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Flow characteristics over a tractor-trailer model with and without vane-type vortex generator installed

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ABSTRACT

An experimental study has been conducted to investigate the effects of vane-type vortex generators in affecting the flow pattern of the wake region using a 1:20 scale tractor-trailer model. The de Haviland wind tunnel of the University of Glasgow was employed in this study. Surface oil flow visualisation, smoke visualisation and two-component time-averaged particle image velocimetry measurements were used for flow diagnostics. Experimental data showed that putting the vortex generators near the front end of the trailer model could reduce the size of the vortex in the wake region. In addition, it was observed that the use of the vane-type vortex generators at the front of the trailer model might change the shear layer angle so that a smaller wake region was formed downstream of the trailer. No obvious effects of wake flow control could be observed by placing the vortex generators near the rear end of the trailer model. Finally, it was found that the vane-type vortex generator with the vane height of 6 mm is more effective in achieving wake flow control than the one with the vane height of 4 mm.

1. Introduction

Lorries play a major role in daily domestic freight transportation within the United Kingdom. According to the document "Transport Statistics Great Britain 2015" (Transport Statistics Great Britain, 2015), issued by the Department of Transport of the UK government, 73.5% of domestic freight was moved by lorries in 2014 (Transport Statistics Great Britain, 2015). In terms of emissions, in 2013, Heavy Goods Vehicles (HGVs) contribute 15.5 million tonnes or 13% of the total transport related greenhouse gas emissions in the United Kingdom (Transport Statistics Great Britain, 2015). Due to the fact that all HGVs have considerably blunt shapes, these vehicles encounter high level of aerodynamics drag during high speed operations. In fact, Bradley, (2000) concluded that about 21% of losses come from aerodynamics drag for a heavy vehicle weighting 36 t operating at 105 km/h. In other words, additional fuel is consumed in order to overcome the aerodynamic drag encountered by a heavy vehicle during high speed operations compared to the vehicle operating at low speed conditions. Altaf et al. (2014) stated that due to the poor aerodynamics efficiency of lorries and buses, up to 65% of fuel is consumed to overcome the aerodynamic drag encountered by these vehicles in long-haul journeys. It is anticipated that a significant amount of fuel could be saved by improving the aerodynamic efficiency of heavy vehicles (Bradley, 2000; Altaf et al., 2014). Quantitatively, (Bradley, (2000) found that about 4% of fuel saving could be achieved if the aerodynamic drag encountered by a heavy vehicle is reduced by 20% when operating at 105 km/h. Similarly, Hsu and Davis, (2010) stated that an annual fuel cost saving of about US$10,000 could be achieved for a 40% cut of the aerodynamic drag that acted on a heavy vehicle.

The aerodynamics characteristics of small-sized vehicles like cars and vans have been investigated extensively in the past two decades (Hucho and Sovran, 1993; Sovran et al., 1978). In contrast, the aerodynamic performance and geometry optimisation of heavy vehicles have received much less attention in both the academia and industrial sector. In fact, until now box-shaped heavy vehicles with sharp edges and corners around their bodies could still be seen frequently. This is partially due to the fact that aerodynamic performance is not a priority area of concern when designing heavy vehicles in most vehicle manufacturers' point of view. Instead, the primary goal that needs to be achieved in heavy vehicle designs is to minimise the space that is occupied by the engine, gearbox and other essential components of a vehicle so that the loading capacity could be maximised. This is particularly true for countries that have stringent regulations governing the maximum length, width and height of HGVs like most countries in Europe and some countries in Asia. Recently, this situation seems to change progressively due to the implementation of more stringent standards in terms of exhaust gas and noise emissions to Diesel-powered vehicles (i.e. most heavy vehicles) (European Commission

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transport emissions regulation webpage, 2016). In order to satisfy these stringent requirements, the aerodynamic efficiency of heavy vehicles needs to be taken into account. As a result, some heavy vehicle manufacturers recently starting to develop and introduce more aerodynamically efficient heavy vehicles into the market.

Amongst various types of HGVs, articulated lorries or tractor-trailers are one of the most common types of HGVs in the world. An articulated lorry is usually formed by joining a motorised tractor unit with a non-motorised trailer unit. As a result, many significant drag generation sources can be found on tractor-trailer vehicles although the majority of drag acting on these vehicles comes from four main areas known as the forebody stagnation region, the under-body flow, the tractor-trailer gap region and the flow separation at the rear end of the trailer. In fact, the drag contribution from these drag sources have been well documented in literatures (Cooper, 2003; Choi et al., 2014; Buil and Herrer, 2009; Wood and Bauer, 2003; Storms et al., 2001). In the past four decades, various flow control devices and strategies have been developed to achieve flow control in these four areas and their details are well documented and can be found in the review article recently published by Choi et al. (2014).

Since most of the trailers in articulated lorries are box-shaped and featured with sharp edges and corners, severe flow separation appears at the rear edge of a square back trailer. The occurrence of massive flow separation leads to the formation of a large wake region downstream of the rear end of the trailer (Altaf et al., 2014; Choi et al., 2014). As a result, significant amount of base drag is generated because the pressure within the wake region is low (Altaf et al., 2014; Hucho and Sovran, 1993). Wood, (2006) concluded that approximately 25% of aerodynamics drag encountered by a tractor-trailer vehicle is caused by the massive flow separation that appears at the rear end of the square back trailer. Due to this reasons, effective measures must be developed in order to reduce the amount of pressure drag that generated in this region. Surprisingly, until now, only a few devices have been developed in attempt to achieve drag reduction in the rear end of the square back trailers. These devices reduce the amount of base drag generated by either reducing the size of the wake region (e.g. vertical splitter plate (Gillieron and Kourta, 2010), flaps (Altaf et al., 2014), base cavities and boat tails (Balkanyi et al., 2002; Verzicco et al., 2002; Yi, 2007; Peterson, 1981; Croll et al., 1996) or by pushing the wake region away from the trailer (e.g. base bleeding (Gillieron and Kourta, 2010; Englar, 2001; Littlewood and Passmore, 2012; Howell et al., 2003)).

