but it has a noticeable impact in the case of an existing wind protection.

To conclude, it can definitely be said that CFD has clear advantages over wind tunnel tests and is essential for accuracy of such investigations because:

- Relative motion is not that obvious to reproduce experimentally;
- Wide range of yaw angles is not practicable in wind tunnels without influencing the flow field by the finite length of the bridge model;
- Scaling is not necessary and real dimension Reynolds numbers can be realised;
- Variations of the vehicle-bridge system can be evaluated more easily and faster;
- Generally larger data sets are obtained, and namely in every point on the vehicle surface.

Eventually, the main goal of the current and the future researches is to generalise the methodology of predicting the aerodynamic coefficients for the stability investigations. Whereas at the same time, it is demonstrated that the generalisation of the results themselves is not possible because of a huge number of various conditions and the complexity of the flow field around the vehicle when wind barrier and relative motion being modelled. Figure 15 exemplarily illustrates the flow for the case 3.1 from Table 1 by means of streamlines. The outer flow (strong lines) generates a recirculation vortex between the wind barriers, which is strongly disturbed by the van and is split in two vortices.

Consequently, for instance the general effects of wind barrier and vehicle velocity on the flow on the bridge deck as well as a parametric study of the interaction between wind direction and vehicle velocity could be subjects for analysis in future studies. Moreover, the vehicle position on the other outer side of the bridge deck is currently analysed in order to cover all wind direction that can occur on a bridge deck. This also serves to investigate the impact of the wind barrier on the leeward side of the bridge deck on aerodynamic coefficients in the case with a wind barrier higher than the vehicle. The implementation process of aerodynamic coefficients for the actual stability analysis will be published separately.

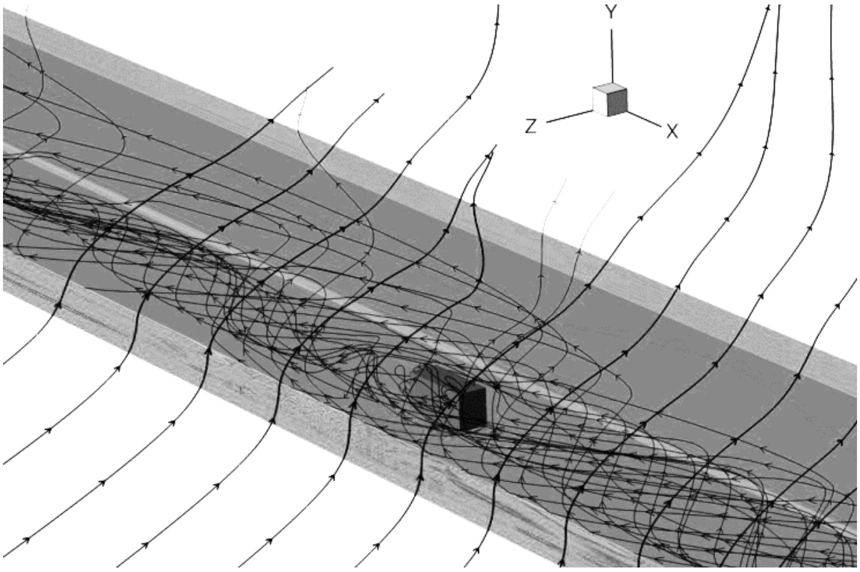

Figure 15. Complex flow around the vehicle caused by the wind barrier and the relative motion between vehicle and the bridge deck exemplarily visualised for wind angle of attack of 90° (case 3.1 in Table 1)

Acknowledgements

The writers are grateful to have the possibility of working on the Kiel Canal bridge project with DEGES Deutsche Einheit Fernstraßenplanungs- und –bau GmbH.

References

Alonso-Estébanaz, A.; Del Coz Díaz, J. J.; Álvarez Rabanal, F. P.; Pascual-Muñoz, P.: Numerical simulation of bus aerodynamics on several classes of bridge decks. *Engineering Applications of Computational Fluid Mechanics*, 11(1), (2017), 435-449.

ANSYS CFX-Solver Theory Guide, (2011).

Baker, C. J.: Ground vehicles in high cross winds. Part I: Steady aerodynamic forces. *Journal of Fluids and Structures*, 5, (1991), 69-90.

