Accident Analysis and Prevention 45 (2012) 195–203

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

A driving simulator study of driver performance on deceleration lanes

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ARTICLE INFO

Article history:
Received 6 May 2010
Received in revised form 31 May 2011
Accepted 18 June 2011

Keywords:
Driving simulator
Deceleration lane
Driving performance
Human factor
Road safety

ABSTRACT

Deceleration lanes are important because they help drivers transition from high-speed lanes to low-speed ramps. Although they are designed to allow vehicles to depart the freeway safely and efficiently, many studies report high accident rates on exit ramps with the highest percentage of crashes taking place in deceleration lanes.

This paper describes the results of a driving simulator study that focused on driving performance while approaching a divergence area and decelerating during the exiting maneuver. Three different traffic scenarios were simulated to analyze the influence of traffic volume on driving performance. Thirty drivers drove in the simulator in these scenarios while data on their lateral position, speed and deceleration were collected. Our results indicate there are considerable differences between the main assumptions of models generally used to design deceleration lanes and actual driving performance. In particular, diverging drivers begin to decelerate before arriving at the deceleration lane, causing interference with the main flow. Moreover, speeds recorded at the end of the deceleration lane exceed those for which the ramp's curves are designed; this creates risky driving conditions that could explain the high crash rates found in studies of exit ramps. Finally, statistical analyses demonstrate significant influences of traffic volume on some aspects of exiting drivers' performance: lower traffic volume results in elevated exiting speed and deceleration, and diverging drivers begin to decelerate earlier along the main lane when traffic volume is low. However, speeds at the end of the deceleration lane and the site of lane changing are not significantly influenced by traffic volume.

1. Introduction

Freeway deceleration lanes and exit ramps are designed to allow vehicles to depart the freeway safely and efficiently. They have long been required in highway interchanges, and planning authorities have employed them when designing new high-speed intersections or when upgrading existing intersections. At both interchanges and intersections, deceleration lanes are built to improve traffic flow conditions by reducing interruptions, increasing capacity and improving safety. However, safety problems can be expected if drivers are forced to reduce speed in the main traffic lanes or if they are forced to decelerate too quickly. This interference may result in traffic conflicts that increase the probability of crash occurrence as demonstrated by the high accident rates reported in previous investigations of freeway exit ramp safety (Harwood and Graham, 1983; Oppenlander and Dawson, 1970; Twomey et al., 1992). Although automotive technology and vehicle design have evolved significantly, deceleration lane safety problems have not been adequately addressed, as demonstrated by recent crash analyses (McCartt et al., 2004; Chen et al., 2009).

Thus, the identification of factors contributing to crashes at freeway divergence areas is obviously a crucial objective for improving the safety of freeway off ramps. According to several crash prediction models proposed over the years, these factors may include the following: the geometric characteristics of the freeway, particularly the deceleration lane; the environmental and traffic conditions; the features of the vehicle; and, of course, the driver's behavior during the exiting maneuver. These models are calibrated and validated by onsite observations, and they relate crash frequency at the ramp to different explanatory variables such as traffic flow and ramp geometry. Nevertheless, there are no guidelines or research results that provide designers with clear and updated criteria for appropriate deceleration lane geometries that are based on real driving behavior and the influence that design variables have on driving behavior. Considering the small body of literature in this area of road design, further research is required to gain a deeper comprehension of the relationship between driving performance and deceleration lane features. Particular attention should be paid to traffic flow because it is a key factor in road safety (e.g., Bauer and Harwood, 1997; Khorashadi, 1998; Chen et al., 2009).

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doi:10.1016/j.aap.2011.06.010

The main objective of this study is to evaluate the driving performance in freeway deceleration lanes using a driving simulator. The present study is a preliminary analysis using the driving simulator to observe drivers performance approaching a divergence area and using the deceleration lane. In addition, we evaluated the extent to which drivers' performances are affected by varying traffic density during the freeway exiting maneuver.

To reach the main objectives of the present study, the lateral positions, speeds and decelerations of the exiting maneuvers of thirty drivers were analyzed and compared across three different traffic configurations. Driving simulations were implemented in the STI driving simulator system at the laboratory of the Inter-university Research Centre of Road Safety (CRISS). Our findings demonstrate the reliability of simulators in the investigation of driving performance in deceleration lanes. Furthermore, they provide insight for future research aimed at the practical application of traffic engineering, including the development of guidelines based on effective driving performance, which remain necessary for the design of safer and more efficient deceleration lanes.

2. Literature review

Over the years, many researchers have studied vehicle operating characteristics in an attempt to establish the safest and most efficient design criteria for the improved efficiency of freeway deceleration lanes and exit ramps. However, as noted by Koepke (1993), many of the current design criteria for interchanges (e.g., AASHTO, 2004; SETRA, 1998; TAC, 1999; Ministerio de fomento, 2001; MIT, 2006; VSS, 1998) are based on studies that are 50–60 years old with geometric requirements that were designed according to kinematic and dynamic equations that neglected driver behavior.

