Accident Analysis and Prevention 104 (2017) 46–57

Contents lists available at ScienceDirect

Accident Analysis and Prevention

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

A simulator-based analysis of engineering treatments for right-hook bicycle crashes at signalized intersections

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ARTICLE INFO

Keywords:
Bicycle safety
Driver behavior
Driving simulator
Intersection design
Engineering treatment
Right-hook crash

ABSTRACT

A right-hook crash is a crash between a right-turning motor vehicle and an adjacent through-moving bicycle. At signalized intersections, these crashes can occur during any portion of the green interval when conflicting bicycles and vehicles are moving concurrently. The objective of this research was to evaluate the effectiveness of four types of engineering countermeasures – regulatory signage, intersection pavement marking, smaller curb radius, and protected intersection design – at modifying driver behaviors that are known contributing factors in these crashes. This research focused on right-hook crashes that occur during the latter stage of the circular green indication at signalized intersections with a shared right-turn and through lane. Changes in driver performance in response to treatments were measured in a high-fidelity driving simulator. Twenty-eight participants each completed 22 right-turn maneuvers. A partially counterbalanced experimental design exposed drivers to critical scenarios, which had been determined in a previous experiment. For each turn, driver performance measures, including visual attention, crash avoidance, and potential crash severity, were collected. A total of 75 incidents (47 near-collisions and 28 collisions) were observed during the 616 right turns. All treatments had some positive effect on measured driver performance with respect to the right-turn vehicle conflicts. Further work is required to map the magnitude of these changes in driver performance to crash-based outcomes.

1. Introduction

Cycling is viewed as an integral component of the multimodal transportation system in the long-range plans of many cities in the United States. As cities have invested in nonmotorized transportation infrastructure to realize this goal, bicycling has become a meaningful alternative mode of transportation for commuting to activities such as school, work, shopping, and recreation (Pucher et al., 1999, 2011; Pucher and Buehler, 2006). However, even with these investments, safety remains an important issue. In 2011 alone, there were 677 bicyclist fatalities and 48,000 bicyclist injuries in the United States (NHTSA, 2013). One of the more prevalent bicycle-motor vehicle crash types at intersections is the *right-hook crash*, a collision that occurs between a right-turning vehicle and an adjacent through-moving cyclist. Between 2007 and 2011, right-hook crashes represented over 500 of reported crashes involving cyclists and 59% of all bicycle-motor vehicle crashes at signalized intersections in Oregon (Hurwitz et al., 2015). Many more crashes or near misses are not reported. Therefore, this type of crash is a safety concern for bicyclists.

There are some published insights into the causal factors behind these crashes. The Institute of Transportation Engineers (ITE) reported that in nearly 70% of bicyclist-motor vehicle collisions at intersections, the motorist reported that "they did not see the bicyclist before the collision" (ITE, 2004). In an earlier phase of this research, Hurwitz et al. (2015) reported that failures in the situational awareness of the driver significantly contributed to the occurrence of right-hook crashes. Specifically, the driver failed to look for the bicyclist, looked but did not see the bicyclist, or looked and saw the bicyclist but failed to predict their behavior accurately. Treatments that improve conspicuity of the bicyclist within the intersection may help to reduce the frequency of right-hook crashes.

The objective of this research was to determine the effectiveness of four types of engineering countermeasures (regulatory signage, intersection pavement marking, smaller curb radius, and protected intersection design) at modifying driver behaviors (driver visual attention, crash avoidance, and potential crash severity) that are known to contribute to right-hook crashes. Participants completed a series of right-turn maneuvers in a high-fidelity, motion-based driving simulator. A partially counterbalanced experimental design exposed drivers to critical scenarios. For each turn, driver performance measures were

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http://dx.doi.org/10.1016/j.aap.2017.04.021
Received 27 November 2016; Received in revised form 25 April 2017; Accepted 27 April 2017

collected and analyzed to determine the effects of treatments on the occurrence of right-turn vehicle conflicts.

We previously identified the highest situational risk factors for drivers and cyclists, including the most common intersection geometries for right-hook crashes occurring in the state of Oregon (Hurwitz et al., 2015). In this paper, we analyzed driving simulator experiments under these critical conditions. We evaluated driver behaviors in collisions that occur during the latter green phase at signalized intersections with a bicycle lane and a shared right-turn and through lane. The term "latter green phase" refers to the second portion of the green signal phase, after the initial vehicle queue has cleared and the green signal indication is still displayed.

2. Literature review

There are many different types of engineering treatments related to bicycle safety, but very few have been identified or evaluated specifically for the right-hook crash scenario. This section reviews the known effects of pavement marking, signage, and geometric design features as they relate to bicycle-motor vehicle crashes.

2.1. Signage

The only right-hook crash signage approved by the U.S. *Manual on Uniform Traffic Control Devices* (MUTCD) is the R4-4 "Begin Right Turn Lane, Yield to Bikes" sign, which is meant to inform roadway users of the merging maneuver at signalized intersections with an exclusive right-turn lane and a bike lane (FHWA, 2009). The Oregon Department of Transportation (ODOT, 2013) suggests an additional option, the ODOT OR10-15b "Turning Vehicles Yield to Bikes" sign, applicable to the mitigation of right-hook crashes occurring at signalized intersections with a shared right-turn and through lane.

