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Korrespondenzadresse:
j.seedorf@hs-osnabrueck.de

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University of Applied Sciences Osnabrück, Postbox 1940, 49009 Osnabrück, Germany
Unit of Animal Hygiene and Food Safety[1]
Laboratory for Fluid Mechanics and Turbomachinery[2]

# Animal transport vehicles as potential bioaerosol emitters: A preliminary contribution to environmental hygiene by means of computational fluid dynamics (CFD) simulation

## *Tiertransportfahrzeuge als potenzielle Bioaerosol-Emittenten: Ein vorläufiger Beitrag zur Umwelthygiene unter Verwendung einer numerischen Strömungssimulation*

Jens Seedorf[1], Ralf-Gunther Schmidt[2]

**Summary**

Several computational fluid dynamics (CFD) studies of cars and trucks are available in the literature, but no comprehensive simulations are currently available to visualize the airflow fields around animal transport vehicles (ATV) as potential objects that emit airborne components such as bioaerosols that can act as infective media. A simple truck was digitally constructed to mimic an ATV with air exchange openings on both sides of a box-like loading area. Using an open-source CFD software, the airflow field was visualized in a virtual wind tunnel. Within the flow domain, varying air velocities and pressure values were calculated. It is remarkable that the air flow shows a specific pattern, that directly influences the spatial distribution and velocity associated release of airborne components and therefore the potential dispersion of bioaerosols into the environment. In the future, critical discussion is additionally required regarding whether adequate CFD adaptations improve and confirm air flow and pressure predictions compared to experimental derived data. Furthermore, the operation of diverse ATV architectures, which are designed for different farm animal species have also to be taken into consideration. Consequently, such investigations will have direct influences on ATV-related bioaerosol emission behaviours of ATVs and will give deeper insight how pathogens are dispersed from ATVs when infected animals are transported. Therefore, the knowledge of ATV-related emission rates is a prerequisite for further studies.

**Keywords:** veterinary public health, livestock transporters, pathogen emission, disease transmission, livestock buildings

**Zusammenfassung**

Trotz der Vielzahl der in der Literatur aufgeführten numerischen Strömungssimulationen an Landfahrzeugen gibt es keine umfassenden Simulationen, die die Strömungsverhältnisse im Umfeld von Tiertransportfahrzeugen visualisieren, um derartige Fahrzeuge als potenzielle Emittenten von Bioaerosolen bzw. Infektionserregern zu charakterisieren. Es wurde daher zu Simulationszwecken ein vereinfachtes digital erstelltes Fahrzeugmodell herangezogen, das einen für Nutztiere vorgesehenen Laderaum mit beidseitigen Öffnungen für den Luftaustausch aufweist. Unter Verwendung eines „open source Programms" im Bereich der numerischen Strömungsmechanik wurde das Strömungsfeld um das Fahrzeug in einem virtuellen Windtunnel berechnet. Aus dem visualisierten Strömungsfeld wird abgeleitet, wie die Umströmung und Durchströmung des Fahrzeuges die räumliche Verteilung und die geschwindigkeitsabhängige Freisetzung luftgetragener Komponenten direkt beeinflusst und damit auch die Verteilung von Bioaerosolen in der Umwelt letztendlich mitbestimmt. Zukünftige Untersuchungen sollten kritisch hinterfragen, inwiefern methodische Anpassungen die Simulationsberechnungen zu verbessern helfen und die erzielten Rechenergebnisse mit experimentell erhobenen Daten vergleichbar sind. Außerdem sollten in die Simulationen auch verschiedene, in der Praxis gebräuchliche Fahrzeugkonstruktionen mit einfließen, die auf unterschiedliche Nutztierarten abgestimmt sind, da hiervon auch das Emissionsverhalten von Tiertransportfahrzeugen abhängt. Diese Vorgehensweise erlaubt Rückschlüsse auf die Herkunft und Dispersion epidemiologisch relevanter Pathogene, wenn infizierte Nutztiere mit entsprechenden Fahrzeugen transportiert werden. Dies setzt voraus, dass zukünftig entsprechende Emissionsraten für Tiertransportfahrzeuge verfügbar sind.

