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Reduction of drag in heavy vehicles with two different types of advanced side skirts

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A B S T R A C T

Investigating the aerodynamic reduction of drag in heavy vehicles, such as trucks or tractor-trailers, has considerable significance given the strong influence on related industries. The underbody flow that passes through the underside of heavy vehicles induces considerable drag while interacting with rolling wheels and other structures. Nonetheless, the reduction of drag caused by underbody flow has received less attention than that attributed to upper and forebody flows. Side skirts are common underbody drag-reduction devices that consist of straight panels curtaining the underspace between the front and rear wheels to control the underbody flow in the ground clearance. In this study, we propose two different types of side skirts with flaps or additional inclined inner panels to maximize drag reduction. Effects of these devices are quantitatively evaluated by wind tunnel tests and computational fluid dynamics analysis. In wind tunnel tests with 1/8 scaled-down vehicle models, drag coefficient is reduced by more than 5% for both side skirts. Effects of various physical dimensions or angle variations on drag reduction are determined. Large-eddy simulation (LES) estimated similar drag reduction with reduced vortical activities, loss of streamwise momentum, strength of turbulent kinetic energy and global pressure difference, compared to the case without side skirts.

1. Introduction

The oncoming shortage of fossil fuels have encouraged research on energy saving, especially fuel saving with effective flow control methods. Among these issues, the aerodynamic reduction of drag in heavy vehicles, such as trucks or tractor-trailers, has considerable practical significance owing to the strong influence on the industry and logistics. Many studies have been conducted to reduce the aerodynamic drag in heavy vehicles (Allan, 1981; Ahmed et al., 1985; Hucho and Sovran, 1993; Cooper, 2003). The drag caused by underbody flow passing through the underside of heavy vehicles deserves as much attention as that attributed to upper and forebody flows. The flow passing through the underbody interacts with complicated undercarriage structures, such as rolling tires, axles, frames, and various mechanical devices. Hence, considerable aerodynamic drag is induced by the underbody flow. Wood (2006) reported that the underbody flow of a tractor-trailer contributes approximately 30% to the total aerodynamic drag. Wickern et al. (1997) found that rolling tires account for 25% of the total aerodynamic drag in a passenger car. Drag is significantly increased when tires of multiple truck or tractor-trailer are exposed to large ground clearance. Choi et al. (2014) recently mentioned that large-scale flow structures existing in the relatively high ground clearance of heavy vehicles actively interact with the vehicle underbody, working as a non-negligible source of aerodynamic drag. Therefore, the underbody flow passing through the ground clearance between the vehicle underbody and the ground needs to be controlled effectively to substantially reduce the drag of heavy vehicles. Cooper and Leuschen (2005) demonstrated effective fuel savings of drag-reducing add-on devices including trailer skirts. The resultant drag coefficient was reduced about 9.5% with the attachment of long side skirts at a wind speed of 24.6 m/s and zero yaw angle. Landman et al. (2009) specified practical limitations in achieving drag reduction of a modern tractor-trailer by adopting add-on devices, including side skirts, a full gap seal, and tapered rear panels. Drag coefficient of the tested side skirts was reduced in the range from 15.7% to 19.9%. Ortega

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et al. (2013) conducted full-scale wind tunnel tests to evaluate the effect of flow-control devices including various trailer skirts on the drag reduction of three heavy vehicles. The top performing side skirts reduced wind-averaged drag coefficient by 0.062. Belly box is another type of underspace structure for enclosing wheels. This belly box reduced drag coefficient by 38% (Storms et al., 2004). Leuschen (2013) carried out wind tunnel experiments for tractor-trailer models with rolling wheels to examine the ground effect and influence of spinning wheels. McAuliffe (2015) performed wind-tunnel tests to evaluate the aerodynamic performances of various tractor-trailer vehicle configurations using 30% scale-down model, in which spinning wheels were reproduced to simulate the ground-effect on the underbody flow with side skirts.

Three representative types of underbody drag-reduction devices have been introduced to control the underbody flow of heavy vehicles: undercarriage straight skirts, belly boxes, and undercarriage wedge skirts (Choi et al., 2014). Undercarriage straight skirts are straight panels affixed to the undersides of trucks or tractor-trailers. They are usually known as side skirts. These skirts usually curtain the underspace between the forward and rear wheels of a vehicle. Side skirts not only prevent the intrusion of unexpected objects for safety reasons, but also control the underbody flow in ground clearance to reduce the aerodynamic drag caused by turbulent gap flow.

Although a few products for heavy vehicles are commercially available, an advanced type of side skirt that can maximize the drag-reduction effect needs to be developed. In the present study, two different types of advanced side skirts are proposed. The first side skirt has front or rear flaps bent inward, which are expected to guide the flow around the rolling tires and the edge of skirt panel. For effective flow guidance, the appropriate position and angle of the bent flaps for maximum drag reduction are experimentally investigated. The other side skirt has additional inclined flap panels, which are adopted to smoothen the underbody flow and isolate the complicated flows around the rolling tires or other vehicle underbody structures. The drag-reduction effects of these two side skirts are evaluated quantitatively based on both wind tunnel experiments using a 1/8 scale model and computational fluid dynamics (CFD) analysis.