Amongst these devices, base bleeding has been proven to be an effective measure to achieve base drag reduction in tractor-trailer vehicles. In general, a minimum of 10% base drag reduction could be achieved using this flow control method (Gillieron and Kourta, 2010; Englar, 2001; Littlewood and Passmore, 2012; Howell et al., 2003). However, the presence of the heavy and bulky components in the jet blowing actuators limits the applicability of this flow control strategy in practice. In addition, although base drag reduction could be effectively achieved using base bleeding, a significant amount of power is consumed by the blowing pumps (Choi et al., 2014). Therefore, the amount of fuel that is saved from the base drag reduction by base bleeding is partially or completely outweighed by the additional fuel consumption for driving the blowing pump which further limits its applicability in actual practical situations (Balkanyi et al., 2002).

Other than base bleeding, the installation of the flaps (Altaf et al., 2014) or boat tails (Balkanyi et al., 2002; Verzicco et al., 2002; Yi, 2007; Peterson, 1981; Croll et al., 1996) could also effectively reduce the base drag by reducing the size of the wake region. Altaf et al. (2014) concluded that about 6–11% of base drag reduction could be achieved by installing trailing flaps with various lengths and shapes on to the rear end of a square back trailer. Similarly, Croll et al. (1996) found that up to 8% of base drag reduction could be achieved by a square back trailer equipped with a boat tail on to its rear end. Surprisingly, Yi, (2007) showed that potentially 42% of base drag reduction could be achieved in a square back trailer equipped with a boat tail with 15° slant angle. Although considerably promising results were obtained from these studies (Altaf et al., 2014; Yi, 2007; Croll et al., 1996), application of the trailing flaps or boat tails in achieving base drag reduction in actual tractor-trailer vehicles is uncommon because of the economical and operational constraints (Altaf et al., 2014; Choi et al., 2014). Moreover, in some countries that have tight regulations on the maximum allowable length of tractor-trailer vehicles, installation of the trailing flap or boat tail on to a trailer means that the trailer itself needs to be shortened so that the vehicle could be legally operated. This further limited the applicability of these devices in actual tractor-trailer vehicles.

Although base bleeding, boat tails and trailer flaps could effectively reduce the base drag generated, their applicability in practice is limited. Therefore, new economical and effective flow control devices that can be legally implemented in tractor-trailer vehicles in daily operation are still require to be developed (Choi et al., 2014). Surprisingly, one of the flow control devices called vortex generators that are commonly used in aircraft wings seems being overlooked in vehicle aerodynamic research. In fact, only a few studies (Leuschen and Cooper, 2006; Patten et al., 2012; Mugnaini, 2015) investigated the effects of vortex generators in achieving flow control in tractor-trailer vehicles. In the experimental study conducted by Leuschen and Cooper, (2006), the authors concluded that the fuel consumption and drag encountered by a full scale tractor-trailer vehicle with vortex generators installed around the rear end of the square back trailer was at least 1% higher than that encountered by the baseline vehicle. In contrast, previous study conducted by National Research Council Canada (Patten et al., 2012) and the numerical study conducted by Mugnaini, (2015) showed that less than 1% of fuel saving could be achieved in a tractor-trailer vehicle with vortex generators installed around the rear end of the trailer.

Although previous research (Leuschen and Cooper, 2006; Patten et al., 2012; Mugnaini, 2015) showed that installing vortex generators around the roof of the trailer could not significantly reduce drag encountered by the tractor-trailer vehicles, these studies did not investigate about how the vortex generators affected the flow pattern downstream of the rear end of a square back trailer. In addition, these studies (Leuschen and Cooper, 2006; Patten et al., 2012; Mugnaini, 2015) only investigated the flow control effects of vortex generators installed immediately upstream of the trailing edge of the trailer. It is unclear whether the flow pattern over a tractor-trailer vehicle could be altered by placing vortex generators to some more upstream locations. In fact, the results shown in (Correale, 2015) using a backward facing step concluded that vortex generators only provided positive effects when they are installed a distance upstream of the front edge of the backward facing step. This is because the function of vortex generators is to generate streamwise vortices that enhance mixing between the boundary layer and the freestream to increase momentum of the flow. This flow mixing process takes time and therefore, in order to obtain positive effects from this flow control method, the vortex generators should be installed a distance upstream of the location where flow separation begins.

The present experimental study aims to investigate the effects of vane-type vortex generators in affecting the flow pattern downstream of the rear end of a square back trailer using a 1:20 scale tractor-trailer model. In addition, the effects of the installation location of the vortex generators in affecting the flow pattern downstream of the rear end of a square back trailer are also investigated. The result obtained could improve our understanding about the effects of vane-type vortex generators in achieving flow control in tractor-trailer vehicles.

2. Experimental setup

2.1. Generic tractor-trailer model

A 1:20 scale generic tractor-trailer model was used in this experimental study. The geometry and dimensions of the model used is