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Experimental analysis of the flow around ahmed bodies in tandem position

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Abstract. *Use of experimental methods is fundamental for the automobile industry, as it allows one to analyze aerodynamic phenomena that are crucial for the development of automobiles. A coherent method is to use Ahmed bodies with different rear inclination angles as a reference model, considering that it has been used in studies that aim to analyze the flow of land vehicles, whilst generating satisfactory results. So, in this experimental work, we explored the impact of the rear inclination angle and the spacing between Ahmed bodies in tandem (simulating a truck convoy), aiming to determine the best configuration concerning the drag reduction. The experimental methodology used flow visualization techniques in the horizontal hydrodynamic tunnel. The flow was visualized and registered by a camera for different rear inclination angles (10°, 20°, 30° and 35°) and different gap ratios (0.5 to 1.0) between the Ahmed bodies at a fixed Reynolds number of 2.06×10^3 . Thus, we observed that, even if differences in the flow were presented in all cases, the body with a rear slant angle of 30° has the biggest wake region not mattering the spacing between models. Additionally, the impact of the gap ratio varied for each rear inclination angle.*

Keywords: *Automobile industry; experimental analysis; flow visualization; horizontal hydrodynamic tunnel; Ahmed body.*

1. INTRODUCTION

Merchandise ground transportation is crucial for the economy since remote times, given that, nowadays, it represents over half of the goods transportation. Furthermore, a rise in the demand is evident in the near future (Outlook, 2013). Additionally, with the development of Intelligent Transportation Systems (ITS), merchandise ground transportation tends to be mostly made by truck convoys, a group of trucks in tandem where only the leader one has a driver, so the study of the flow around vehicles in tandem is indispensable.

Terming ground vehicles as bluff bodies moving next to a road surface, Ahmed *et al.* (1984) aimed to identify the time-averaged flow structures present in the wake of a basic vehicle, and to analyze the effect of body geometry on wake structure. The study considered that the model chosen should generate a strong three-dimensional displacement flow in front, a relatively uniform flow in the middle and a large structured wake at the rear. This model, similar to the bluff body used by Morel (1978), became known as the Ahmed body, and it has been extensively used as a simplified model of a ground vehicle. Ahmed *et al.* (1984) analyzed different rear slant angles for isolated Ahmed bodies in a wind tunnel to measure the aerodynamic forces and pressure. In Ahmed *et al.* (1984) study, were also obtained satisfactory results for the flow visualization. As one of the main results, considering a fixed Reynolds number of 4.29×10^6 , we have the drag variation with the rear slant angle, which is shown in Figure 1. Considering these, flow visualization techniques in the horizontal hydrodynamic tunnel play an important role together with the use of Ahmed bodies as a simplified model of a ground vehicle (Minguez *et al.*, 2008; Krajnović, 2014).

Fletcher and Stewart (1986) used a wind tunnel to observe the aerodynamic behavior of a Denning Mono Mark II bus model in scale. The authors used different back and front parts and got considerable reductions in the drag coefficient. In addition, the flow around two buses in tandem was also analysed, and for short distances between models was achieved a substantial drag reduction.

Substantiated by the same idea, Hammache *et al.* (2002) used a simplified model truck in a wind tunnel and analyzed the influence that the gap between the cab and the trailer has on the aerodynamic forces. Additionally, using two models in tandem with no distance between cab and trailer, the authors examined the effects of different gaps between models and achieved a 50% drag reduction to the follower model on short gaps.

