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Impacts of heavy vehicles on inter-vehicle interactions and passenger car equivalents for tunnel traffic

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ABSTRACT

Although traffic parameters for tunnel sections may vary significantly as compared to an open freeway section due to difference in geometric conditions and driving condition, very limited number of research has been done to understand traffic operations on tunnels. This paper aims to fill this gap by evaluating the Passenger Car Equivalent (PCE) factors for heavy vehicles (HV) based on individual vehicle observations from a study section containing the Hampton Roads Bridge Tunnel (HRBT) in Hampton Roads, VA. In addition, the impacts of bottleneck location on the PCE factors under different HV percentages in the traffic stream is also examined in the paper. The analysis revealed new insights into the inter-vehicle interactions for tunnels. It is found that the level of HVs in the traffic stream has a significant influence on passenger car (PC) as well as HV headways. Also, the estimated PCE values for the tunnel section were found to be different than the Highway Capacity Manual (HCM) 2010 suggested PCE values. The location of bottleneck was found to impact the PCE values.

1. Introduction

Underground and underwater tunnels are built to provide mobility solutions in constricted urban environments and in rural areas to navigate around steep grades. Underwater tunnels also enable vehicular traffic to continue without interfering with maritime vessel traffic. Tunnels typically tend to have lower capacity than the road segments feeding them, and consequently are potential bottleneck locations. However, traffic flow characteristics, more specifically the impacts of heavy vehicles (HV), at tunnel facilities have not received as much attention as other highway segments.

There are several past studies on understanding the impacts of tunnel environments on driver behavior. For example, Arias et al. (2008) employed responses from a questionnaire from 485 drivers in Spain to understand the psychosocial factors that impact drivers while driving through tunnels. Their investigation indicated that, drivers perceive tunnels as riskier than open sections and feel more vulnerable to accident occurrence while driving through those. Similar observation was obtained by Yeung and Wong (2014) in his analysis utilizing responses of a survey. The survey indicated that people perceive higher risks while driving in tunnel environment than open road sections. This finding contradicts with the findings of Calvi et al. (2012), who found that drivers experience higher comfort while driving through tunnels compared to open section. The authors employed tunnel scenario in a driving simulator and compared the driving parameters with open section scenario. They measured the driving comfort level by measuring the correction of vehicle trajectory made by the driver. According to the authors, if the driver corrects the vehicle's trajectory more than what road curvature imposes, the road is not self-explaining and is unsafe. Drivers were found to be have higher comfort level driving in tunnels compared to open sections. The authors stated that, this might be due to the fact that, tunnel walls provide a guidance for driving trajectory resulting driver not needing to correct their trajectories, which in turn, result into higher comfort during driving. Their experiment indicated that the drivers maintain lower speed in tunnels compared to open sections and maintain longer lateral distance from tunnel wall.

Some studies also focused on how tunnel features impacts drivers. Examining driving data collected from simulated tunnel environments, Manser and Hancock (2007) found that the pattern and texture on tunnel wall impact driving speed. Analyzing driving simulator experiments, Kircher and Ahlstrom (2012) observed that tunnel design (tunnel wall color and lighting) influence driving behavior and impacts drivers' visual attention. However, these findings contradicts with Törnros (2000), who examined driving behavior in simulated tunnel environment and found that tunnel wall pattern do not significantly affect driving behavior. On the other hand, his study agreed with the

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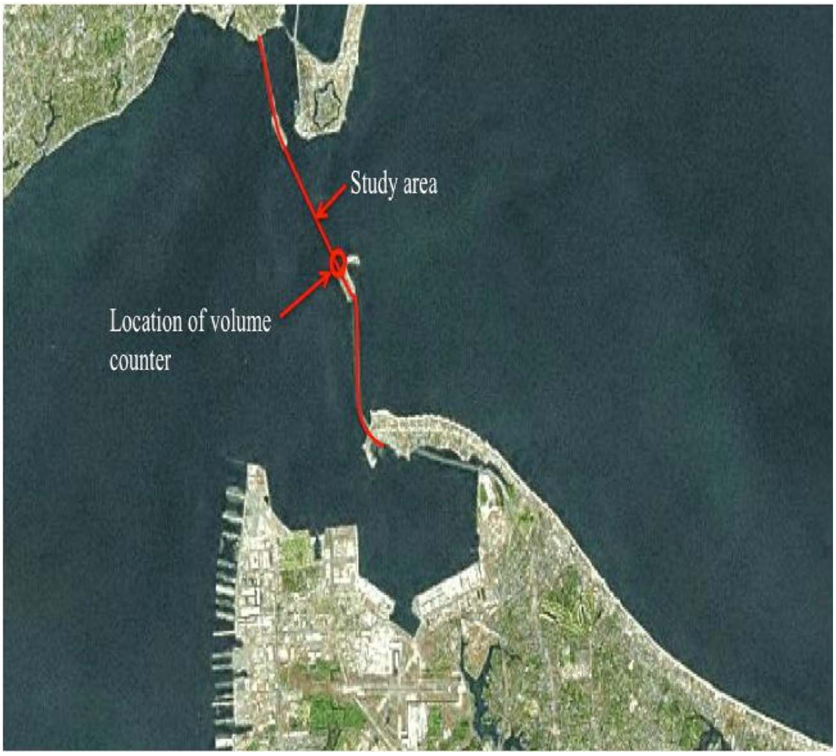