Since the 1950s, a number of studies have identified interchanges as the most frequent site of freeway collisions (Conklin, 1959; Oppenlander and Dawson, 1970; Twomey et al., 1992). Specifically, the greatest percentage of accidents at interchanges are observed in the deceleration lanes as shown by Lundy (1967) and, more recently, by McCartt et al. (2004) and Lord and Bonneson (2005). Notwithstanding the great efforts expended on the improvement of vehicles, their control technologies, road materials and design standards, the safety problems of deceleration lanes have by no means been solved.

A wealth of research into accident prediction modeling has been developed with the goal of identifying the most critical factors affecting the safety of deceleration lanes (Batenhorst and Gerken, 2000; Janson et al., 1998; Vogt and Bared, 1998). The most relevant contribution to crash events at interchanges is traffic (Cirillo et al., 1969). Similar results presented by Bauer and Harwood (1997) have demonstrated that most of the variability can be explained by the ramp and main lane traffic flows, the area type (e.g., rural or urban), the ramp configuration and the combined length of the ramp and speed-change lane. Similarly, Khorashadi (1998) confirmed that, compared to traffic, geometric design is not a determining cause of collisions. A recent study of Chen et al. (2009) analyzed the safety performance of deceleration lanes of a freeway in Florida and again confirmed the significant influence of traffic on the safety of freeway divergence areas.

Given these and similar results, the present paper investigates the effects of traffic flow on driving performance during the exiting maneuver. In this first phase of research, the influence of geometric standards (e.g., length of the deceleration lane, radius of the exit curve) is omitted. There are few studies in the literature that investigate driving performance in deceleration lanes through site observations, and most of this research is rather dated. Fukutome and Moskowitz (1963) investigated the behavior of drivers approaching deceleration lanes in terms of speed. They found that drivers continue to decelerate on the ramp that follows the deceleration lane, and exiting drivers adopt speeds significantly lower than the speed of through traffic at the beginning of the deceleration lane. Further, this difference in speed is reflected backward and interferes with through traffic on the freeway. Similar results were obtained by Livneh et al. (1988). These authors also found significant differences between their observations and the AASHTO model for the determination of deceleration lane length; specifically, actual deceleration values are lower than the values suggested by AASHTO. Recently, El-Basha et al. (2007) demonstrated that divergence speed is highly dependent on the freeway's mean speed and that the deceleration lengths, the diverging traffic volume and the deceleration rates depend on the freeway's geometry and traffic flow. Moreover, the authors found that the speed differential between vehicles continuing on the main lane and those diverging is influenced by the deceleration length, the traffic flow upstream and the traffic composition.

In any case, it is difficult, if not impossible, to use only site observations to achieve in-depth investigations of human factors. Emerging technologies make it possible to evaluate the interactions between the driver, the vehicle and the road environment through an interdisciplinary approach based on driving simulations. Driving simulators enable one to study the variability of driver performance under different conditions (e.g., geometries and traffic flows) and offer a promising perspective for road safety design and management. Although there are numerous applications that demonstrate the potential of interactive driving simulations for road safety investigations and evaluations, there are few simulation studies in the literature focused on driver behavior in deceleration lanes. Among the studies that do exist, two (Bella et al., 2007; Yan et al., 2008) validate the use of driving simulators for speed and trajectory analyses and encourage the incorporation of these analyses in the design of deceleration lanes.

Starting from the aforementioned results, we have investigated drivers' performance while approaching a divergence area and during the exiting maneuver. More specifically, this study represents a first attempt to answer the following questions: (1) Considering that most studies demonstrate that exiting drivers decelerate before the deceleration lane, is it possible to understand where drivers begin their deceleration? (2) Is driving performance during the exiting maneuver influenced by traffic volume on the freeway? (3) Are driving simulators able to provide significant information about driving performance in deceleration lanes? (4) Are the results of this simulator study consistent with the main assumptions of technical regulations, and are they consistent with previous results based on site observations?

3. The experiment

3.1. Apparatus

Driving simulations were performed using the STI driving simulator system at the laboratory of the Inter-university Research Centre of Road Safety (CRISS, Fig. 1).

The full apparatus has been validated extensively (Benedetto et al., 2004; Bella, 2005, 2008). The hardware consists of four networked computers and three hardware interfaces (the steering systems, the pedals and the manual gearshift). The road scenario is projected onto three big screens providing a 135° field of view. The resolution of the visual scene is 1024×768 pixels with a refresh rate of 30–60 Hz depending on scene complexity and the traveling conditions of the vehicle. The simulator allows the recording of the intensity of the actions of the driver on the brake, the accelerator