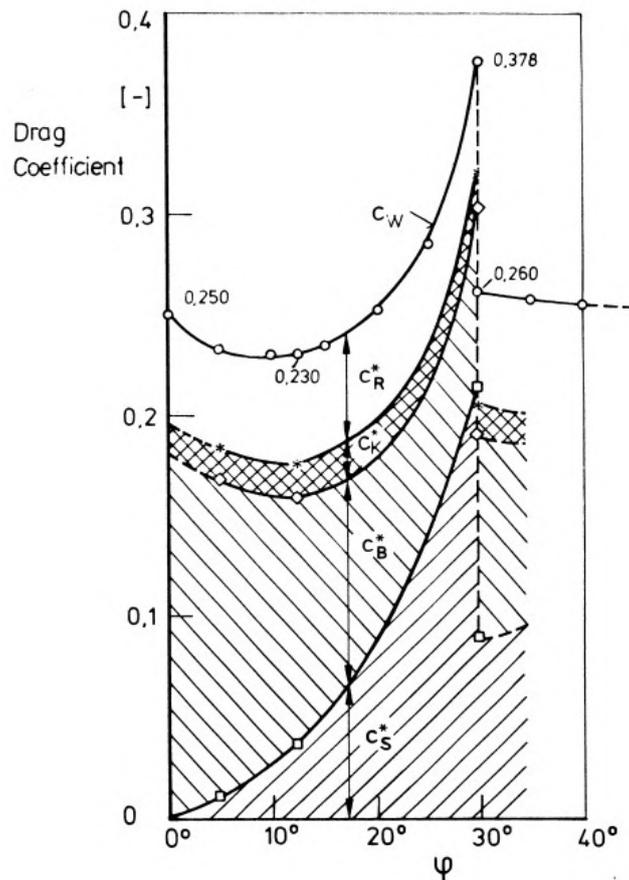


Figure 1: Variation of drag coefficient with the rear inclination angle for the Ahmed body. Available from: Ahmed *et al.* (1984)

Considering inter-vehicle spacing on highways, Gnatowska and Sosnowski (2018) studied aerodynamic parameters and safety limits aiming to determine the best distance between vehicles in traffic conditions. An experimental methodology was used together with a numeric analysis. The authors concluded that, for short gaps between vehicles, a change in the flow structure generated an increase of the drag coefficient.

Watkins and Vîno (2008), also considering inter-vehicle spacing on highways, studied the effects of this parameter in a wind tunnel using two Ahmed bodies with 30° for the rear inclination angle, as can be seen on Figure 2. The authors observed an increase in the drag of the follower model for short gaps. The study also concluded that the vortices existing in the flow were responsible for the drag alteration and, considering that spacing tend to be smaller with the extensive use of ITS, it is crucial to study the impact of this parameter.

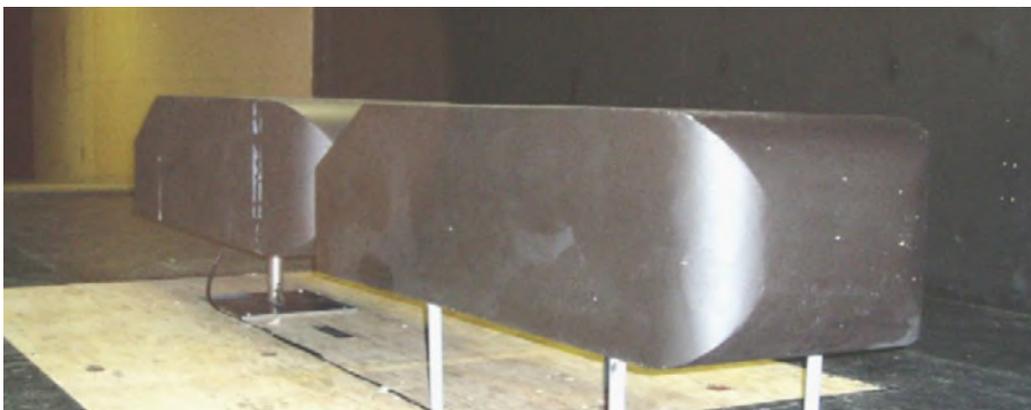


Figure 2: Sample drafting arrangement. Available from: Watkins and Vîno (2008).

Essel *et al.* (2020), considering the knowledge of strategies for reducing in-cabin air pollution, used two in tandem Ahmed bodies to investigate the effects of the rear inclination angle of the leader model. The experiment was performed at

a fixed Reynolds number of 1.7×10^4 and with a gap between models of $0.75L$, where L is the length of the Ahmed body used. Furthermore, the rear inclination angles used were 0° , 25° and 35° . As a result of the study, the authors observed that there was an increase in the recirculation behind the 0° model, whilst it was minimized for the rest of the models in the same configuration. A 7% and 10% recirculation zone reduction was also achieved for the 25° and 30° models, respectively.