Fig. 1. Location of volume counter on the EB direction of HRBT.

finding of Calvi et al. (2012) that drivers maintain lower speed in tunnels than in open sections.

Few studies have been devoted to understand the impact of tunnel environment on inter-vehicle interactions. One such study is done by Yeung et al. (2013), who investigated the factors that affects inter-vehicle interactions inside tunnel versus open sections using car following headway data collected from a tunnel expressways and an open expressway in Singapore. Their study indicated that, while speed and lane significantly affect headway while driving through both a tunnel and an open section, significant effect of leading vehicle type on headway is found only for tunnel. Both the time and space headways were found to be larger for tunnels than open sections.

Most of these studies focused on the impacts of tunnel environment on driver behavior. The impact of HV on tunnel traffic operations is an area that has received limited attention. The significant impact of HV on the traffic operations has been identified since the first edition of the highway capacity manual (HCM) Manual (2010). Passenger car equivalent factor (PCE) is the most frequently used variable to incorporate their impact in roadway capacity calculation. However, HCM does not differentiate PCE values for tunnels, rather, the suggested PCE values are for both open and tunneled freeway sections. Very few studies have been found to focus on estimating PCE values exclusively for tunnels. For example, Mahdy (2012) estimated PCE for HV using traffic data collected from four two-way two-lane Austrian tunnels during the period of maximum expected traffic demand. Analyzing the estimated PCE values, the author suggested that the PCE value for tunnels at all percentage of HV at traffic stream should be lower than 2.0. However, this study did not suggest any definitive PCE value for tunnels. Lin et al. (2009) analyzed traffic data collected from a 12.9 km long Shan-shea tunnel in Taiwan and suggested that rather than HCM suggested constant PCE value of 1.5 for level freeway section, PCE for tunnels with level sections should vary within a range of 1.0 to 1.5 based on traffic density.

The PCE values in HCM 2010 rely on extensive simulation runs and calibrated based on steady-flow traffic conditions on open freeways, whereas the effect of HV on traffic flow can reasonably be expected to vary with traffic conditions and tunnel environment. The study by Ahmed et al. (2013) signified the importance of considering congested traffic conditions for PCE calculation. Using a field dataset collected from level freeway section during congested and forced-flow conditions, Ahmed et al. (2013) estimated PCE values. The PCE value, under congested conditions and more than 3% HV presence, was found to be higher than the HCM 2010-recommended value of 1.5 for level freeway sections. Thus it showed the necessity to consider traffic conditions for PCE calculation. As HCM does not consider congestion conditions for PCE calculation, whether the location of congestion (bottleneck location) has any effect on PCE value for a particular road section is also overlooked. In addition, as mentioned above, there is a lack of understanding of how HV impact traffic operations specifically at tunnels during congested conditions. Thus, this paper significantly complements the existing literature by 1) examining PCE values for tunnels during congested condition, 2) examining how the PCE values for tunnels changes based on the bottleneck location and 3) analyzing the impact of HV on flow rate and illustrating potential improvements of tunnel capacity.

The remainder of this paper is organized as follows. In the next Section, a description of the data collection system and collected traffic data is provided. An overview of the chosen methodology and the main results of the analysis as well as the discussion are provided in the subsequent two sections. Finally, conclusions are presented in the final section.

2. Data description

The current study employs field data collected in the eastbound (EB) direction of Hampton Roads Bridge Tunnel (HRBT) located near Hampton, Virginia during 3.5 months time period from June 20, 2014 and September 30, 2014. The HRBT is a 3.5-mile, four-lane highway segment (two lanes in each direction) crossing the mouth of the James River and serves as a critical link for regional mobility. The underwater tunnels are about 1.4 miles long and allow for vehicular traffic to continue without interfering with shipping traffic. The tunnel has 4% downgraded section of 0.58 mile after the tunnel entrance, then 0.5% upgraded section for 0.6 mile and followed by 4% upgraded section for