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An evaluation of factors influencing drag coefficient in double-deck tunnels by CFD simulations using factorial design method

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ABSTRACT

Vehicular drag coefficients in road-tunnel systems are complexly affected by traffic conditions, in terms of vehicle speed and density. Using computational fluid dynamics (CFD)-based factorial design, this study evaluates factors influencing the drag coefficient of a sedan in the Korean double-deck tunnel (KDDT) system, which divides the roadway into upper and lower levels within a single-tube tunnel. The tested factors included blockage ratio, Reynolds number, spacing ratio, and roughness height of the vehicular surface. Results showed that the blockage ratio had the most significant effect in the KDDT system, followed by the spacing ratio and the Reynolds number. A negative interaction effect was observed between the Reynolds number and spacing ratio, thereby indicating that dense traffic scenarios with fast-moving dense vehicles serve to reduce the averaged drag coefficient. In conjunction with the face-centered cube design, a response surface model (RSM) was constructed using a second-order polynomial model. For various tunnel configurations, data predicted by RSM were compared against results obtained from CFD simulations. A good agreement was observed between CFD and RSM with relative errors not exceeding 8.3% in most tunnel configurations investigated. Findings of this study suggest that the RSM can provide accurate estimates of the drag coefficient.

1. Introduction

Exposure to polluted ambient air in urban vehicular tunnels has a strong influence on commuter health (Larsson et al., 2010; Orru et al., 2015; Raaschou-Nielsen et al., 2012; Svartengren et al., 2000). To ensure a safe, healthy, and secure environment, ventilation systems are often designed and operated in such a way to maximize the utilization of natural ventilation induced by vehicle movement. Urban tunnels are becoming longer and geometrically more complex with the recent shift towards underground ring-road networks and double-deck tunnels (Broere, 2016; PIARC, 2016). A double-deck tunnel is an innovative tunnel configuration that divides a roadway into upper and lower levels within a single-tube tunnel, such as the 10-km-long A86 Duplex tunnel in Paris. With continuous increase in tunnel complexities, accurate prediction of vehicle-induced pressures, also known as the piston effect, is required for designing effective and efficient ventilation systems.

The piston effect has been studied under various traffic conditions, such as vehicle types, one- or two-way traffic, and traffic density and composition (Bhautmage and Gokhale, 2016; Kim et al., 2016). Katolický and Jícha (2005) found that an increase in traffic flow had a limiting effect on the piston effect. One of the major parameters influencing the piston effect was the speed of vehicle motion in the experimental studies (Chen et al., 1998; Sike et al., 2015). Indeed, computational fluid dynamics (CFD) simulations and field measurements have shown that the piston effect considerably dilutes air pollutants (Chen et al., 2002; Chung and Chung, 2007) and affects their spatial distribution (Ma et al., 2011; Tong et al., 2014) in free traffic flow. In contrast, an estimation of the piston effect does matter under the traffic jam condition where an excessive concentration of air pollutants occurs (Bari and Naser, 2010; Dong et al., 2017). The piston effect can be more considerable in the tunnel network, where air is discharged and supplied air through small-diameter ramps, and 32.5% of the air required to dilute NO_x is provided even in the congestion condition (Li et al., 2015).

However, although the variation in the drag coefficient is the key factor used to estimate the piston effect, studies on the drag coefficient in the tunnel system are still scarce. Eftekharian et al. (2015) and Cascetta et al. (2016) showed that estimating the piston effect by an one-dimensional mathematical model can result in underestimates or overestimates depending on the drag coefficient data and the traffic condition Jang and Chen (2002) found that the averaged drag coefficient can fall noticeably when the averaged traffic density increases during rush hour. Wang et al. (2011) showed that a decrease in tunnel radius led

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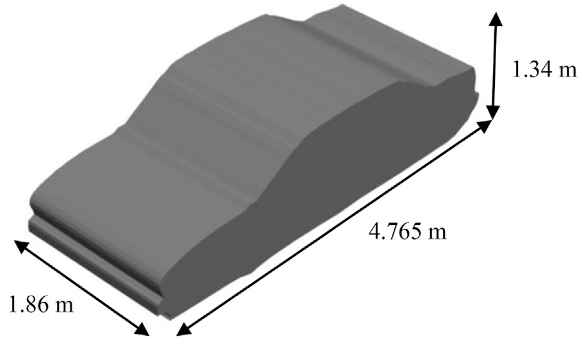

Fig. 1. Sedan-type vehicle model.

to an increase in the effective drag coefficient for a curved tunnel with a radius less than 2000 m. Furthermore, it was found that the effective drag coefficient increased significantly with an increase in vehicle spacing in a curved tunnel (Wang et al., 2014).