Zhang *et al.* (2020) aimed the fuel economy by considering trucks in tandem position and presented an overview of existing studies, pointing out the methodologies, the contributing factors of fuel consumption, the best convoy configurations and a couple of look-ahead control strategies for fuel savings. The authors concluded that the determination of the gap between vehicles is a key to better results.

The objective of the current study is to investigate the flow around Ahmed bodies in tandem and understand the influence of the spacing between models and the rear inclination angle. The Ahmed bodies used have rear inclination varying from 10° to 35° and gap ratios between 0.5 and 1.5. The experimental methodology used flow visualization techniques in a horizontal hydrodynamic tunnel, where the flow was registered by a camera at a fixed Reynolds number of approximately 2.06×10^3 .

2. METHODOLOGY

2.1 Horizontal Hydrodynamic Tunnel

Constructive and operational simplicity is a good aspect of hydrodynamic tunnels. Their main advantage is the use of a liquid, generally water, as a working fluid, promoting easier visualization of the flow. According to Lindquist (1999), the acquisition of high-definition flow images makes this type of installation an excellent working tool for research development and didactic applications. Tests of this nature were conducted by Chandrasekhara *et al.* (2016) and Han and Patel (1979), for example, and make it possible to infer that research development in this field is necessary for the international scientific scenery, so that have contributions to increase the knowledge in this area.

The tunnel used has a horizontal configuration that allows clear visualization of the flow in the test section. Figure 3 presents a scheme of the horizontal hydrodynamic tunnel used in the study.

The tunnel consists of a stabilization section (SS) equipped with grilles (G) and a quadrangular honeycomb (QH) to get a laminar flow, a restriction (R) and the test section (TS) where the Ahmed bodies are fixed. There is also a radial pump (RP) and a flow control valve (FCV) between this pump and the diffuser (D). A pipe (P) with a flowmeter (F), to control the volumetric flow, connects the pump and the discharge reservoir (DR). The tunnel consists of an open channel, which means the change of the fluid after each test.

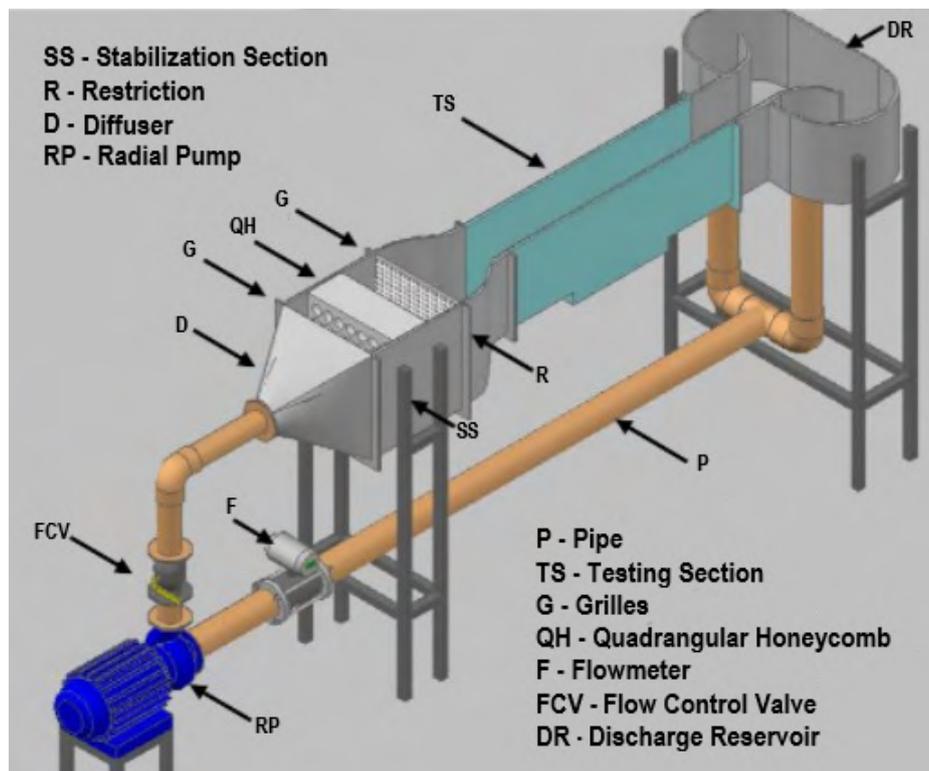


Figure 3: Horizontal Hydrodynamic Tunnel. Adapted from Florencio Mega (2009).