Right-hook crash signage is often used in conjunction with another right-hook crash treatment, such as colored pavement markings. The National Association of City Transportation Officials (NACTO) *Urban Bikeway Design Guide* states that "A 'Yield to Bikes' sign should be used at intersections or driveway crossings (with colored pavement marking) to reinforce that bicyclists have the right-of-way at colored bike lane areas". This guide provides three alternative designs that are variations of existing MUTCD-approved signage (NACTO, 2011). The City of Portland, OR (2012) found that the additional "Yield to Bikes" sign was a critical aspect of the effectiveness of blue pavement marking (intended to help roadway users identify the potential conflict area), as "substantially more motorists who noticed the sign correctly identified the meaning of the blue area". The authors suggested that the supplementary sign is even more important than the blue pavement markings, due to its clarification of the regulatory message and the prioritized right-of-way. In another study by Brady et al. (2011), however, the signage did not appear to alleviate driver confusion over the appropriate yielding behavior. The researchers reported a reduction in driver yielding after installation of a similar sign. They concluded that driver confusion would likely occur over whether to cross the green-colored bicycle lane or to cross after the colored section.

2.2. Pavement markings

Most guidance and research on pavement marking designs in the context of right-hook crashes relate to treatments for signalized intersections with exclusive right-turn lanes, such as intersection crossing markings (e.g., dotted bike lane extensions, elephants' feet markings, bicycle symbols, sharrow symbols, or colored pavement). Pavement markings may raise awareness of intersection conflict areas for bicyclists and motorists and may positively influence driver yielding behaviors (NACTO, 2011; Sundstrom and Nabors, 2014; Department for Transport, 2008; PBIC, 2002). Furthermore, U.S. guidance documents reinforce the optional use of dotted bicycle lane lines with or without colored pavement to designate a bicycle lane across an intersection (NACTO, 2011; FHWA, 2009, 2011; ODOT, 2011).

Although design guidance exists, there is little experimental research on the effectiveness of these treatments. Several before-and-after studies evaluated the effectiveness of colored pavement treatments for conflict areas. However, very few studies have focused specifically on impacts to driver behavior in an experimental manner. Most before-and-after studies generally found that colored pavement markings positively influenced driver yielding behavior or crash rates (City of Portland, 2012; Hunter et al., 2008; Singh et al., 2011). However, one study in Austin, TX found that motorists were less likely to yield with these markings (Brady et al., 2011). Researchers of that study hypothesized that the reduction in yielding was due to driver confusion over whether they should cross within or after the green-colored weaving area. They concluded that this confusion could be alleviated with an educational campaign. An experimental study at the University of Calgary evaluated four different bike lane crossing treatments at channelized right-turn conflict areas, using a full-cab driving simulator and an Applied Science Laboratories (ASL) eye-tracking system (Caird et al., 2008). Although results for two of the four treatments were not presented, the authors showed that a blue skipped pavement marking treatment resulted in a higher yielding rate (90%) than a sharrow symbol treatment (77%).

2.3. Geometric design

Effects of geometric elements on right-hook bicycle crashes are not well documented. Reduction of the curb radius is a key element that has the potential to improve bicyclist safety at intersections by slowing down turning vehicles. This reduced velocity lessens the severity of collisions if they do occur and provides more time for the motorist or bicyclist to perform an avoidance maneuver. Multiple guidance sources recommend the use of smaller corner radii to improve pedestrian safety in a similar manner, but do not provide bicycle-specific curb radius design guidance (ODOT, 2011; NACTO, 2013).

Another, relatively novel, geometric design treatment for bicycle safety is the "protected" or Dutch-style intersection. Protected intersections incorporate a specific combination of geometric design and traffic engineering features to increase bicyclist safety and visibility. Literature regarding this design treatment largely comes from Europe, where these intersections are more common. For example, Goeverden and Godefrooij summarized before-and-after case studies of bicycle-related infrastructure interventions in the Netherlands. The common theme of these case studies was the redesign of intersections with respect to geometric design elements that are similar to those of protected intersections. Although these changes led to significant improvements in the perceived safety of the facilities, this effect "was not fully reflected by the observed decrease in accidents and casualties". However, because the Dutch bicycle infrastructure is already fairly well integrated into the Dutch transportation system, other countries may see "different (probably larger) impacts" (Goeverden and Godefrooij, 2011). At present, there is little U.S. guidance for protected intersections, although this situation is likely to change. The *Separated Bike Lane Planning & Design Guide*, recently released by the Massachusetts Department of Transportation (MassDOT, 2015), prominently features and describes protected intersections and associated best practices.

3. Methodology

To address the gaps in knowledge identified in the literature review and to mitigate the causal factors for right-hook crashes that were identified in a previous experiment (Hurwitz et al., 2015), we designed a second experiment to test various design treatments and controls in a simulated driving environment under specific environmental conditions. We examined and analyzed motorist behavior, including the