**Schlüsselwörter:** Veterinary Public Health, Tiertransporter, Pathogenfreisetzung, Krankheitsübertragung, Nutztierhaltung

## Background and Introduction

Traffic generally contributes to a range of gaseous air pollutants and to suspended particulate matter, which are capable to cause an increased risk of cardiopulmonary diseases (WHO, 2005). However, environmental hygiene can also be influenced by biological aerosols, that particularly originate from agricultural activities. Typically, livestock operations are well known as sources of solid, liquid and gaseous emissions that can both be nuisances and environmentally harmful (Hartung and Wathes, 2001; Seedorf, 2004a). Among these emission qualities, the bioaerosols represent an important fraction, because these types of airborne particulate matter consist of a complex mixture of organic dust (e. g., proteins and polycarbohydrates), biologically active components (e. g., endotoxins and glucans) and microorganisms (e. g., bacteria and fungi) (Seedorf, 2004b).

Bioaerosols not only are capable of causing detrimental effects to animals' and farmers' health (Cambra-Lopez et al., 2010) but can also to be dispersed via the airborne route into the environment (Seedorf et al., 2005; Dungan, 2010; Schulz et al., 2011) where livestock-related components of public concerns can be detected (Gibbs et al., 2006; Schulz et al., 2012). Highly infective and aerially dispersible animal pathogens, such as the porcine reproductive and respiratory syndrome virus, *Mycoplasma hyopneumoniae* and the food-and-mouth disease (FMD) virus are not less important from the epidemiological perspective (Donaldson and Alexandersen, 2002; Dee et al., 2009). Therefore, numerical plume dispersion models have been applied to predict and to assess the likely airborne spread of pathogens among farm sites (e. g., Gloster et al., 2011).

In contrast to bioaerosol releases from livestock farms, more vague information exists regarding the role of animal transport vehicles (ATV) as bioaerosol emission sources (Hartung, 2006; Greger, 2007). Such mobile emission sources might also come into contact with farm animals and livestock buildings located in the vicinities of roads and motorways as basically demonstrated in an animated virtual scene (Supplementary material S1). The outbreak of classical swine fever in The Netherlands in 1997, for example, was spread by transport vehicles on some occasions (European Commission, 2002). It was assumed that the vehicle-based transfer of infectious material (e. g., secreta, excreta, soiled boots) could be associated with infections of pig herds (Elbers et al., 2001). That means a ground-based transfer is more likely rather than an airborne dissemination of viruses. However, the circumstances of potential airborne transmissions from ATVs to livestock operations need to be clarified, because a considerable number of farm animals are transported on the roads. For example, according to the inspection report of the European Commission (EC) from 2012, 83,403,494 pigs were transported in Germany. Compared to 2011, this represents a noteworthy increase of 12.4% (European Commission, 2011, 2012). Findings such as these have led to the assumption that the 'hit probability' for vehicle-related bioaerosols at farm sites should not be underestimated and that favourable combinations of spatial, traffic and meteorological conditions might increase the risk of bioaerosol transmissions.

The abilities to predict the plume dispersions of ATV-related bioaerosols in the atmosphere and their effects on the neighbourhood are obviously highly desirable. Compared to the large expenditures required for field studies, the application of computational fluid dynamics (CFD) offers a great opportunity to investigate and analyse various phenomena of agri-environmental areas with an acceptable use of resources (Lee et al., 2013).

Hence, the aim of this preliminary study was to focus on the applicability of CFD for the calculation of the airflow around a simplified vehicle (truck) and to feed the results into a post-processing procedure to illustrate the potential truck-related emission forces that drive airborne components such as bioaerosols. This also includes a critical analysis of the methodology used in this first research approach.

## Methods

Calculations of the velocity and the air pressure patterns around and within the loading compartment of an animal transport vehicle were performed using the open-source CFD program OpenFOAM 2.3.0 (http://www.openfoam.org) running in the Ubuntu 12.04 LTS (http://www.ubuntu.com) Linux environment. The typical command-line based application of OpenFOAM was replaced with the HELYX-OS software (http://engys.com/de/products/helyx-os), which is an open-source pre-processing graphical user interface (GUI) that is designed to work with OpenFOAM.