Baker, C. J.; Cheli, F.; Orellano, A.; Paradot, N.; Proppe, C.; Rocchi, D.: Cross wind effects on road and rail vehicles. *Vehicle System Dynamics*, 47(8), (2009), 983-1022.

Baker, C. J.; Humphreys, N. D.: Assessment of the adequacy of various wind tunnel techniques to obtain aerodynamic data for ground vehicles in cross winds. *Journal of Wind Engineering and Industrial Aerodynamics*, 60, (1996), 49-68.

Bettle, J.; Holloway, A. G. L.; Venart, J. E. S.: A computational study of the aerodynamic forces acting on a tractor-trailer vehicle on a bridge in cross-wind", *Journal of Wind Engineering and Industrial Aerodynamics*, 91, (2003), 573-592.

Chen, N.; Li, Y.; Wang, B.; Su, Y.; Xiang, H.: Effects of wind barrier on the safety of vehicles driven on bridges. *Journal of Wind Engineering and Industrial Aerodynamics*, 143, (2015), 113-127.

Coleman, S. A.; Baker, C. J.: The Reduction of Accident Risk for High Sided Road Vehicles in Cross Winds. *Journal of Wind Engineering and Industrial Aerodynamics*, 41-44, (1992), 2685-2695.

Dorigatti, F.; Sterling, M.; Rocchi, D.; Belloli, M.; Quinn, A. D.; Baker, C. J.; Ozkan, E.: Wind tunnel measurements of crosswind loads on high sided vehicles over long span bridges. *Journal of Wind Engineering and Industrial Aerodynamics*, (2012), 214-224.

Guo, W. W.; Wang, Y. J.; Xia, H.; Lu, S.: Wind tunnel test on aerodynamic effect of wind barriers on train-bridge system. *Science China Technological Sciences*, 58, No. 2, (2015), 219-225.

Ingenieurgesellschaft Niemann & Partner GbR; Ruhr-Universität Bochum, Arbeitsgruppe Aerodynamik und Strömungsmechanik im Bauwesen: WINDTECHNOLOGISCHES GUTACHTEN ZUR BAB A71; Entwicklung von Windschutzeinrichtungen für die Talbrücke Zahme Gera, (2007).

Krajnovic, S.; Ringqvist, P.; Basara, B.: Comparison of Partially Averaged Navier-Stokes and Large-Eddy Simulations of the Flow Around a Cuboid Influenced by Crosswind. *ASME. Journal of Fluids Engineering*, 134, (2012).

Malviya, V.; Mishra, R.; Development of an analytical multi-variable steady-state vehicle stability model for heavy road vehicles. *Applied Mathematical Modelling*, 38(19-20), (2014), 4756-4777.

Menter, F. R.: Eddy Viscosity Transport Equations and Their Relation to the k-ε Model. *ASME, Journal of Fluids Engineering*, 119(4), (1997), 876-884.

Proppe, C.; Wetzel, C.: A probabilistic approach for assessing the crosswind stability of ground vehicles. *Vehicle System Dynamics*, 48(1), (2010), 411-428.

Sterling, M.; Quinn, A. D.; Hargreaves, D. M.; Cheli, F.; Sabbioni, E.; Tomasini, G.; Delaunay, D.; Baker, C. J.; Morvan, H.: A comparison of different methods to evaluate the wind induced forces on a high sided lorry. *Journal of Wind Engineering and Industrial Aerodynamics*, 98, (2009), 10-20.

Wang, B.; Xu, Y.; Zhu, L.; Cao, S.; Li, Y.: Determination of aerodynamic forces on stationary/moving vehicle-bridge deck system under crosswind using computational fluid dynamics. *Engineering Applications of Computational Fluid Mechanics*, 7(3), (2013), 355-368.

Zhu, L. D.; Li, L.; Xu, Y. L.; Zhu, Q.: Wind tunnel investigations of aerodynamic coefficients of road vehicles on bridge deck. *Journal of Fluids and Structures*, 30, (2012), 35-50.

Address: Institute of Fluid Machinery, Karlsruhe Institute of Technology. Kaiserstr. 12, 76131 Karlsruhe
email: pritz@kit.edu