2.2 Models

The models investigated are Ahmed bodies with rear inclination angles of 10° , 20° , 30° and 35° . Salome¹, a computer-aided design software, was used to design the models, which were printed in the 3D MakerBot Replicator Plus printer. After printing, a surface treatment was required to eliminate the inherent roughness of 3D printing. Figure 4 exemplifies the distance between models (G) and the rear inclination angle, which is determined by the value of α .

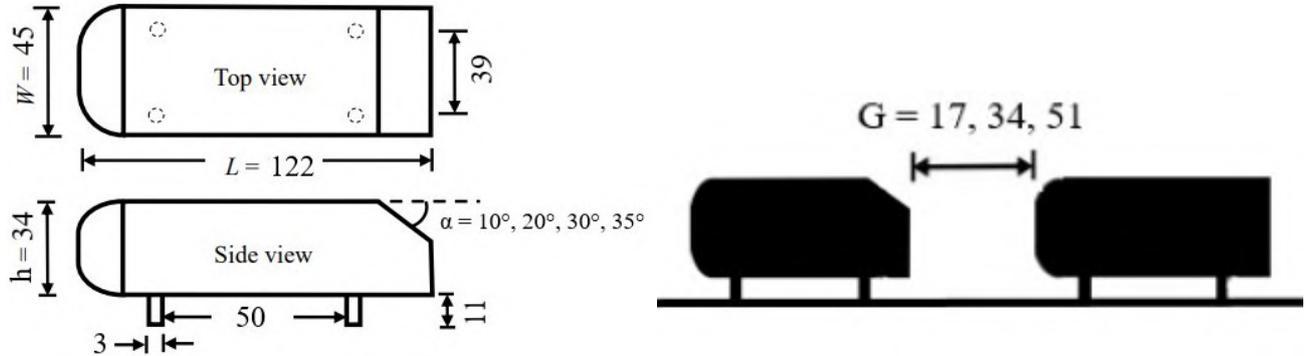


Figure 4: Scheme of the Ahmed body with the dimensions in millimeters used during the study. Adapted from: Essel *et al.* (2020)

2.3 Procedure

The first step of the study was to fix in the test section an Ahmed body with 0° of rear inclination, which was the follower model in all the tests. After that, we positioned the Ahmed bodies with rear inclination angles from 10° to 35° in the front of the fixed one, generating a platooning configuration, considering three values of gap ratio ($G/h = 0.5$, 1.0 , and 1.5 , where G is the distance between models and h is the height of the model). Then, the section between the models was registered by a camera, recording the flow behavior in this area. All the tests were done at a fixed Reynolds number of 2.06×10^3 and all the data obtained during each test were compared, aiming to analyze the aspect and influence of each configuration tested. Finally, GIMP², an open source GNU Image Manipulation Program, was used to work on the images obtained.

The flow was controlled by a valve and measured by the magnetic flowmeter of the brand Yokogawa model ADMAG AE208MG. With the fluid flow value measured by the flowmeter, we calculated the free current speed using Equation 1.

$$U = \frac{Q}{A} \quad (1)$$

Where U is the free flow speed, Q is the volumetric flow, and A is the cross-sectional area of flow.

Most phenomena in fluid mechanics show complex dependence on geometric and flow parameters. Therefore, it is necessary to use dimensionless for a better analysis of such phenomena. The Reynolds number, as can be determined in Equation 2, describes the flow regime, representing a ratio between inertial and viscous forces.

$$Re = \frac{\rho U L}{\mu} \quad (2)$$

Where L is the Ahmed body used length, ρ is the fluid density and μ is the fluid dynamic viscosity. Table 1 presents the experiment operation conditions.