The steady-state solver simpleFoam for incompressible, turbulent flow was implemented within OpenFOAM in conjunction with the so-called Menter's Shear Stress Transport ($\kappa$-$\omega$-SST) turbulence model as part of the Reynolds-averaged simulation (RAS) model (also known as the Reynolds-averaged Navier-Stokes, RANS, model). Although air is generally thought to be a compressible medium, incompressibility was ensured because the Mach number could be assumed to be < 0.3, which is typical of fluid simulations related to vehicles (Laurien and Oertel, 2011).

The workflow began with the definition of the geometry of the ATV, which was digitally constructed as a simplified truck in the free version of the computer program

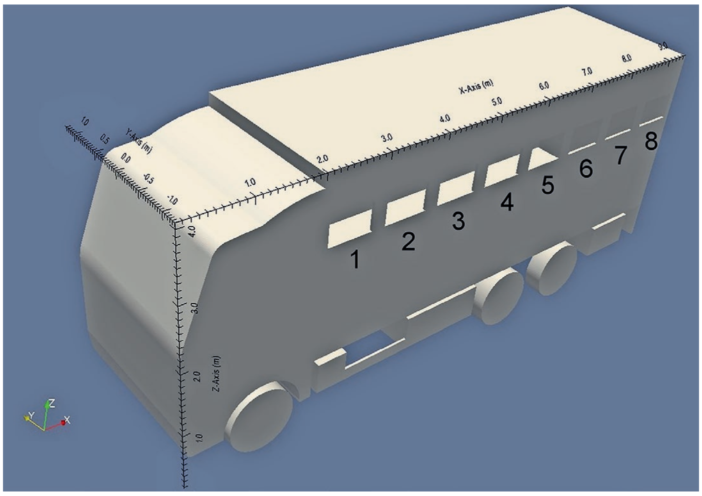


**FIGURE 1:** *The shape of the simplified animal transport vehicle with eight openings (1-8) on both sides (only the left side is shown) in the upper part of the loading compartment (perspective view).*

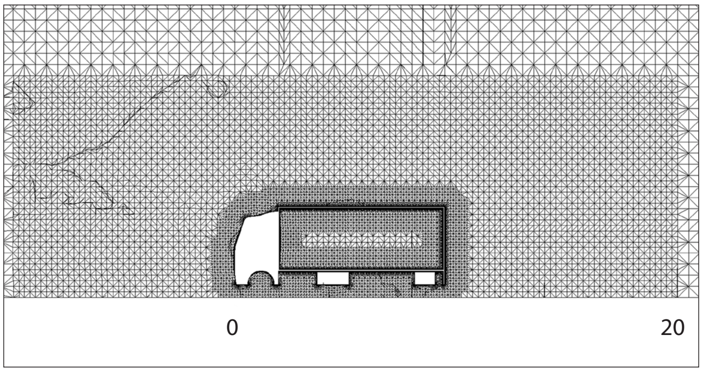


**FIGURE 2:** *Part of the longitudinal mesh structure (XZ plane cross-section) of the flow domain and its increasing resolution close to the vehicle along the middle of the y-axis that was constructed to sufficiently consider truck-air flow interactions.*

Sketchup 8 (http://www.sketchup.com/de/download/all). The box-like loading area of the truck was designed with several openings on both sides that indicated air inlets and outlets. The dimensions, shapes and numbers of the openings were arbitrarily chosen, but the openings were typically distributed along both side walls of the truck as commonly observed in large animal transportation vehicles to guarantee fresh air supply for the animals on one hand and the removal of heat to the outside on the other hand (Fig. 1). After finalizing the truck, the geometry was saved as an STL file containing the basic three-dimensional grid information about the vehicle.

After initiating HELYX-OS, the mesh panel within the program served as the user interface for defining the meshing parameters for the subsequent CFD calculations. The bounding box was designed as a structured grid with OpenFOAM's blockMesh utility, and OpenFOAM's snappyHexMesh was used to realize the truck's geometry within the domain. The second tool determined the intersection between the geometry and the initial structured grid and subtracted the truck's inner volume from the flow domain. The program then proceeded to smooth the mesh, insert refinement zones and add layers to overflown surfaces (Fig. 2). The resulting mesh contained unstructured areas due to cell deformation within the so-called snapping process. A three-stage volume refinement around the truck was combined with five layers on its surface to allow for sufficient resolution of the velocity gradients. The final virtual wind tunnel exhibited an approximately 5-fold expansion of the truck's length dimension concerning the width, height and distance from the inlet. The outlet distance was chosen as a 10-fold expansion to minimize the influence of wake flows.