2. Experimental apparatus and method

2.1. Wind tunnel and drag-coefficient evaluation

Wind tunnel tests are conducted in a closed-return type subsonic wind tunnel with a test section of 1.8 m high, 1.5 m wide, and 4.3 m long. The maximum speed is 75 m/s and the contraction rate is 9:1. Flow uniformity and turbulence intensity are less than 0.25% and 0.2%, respectively. Freestream wind speed is monitored with a micro-manometer (FCO510, Furness Controls) connected to a pitot tube attached at the ceiling of the wind tunnel test section. The pitot probe was located at 1.1 m above the head of the model vehicle and 0.5 m in front of the head.

The aerodynamic forces and moments exerted on the test vehicle model are measured with a seven-component external balance manufactured by the German Aerospace Center (DLR) in Braunschweig. Measurement accuracy is approximately 0.2% of full scale $dX = 1$ N, $dY = 2$ N, and $dZ = 8$ N. The drag force along the wind direction (X axis) is determined by statistically averaging the data acquired from three independent measurements. A vehicle model is affixed to the seven-component external balance through the bottom surface of the wind tunnel test section by connecting four contact points under the fairs of front and rear wheels, as shown in Fig. 1.

The drag coefficient is evaluated using the following equation:

$$C_d = \frac{2F_d}{\rho U_0^2 A}$$

where F_d is the drag force measured along the flow direction; ρ is the fluid density; U_0 is the wind speed; and A is the frontal cross-sectional area of the vehicle model. In this study, only zero yaw angle condition was tested as a first step towards an improved approach. The effects of cross-winds/yaw-angle on the heavy-vehicle aerodynamic performance are also important. Thus, this cross-wind effect should be considered in evaluating the performance of heavy vehicles and their accessories. During the whole experiments, temperature in the wind tunnel test section was maintained at 26.5–28.2 °C and relative humidity of 65–76%.

2.2. Vehicle models

Two different types of heavy vehicles are tested in this study. A vehicle model of a 15-ton truck is manufactured based on the prototype of a commercial truck (Hyundai Trago Xcient) that is 3.3 m high, 2.5 m wide, and 12.0 m long. Another vehicle model of a 40-foot trailer is based on Scania G440, which is 4.0 m high, 2.5 m wide, and 18.0 m long. Both vehicle models are downsized to 1/8 scale to maintain the blockage ratio of the models to the cross-sectional area of the wind tunnel test section at less than 6%. The actual blockage ratios of the 15-ton truck and the 40-foot trailer models are 4.7% and 5.7%, respectively. According to West and Apelt (1982), the effects of model blockage on the measured pressure distribution and drag coefficient are negligible when blockage ratio is less than 6%. Meanwhile, Leuschen and Mébarki (2012) reported that the blockage correction to drag coefficient for a model with blockage ratio less than 4% is on the order of 0.03–0.05. A model with a drag coefficient around 0.6 has a drag coefficient difference of 5–10% range. Therefore, the drag coefficients measured in this study might be affected by the blockage effect of vehicle models. However, the relative improvements of the

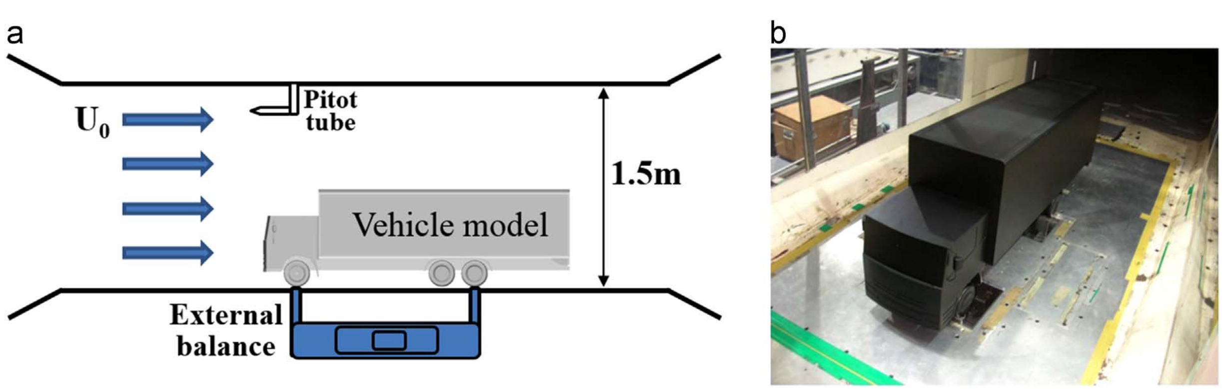

Fig. 1. (a) Schematic and (b) Photograph of the wind tunnel test section and 15-ton truck model.