In fact, parameters influencing the drag coefficient have been widely investigated with a circular and square model (Saha et al., 2000; West and Apelt, 1982), and the Ahmed model, which is a simplified car model (Ahmed et al., 1984; Guilmineau, 2008). Ahmed et al. (1984) showed that pressure drag accounted for 85% of the total drag and the friction drag constituted the rest. Watkins and Vino (2008) used the two Ahmed models to investigate the influence of vehicle spacing on the drag coefficient, and it was found that the drag coefficient of the combined vehicles at various vehicle spacings differed from that of an isolated single model. The drag coefficient of a single car model was also investigated experimentally and numerically for the effects of the Reynolds number (Strangfeld et al., 2013) and for the influences of blockage ratio (Altinisik et al., 2015). Practically, these factors have an insignificant effect on the drag coefficient in the conventional vehicular tunnel system as the large cross-sectional areas of a tunnels in these systems result in the high Reynolds number regions in the airflow field and the change in blockage ratio is negligible. However, previous studies showed that the drag coefficient of a car model increased significantly at Reynolds numbers less than 2×10^6 and at large blockage ratios. This information implies that these parameters may become more important especially in small-roadway tunnels, such as the double-deck tunnel, the small-diameter branch (or ramp) tunnel, and the tunnels only available for light vehicles.

A literature review showed that drag coefficient can be affected by the vehicle type and spacing, tunnel curvature, Reynolds number, and blockage ratio. However, these factors have not been examined in a double-deck tunnel system. The aim of the present work is to evaluate the impact of selected factors (blockage ratio, Reynolds number, vehicle spacing ratio and roughness height) on drag coefficient in a double-deck tunnel by CFD simulations using the factorial design method. The factorial design is a statistical methodology that enables researchers to examine the effect of each independent factor and factors' interaction effects (Montgomery, 2012). Furthermore, this study suggests a regression model of a response surface model (RSM) for drag coefficient as a function of significant factors, which can be useful for the engineering design of the ventilation system in various double-deck tunnels.

2. Model description

The vehicle model is described in Section 2.1. The same vehicle model was used for all tunnels modeled in this work. Two groups of tunnels were modeled: (i) the double-deck tunnel to evaluate the factors influencing drag coefficient using factorial design and to establish the RSM using additional design points and (ii) various tunnels to verify the RSM. The first and second model configurations are detailed in Section 2.2 and in Section 2.3, respectively. The drainage system including pipe

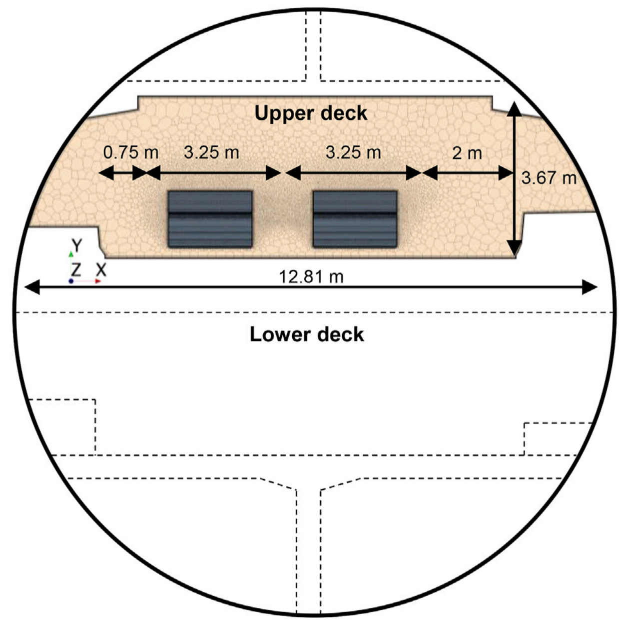

Fig. 2. Geometry of the KDDT with the frontal mesh of the upper deck model.

geometry and lateral slope was neglected for all tunnels modeled in this study.

2.1. Vehicle model

A sedan-type vehicle was modeled as shown in Fig. 1. To match the average frontal area of passenger cars used in Korea, the vehicle was modified from the model studied by Angelis et al. (1996), and scaled up to around 16 times. The maximum length, height and width were 4.765 m, 1.34 m and 1.86 m, respectively, and the ground clearance was 0.238 m.

2.2. Korean Double-Deck Tunnel for full factorial design

The Korean Double-Deck Tunnel (KDDT) is a double-deck tunnel only available for light vehicles that was developed in Seoul and designed as an underground tunnel network connected to another tunnel at interchanges (Kim et al., 2011). Fig. 2 shows a schematic of the two-lane KDDT geometry; the upper deck of the tunnel was modeled as 230 m long straight in this work. The maximum height and width were 3.67 m and 12.81 m, respectively. The right- and left-shoulders were 0.75 m and 2.00 m, respectively, to define the lane-based position of vehicle models.

Modeling of the KDDT system was conducted systematically after choosing the key parameter. As the goal of this study was to investigate

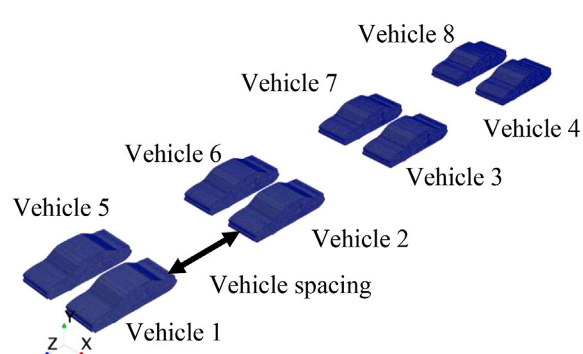

Fig. 3. Isometric mesh view of vehicles and vehicle numbering for the factorial design.