The finalised hybrid mesh with 5,844,958 cells (92.8% hexahedra, 7% polyhedra and 0.2% prisms) was used to set up an OpenFOAM case using the HELYX-OS Case Setup-panel. HELYX-OS configures the file structure and text files (so-called dictionaries) for OpenFOAM,

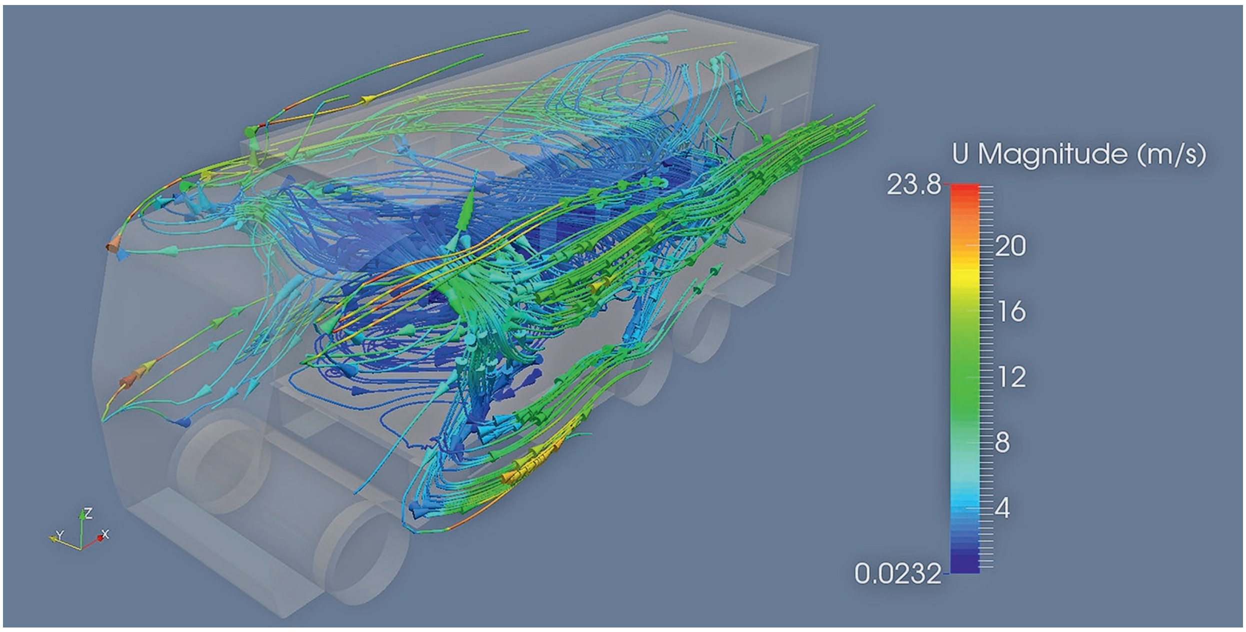


**FIGURE 3:** *Streamline pattern within and outside the ATV. The cones are randomly integrated into the streamlines to indicate the general flow direction.*

which typically require manual editing and are needed for the full OpenFOAM operations. Apart from the basic input values, for example velocity and pressure, the material was specified with 20 °C air with a density of 1.21 kg/m$^3$ and a kinematic viscosity of 1.58813 × $10^{-5}$ m$^2$/s.

For the calculation, the air velocity at the inlet boundary was set to 22.22 m/s (80 km/h) along the x-axis, and the shear stress of the side and top walls of the virtual wind tunnel was set to zero. The bottom wall of the wind tunnel, which represented the road, was modelled as a wall moving at the same speed as the surrounding air. The steady-state simulation was performed with 1000 pseudo-time steps. Within each step, the velocity and pressure field were calculated iteratively between four and twelve times such that decreases in the residuals of 2 orders of magnitude were ultimately achieved. The field values of the last step were then transferred to the post-processing procedure.

For post-processing purposes, the OpenFOAM case was opened in Paraview 4.0.1 (http://www.paraview.org), which is a data analysis and visualization application. The flow and pressure patterns can be locally specified and shown with different visualization tools via internal program filters.