Table 1: Experiment operation conditions. Developed by the authors

Parameter	Value
Temperature ($^\circ\text{C}$)	25 ± 1
Q (m^3/h)	2.18 ± 0.01
Re	$2060 \pm 0.46\%$

¹<https://www.salome-platform.org>

²<https://www.gimp.org>

3. RESULTS AND CONCLUSION

The first flow visualized was the one with gap ratio of 0.5 and a fixed Reynolds number of 2.06×10^3 , in Figure 5 is presented the comparison of the behavior of the flow with the rear inclination angle (α) variation.

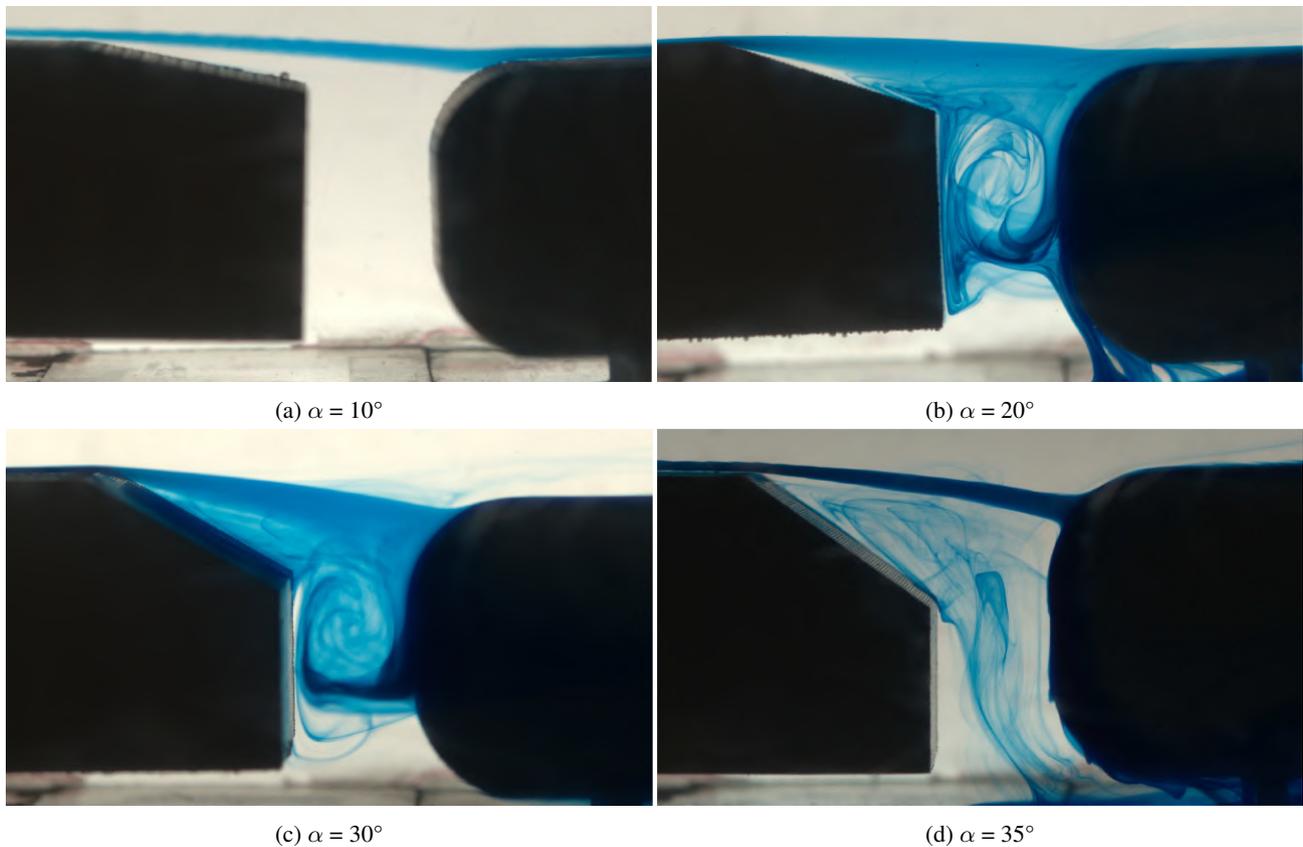


Figure 5: Flow visualization for $G/h = 0.5$. Developed by the authors

In Figure 5, it is possible to notice for $\alpha = 30^\circ$ that the rear slant angle increased the reverse flow region up to its peak. Accordingly, when comparing figures 5c and 5d, it is visible that the increase in the rear slant angle decreased the inter-model wake region, which agrees with what was reported by Ahmed *et al.* (1984).

Additionally, it is observed in Figure 5 the formation of a transversal vortex approximately in the mid-distance between the bodies, considering the angles of 20° and 30° . In Figure 5d, even though there is a noticeable wake region, the same vortex can no more be seen, matching the statement that with the rear slant angle of 35° , the reverse flow region is smaller than the one with 30° .

As observed in Figure 5, the flow considering a rear slant angle of 10° has no visible wake region, indicating that this case has the lowest drag on a fixed gap ratio of 0.5.

In the second visualization, we considered a gap ratio of 1.0 and a Reynolds number of 2.06×10^3 , in Figure 6 is presented the flow behavior according to the variation for this case.

Comparing figures 5 and 6, it is possible to observe a similar flow, considering that the body with a rear slant angle of 30° has the biggest recirculation zone. However, for a gap ratio of 1.0, the wake region formed behind the body with $\alpha = 35^\circ$ (Figure 6d) is considerably bigger than the one formed behind the model with $\alpha = 20^\circ$ (Figure 6b).