## Results and Discussion

Numerical simulations of air flow pattern in conjunction with running trucks commonly seek to investigate how the flow around a truck is influenced by drag-reducing trailer devices (Håkansson and Lenngren, 2010) or to determine the drag coefficients during air flow around a yawing truck (Mu, 2011), for example, to develop more fuel-efficient vehicles. However, from the hygienic perspective, trucks such ATV also interact with the environment due to their semi-open construction properties. Any openings, with or without installed fans, are not only inlets for the ambient air but can also act as outlets for airborne agents that originate from the transported animals and their liquid and solid releases. Moving ATVs are undoubtedly a source of emitted odours that are frequently experienced by car drivers following behind such trucks. Such sensory experiences attest to the fact that the aerodynamic forces and related airflow conditions are responsible for the release of ATV-related agents into the ambient air. Consequently, not only odour but also bioaerosols likely follow the trajectories of the airflow field.

Animal transport systems are ideally suited for spreading disease (FAO, 2002). Once become airborne and released into the ambient air, the meteorological and microbial tenacity conditions determine the on-going destiny of the bioaerosols. The passing of other ATV and farms close to routes with frequent ATV movements might then cause interactions. This hypothesis could be of current importance due to pig transportation on the roads and the latest African swine fever (ASF) outbreaks in the eastern part of Europe, and it is believed that the introduction of the ASF virus into the EU was primarily caused by the legal movement of live pigs (Mur et al., 2012a) or by other transport-associated routes, such as returning trucks (Mur et al., 2012b). However, recent data regarding the ASF virus excretion patterns from persistently infected animals (de Carvalho Ferreira et al., 2012) and the detectability of ASF viruses in the air with half-life times between 14 and 19 min (de Carvalho Ferreira et al., 2013) support the assumption that the transmissibility of such epidemiologically important pathogens between trucks and farms is quite possible and not limited to ASF; for example, livestock-related health hazards, such as classical swine fever (Ribbens et al., 2004; Weesendorp et al., 2008, 2009) and FMD (Gloster et al., 2008), are also potential candidates for such transmissions. For a very first future transmission scenario FMD seems to be the most ideal pathogen, because during the last decades plenty of research results have been published with respect to the amount of airborne FMD virus emitted by livestock animals, the minimum doses of FMD virus required to infect different species or the aerobiological behaviour of the virus (Donaldson, 1986; Donaldson and Alexandersen, 2002).

Our simulation revealed that, under steady-state conditions, ATVs travelling at speeds of 80 km/h induce varying truck-related air flow velocities that are below 4 m/s within a vortex-like air flow pattern in the interior of the loading area and approximately 12 m/s close to the outer surface of the loading compartment (Fig. 3). Regarding the pressure distributions at the openings and the spaces around those openings, local pressure differences that contribute to the air exchange between inside and outside exist (Fig. 4A, Supplementary material S2). To make the pressures more numerically visible, the pressure values are plotted over lines that horizontally

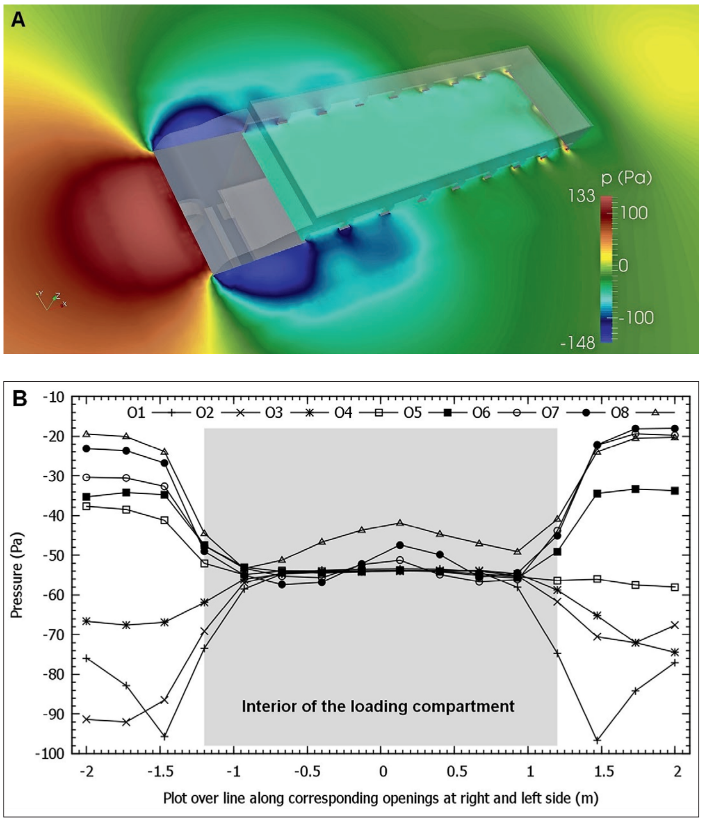


**FIGURE 4:** *A Pressure distribution on a horizontal plane in the virtual wind tunnel crossing the centres of the openings. B Pressure distributions inside and outside of the loading compartment along openings (O) 1 to 8 of the truck. The grey area indicates the loading area between the both of the opening rows on the left and right side of the truck.*

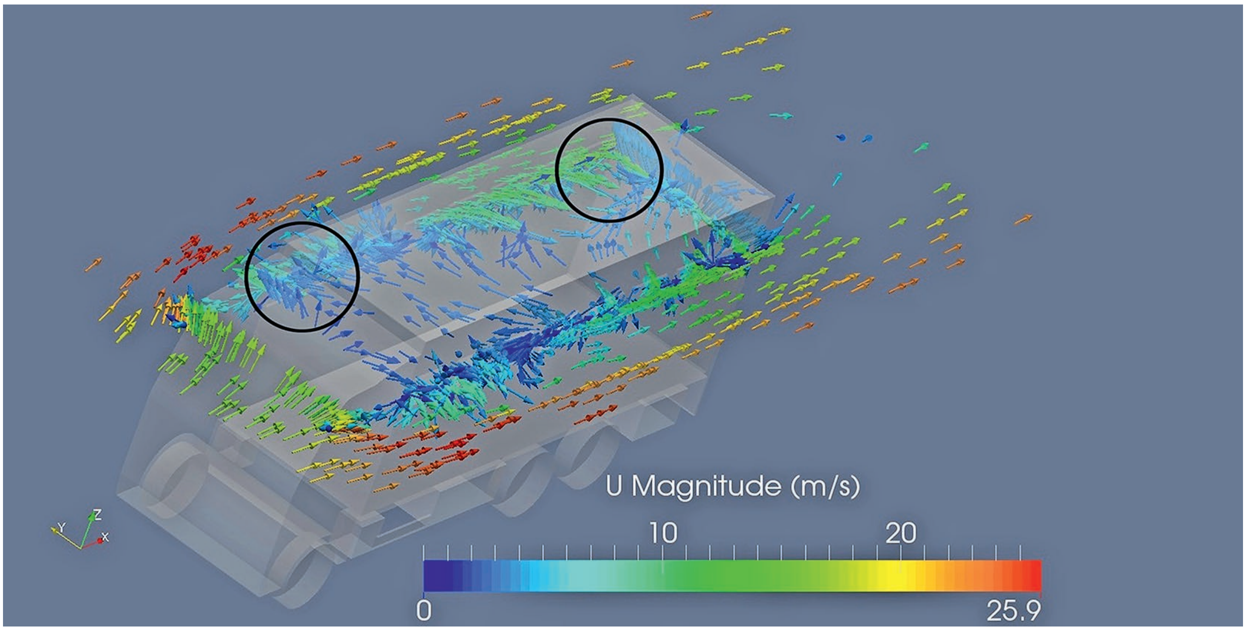


**FIGURE 5:** *Velocity vectors in and around the ATV in a horizontal plane cutting the centres of the openings 1 to 8 of the truck. The black circles are examples that indicate the airflow from inside to outside and vice versa.*