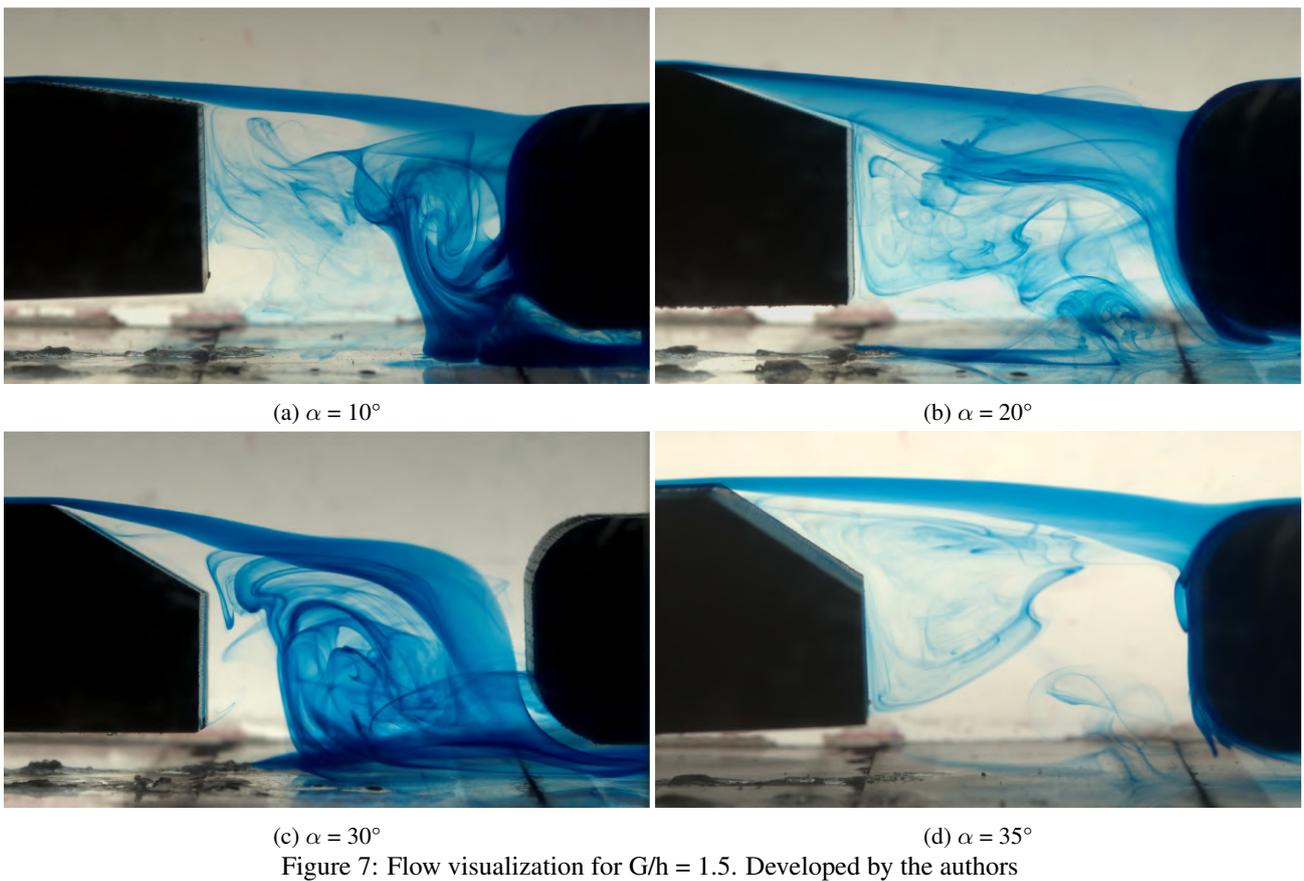
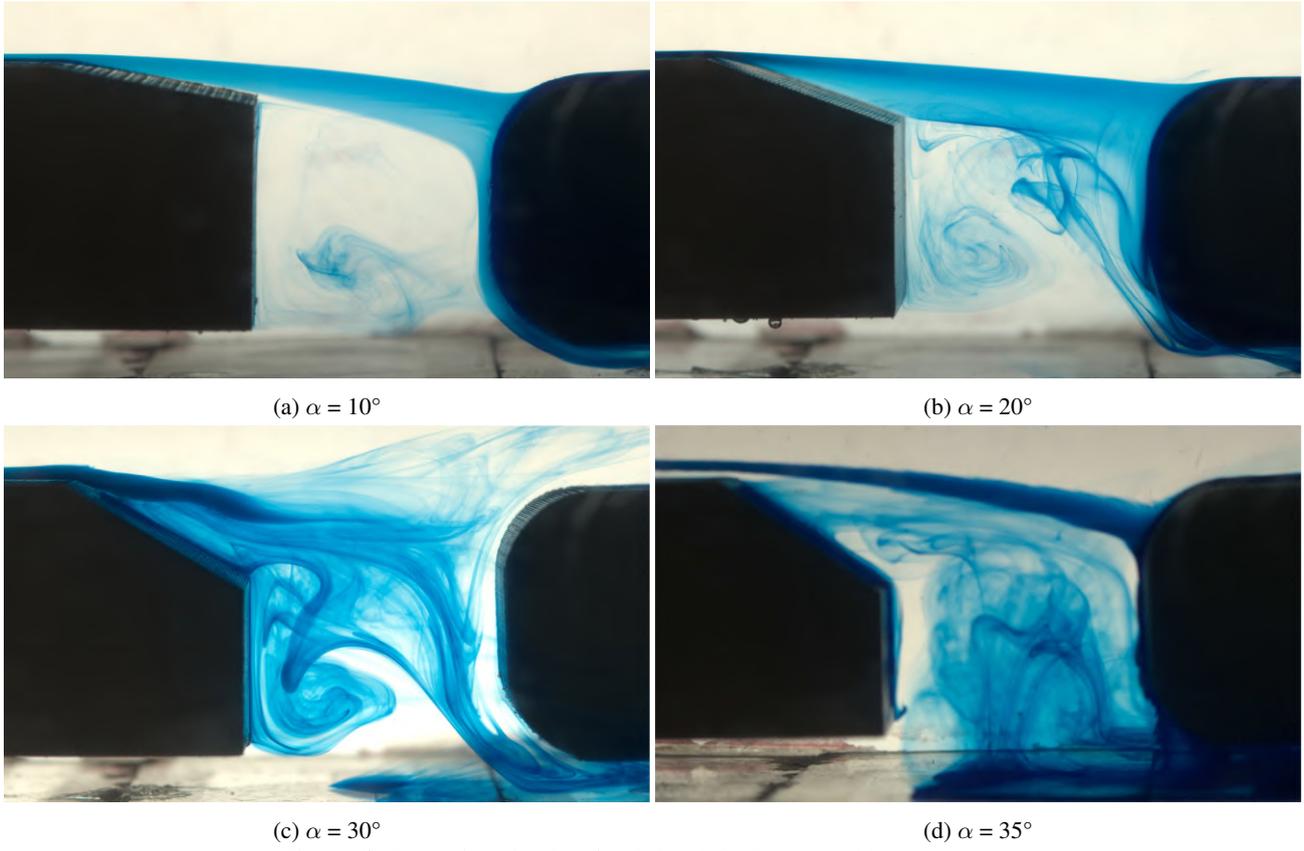
In Figure 6c, it is noticeable a group of vortical formations near the leader model. Considering the vortical phenomena and a fixed gap ratio of 1.0, the 30° rear slant angle body is the only one with this particular behavior, even if the other bodies have slightly less visible vortex.