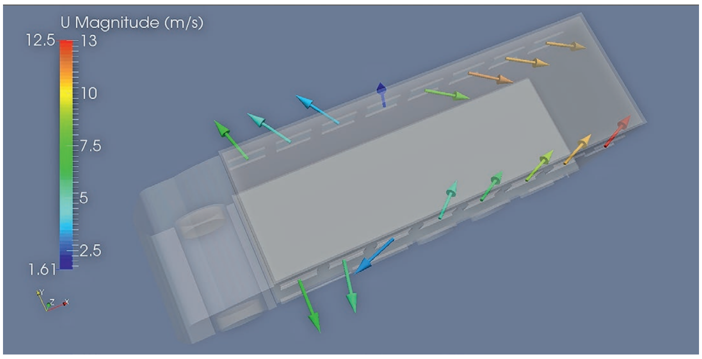


**FIGURE 6:** *Directions of the velocity vectors that were each originated in single selected mesh cells near the centres of openings 1 to 8 (top view).*

cross the centres of the corresponding openings at each location from 1 to 8 and continue for an additional 0.8 m to the left and right sides of each opening in the wind tunnel. Based on the chosen resolution, each of the eight lines represents 16 pressure values that confirm that the inverse pressure conditions increase from the front to the rear part of the truck (Fig. 4B). This observation was accompanied by mean values of –58.8 Pa and –46.3 Pa that were each calculated from 10 values located along the interior parts of the lines that crossed openings 1 and 8, respectively. The calculated and imaged flow-driven forces were highlighted by a bundle of randomly distributed velocity vectors that were implemented in a horizontal sliced mesh area along the centre of the openings (Fig. 5). This implementation created the impression that the front openings generally acted as outlets, and the rear openings acted as inlets. To confirm this hypothesis, mesh cells that were nearly in the centres of each of the openings were selected to create additional displays of the cell-specific velocity vectors and flow directions (Fig. 6). The slight asymmetrical flow pattern has been caused by small deviations in the geometry and misalignments of the openings, that was already indicated by the asymmetrical pressure conditions in Fig. 4B. However, any misalignment of an object in the wind tunnel provides an obvious hint regarding how flow and therefore emission patterns vary when the air moves from different directions (e. g., side wind) to the vehicle in conjunction with varying air and vehicle velocities. Nevertheless, once released, the air masses from the interior of the loading compartment partially underlie a flow circuit whereby other parts of the released air masses are directly influenced by the overall air flow along the ATV, which then likely results in emissions into the ambient air. Due to the uncertainty regarding the quantitative relationships between the re-entry of previously released air masses and those that freely flow into the atmosphere, no reliable flow rate predictions based on a simple application of the continuity equation are currently possible. Moreover, sufficient data regarding the bioaerosol concentrations in ATVs seem to be currently unavailable, which also makes comprehensive emission calculations nearly impossible at this stage of the study.

Simulations all attempt to imitate the actions and events that occur in real life or to visualize phenomena in nature. The design of nearly realistic conditions depends on what are known as the necessary input parameters and the factors that play major and minor roles in the model. Obviously, the modelled ATV shown in Fig. 1 is simplified, but it fulfils some of the basic design features that make the model recognizable as a truck. The simplification of objects for the purposes of CFD is not unusual. The so-called Ahmed body is capable of permitting accurate flow simulations in automotive research, although this body is composed only of a round front part, a moveable slant plane that is placed in the rear of the body and used to study separation phenomena at different angles, and a rectangular box that connects to the front part and the rear slant plane. Rather than wheels, four pillars are merged with the box (Ahmed and Ramm, 1984; Liu and Moser, 2014). However, in contrast to fully closed objects such as the Ahmed body, the geometries and locations of any openings that act as transboundary interfaces between the inside and outside require additional considerations in CFD, and such considerations were made here.

Another important point is the occupation of the loading area by farm animals. On the one hand, these animals release components into the surrounding air. On the other hand, they act as airflow obstacles and heat transfer sources (Wu and Gebremedhin, 2001; Gebremedhin and Wu, 2003) that will influence the airflow field in conjunction with seasonal conditions (e. g., summer vs. winter temperatures). Furthermore, loaded animals are not stationary but locomote to varying extents depending on the loading density and the behavioural properties of the animals, and all of these factors place special demands on the simulation. These circumstances have been highlighted by Bjerg et al. (2011) in an exemplary manner; these authors examined the flow resistance properties of animal-occupied zones to improve the air distribution in a pig barn. They stated that the full consideration of the animals' geometries in CFD is a very time-consuming effort and therefore requires an acceptable simplification, which leads naturally to the next topic. The type of mesh that is to be used must be considered because it plays a direct role in the quality of the analysis. Because the geometries of real ATVs are complex, only unstructured or hybrid meshes can be created within a reasonable time period. However, it is necessary to further quantify the model's error via comparison with experimental (wind tunnel) data or to at least demonstrate the robustness of different mesh types in terms of reliable CFD calculations. Additionally, a critical review of the solver configuration seems to be advisable when supported by the implementation of adequate experimental data and might serve as a fine-tuning measure to improve convergence criteria or numerical calculation schemes. All these measures could help to validate the set-up in prospective studies.

## Conclusions and Outlook

The application of CFD offers great scientific opportunities to examine the fluid behaviours of obstacles such as vehicles that are exposed to air movements in a virtual wind tunnel. This study revealed that ATVs can be regarded as potential emission sources of agents due to the pressure gradients that exist between the interiors and exteriors of the loading areas of such trucks. In contrast to the emissions of stationary livestock buildings, ATV traffic-induced emissions of airborne components are more challenging in terms of predictable quantities and dissemination behaviour in the environment across the countryside; therefore, greater attention should be given to this potential and complex biosecurity problem in terms of bioaerosol dispersion and transmission.

Specifically, research efforts should include important factors (e. g., atmospheric and environmental stability of infectious pathogens), which have also to be considered for atmospheric dispersion models (van Leuken et al., 2016). Additionally, local topographic effects may play a significant role in influencing the pattern of disease spread as shown for FMD (Mikkelsen et al., 2003). This aspect is particularly relevant for moving ATVs, because landscapes are different along the driving distance (e. g., marsh landscape vs. arable land vs. forestry vs. buildings). But from this point of view ATV-related emission rates are certainly needed first in future. This is principally underlined by Guinat et al. (2016), for example, who propose research priorities also in the field of movements of animal and trucks to explore potential transmission pathways of ASF.

Future work should also focus on the appropriate fine-tuning of the input data to increase the reliability of CFD results because the results presented here are preliminary. From this point of view a catalogue of considerations needs attention:

- the application of CFD to alternative but common ATVs that are constructed by computer aided design (CAD) programs (e. g., typical 3-stage pig transport vehicle, tractors with trailers and the influence of tractor-trailer gaps) is needed,
- the tolerable magnitude of simplification in terms of vehicle geometry (e. g., the lack of wheel axes, the contours of the cab, the lack of structural separation between cab and the box-like loading area, details of the construction of the underbody, and internal structures of the loading area such as gates) needs to be determined,
- the influence of animals within the loading compartment on the air flow field (e. g., different sized and shaped animals such as pigs and cattle, load density) needs to be determined,
- the size of the virtual wind tunnel should be optimized,
- the boundary conditions should be identified,
- the influence of the opening geometry (e. g., dimensions and obstacles such as horizontal built-in round bars and installed fans) should be determined,
- the resolution and topology characteristics of the meshes (e. g., the required number of cells and structured vs. unstructured meshes, distance based refinement of the mesh) should be optimized and this will also include a grid independence study,
- the CFD settings should be optimized where suitable (e. g., the comparability of different software versions, solver choices, and the durations of the time steps),
- ambient wind directions that interfere with the vehicle-caused air flow (e. g., the influence of side-wind effects on the emission driving forces) should be considered,
- CFD results should be generally validated in wind tunnel experiments (e. g., lab-scale and full-scale), if possible,
- the airflow through each ATV opening should be determined by numerical experiments (e. g., passive forces by ambient air pressures vs. airflows caused by active ventilation due to mounted fans in the trailer),
- particle releases from ATVs should be integrated to calculate plume dispersions and to assess potential effects on the environment (e. g., the determination of critical transmission distances for pathogens),
- the effects of barriers, such as vegetation in or near the road environment, on the mitigation of aerosols (e. g., Steffens et al., 2012) and subsequent transmission of infectious pathogens or selected surrogate microorganisms should be explored,
- field investigations should be conducted as supportive measures (e. g., studies in the vicinity of roads and motorways with frequent ATV traffic and studies of planned ATV transports along defined roads for targeted investigations).

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## Conflict of interest

The authors have no conflict of interests to disclose.

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**Address for correspondence:**
Prof. Dr. Jens Seedorf
University of Applied Sciences Osnabrück
Oldenburger Landstr. 62
49090 Osnabrück
Germany
j.seedorf@hs-osnabrueck.de