The last flow visualized during the study considered a gap ratio of 1.5 and a Reynolds number of 2.06×10^3 . In this case, the comparison of the flow behavior with the rear slant angle is presented in Figure 7.

Considering Figure 7a and Figure 7c, a main vortex formed between the two models. Yet, in the first one ($\alpha = 10^\circ$) this vortex is generated closer to the follower body, while it is between the mid-distance and the leader back when $\alpha = 30^\circ$.

Comparing the rear slant angles of 20° and 35° in figures 5 and 7, it is possible to observe that the images presented a similar behavior, which is featured by a smaller wake region for the body with $\alpha = 35^\circ$.

Agreeing with what was observed by Ahmed *et al.* (1984), the wake region for the 30° rear slant angle body is



significantly bigger compared with results obtained for the rest of bodies tested, not mattering the gap ratio established. Considering that the drag measurements obtained by Ahmed *et al.* (1984) for an isolated Ahmed body had its peak on $\alpha = 30^\circ$, the results derived by this study matched the expected ones, making it possible to infer that the same behavior is observed for the bodies in tandem at a fixed Reynolds number of 2.06×10^3 . Overall, the previous behavior achieved for isolated Ahmed bodies also seems to characterize the bodies in tandem position, given that the recirculation zone is gradually increased until the body with a rear slant angle of 30° and then, decreased in the one with $\alpha = 35^\circ$.

Relative to the gap ratio, it is possible to perceive that this parameter has different impacts for each rear slant angle. While for $\alpha = 10^\circ$ the gap ratio of 0.5 resulted in no visible wake region, a fact that makes this spacing the best for this angle, the smaller recirculation zone for $\alpha = 20^\circ$ and $\alpha = 35^\circ$ was achieved with a gap ratio of 1.0 and 1.5, respectively. As can be observed, for each rear slant angle exists an ideal spacing between vehicles, which leads to saying that the convoy configuration depends on the vehicle shape used. In other words, there is no configuration, in terms of separation distance that will match all types of vehicles. Additionally, it is noticeable that a slight variation in the gap ratio (0.5) changes considerably the flow behavior between bodies. Considering that, it is crucial to study the precision of spacing control in ITS applications.

Moreover, the best configuration is the set with $\alpha = 10^\circ$ and $G/h = 0.5$, presented in Figure 5a, considering that the flow visualization showed no visible wake region, making it possible to infer that, compared with other sets, there is less energy dissipation between the bodies and, consequently, a favorable pressure gradient, resulting in a lower drag coefficient.

Thus, this study obtained satisfactory results, considering that it pointed out a group of observations that are exceptional to achieve good numbers in ITS truck convoy efficiency, as a consequence of drag reduction. Furthermore, the conclusions derived from this work can also be used to validate qualitatively numerical simulations developed in this scope of study.

4. ACKNOWLEDGEMENTS

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