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Safety impacts of bicycle infrastructure: A critical review

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ABSTRACT

Problem and method: This paper takes a critical look at the present state of bicycle infrastructure treatment safety research, highlighting data needs. Safety literature relating to 22 bicycle treatments is examined, including findings, study methodologies, and data sources used in the studies. Some preliminary conclusions related to research efficacy are drawn from the available data and findings in the research. *Results and discussion:* While the current body of bicycle safety literature points toward some defensible conclusions regarding the safety and effectiveness of certain bicycle treatments, such as bike lanes and removal of on-street parking, the vast majority treatments are still in need of rigorous research. Fundamental questions arise regarding appropriate exposure measures, crash measures, and crash data sources. *Practical applications:* This research will aid transportation departments with regard to decisions about bicycle infrastructure and guide future research efforts toward understanding safety impacts of bicycle infrastructure.

1. Introduction and background

Increased use of active transportation can make direct and indirect contributions toward addressing both the health concerns arising from sedentary lifestyles and other societal transportation issues including congestion, pollution, and equity problems (Barnes & Schlossberg, 2013; MacDonald, 2007; Pucher & Renne, 2003; Saelensminde, 2004; WHO, 2002). While 10.9% of trips in the United States were made by walking or by bicycling during 2009 (PBIC, 2010), those modes made up 14% of all traffic fatalities nationally during the same year (NHTSA, 2014a, 2014b). The data suggest an over-representation of walking and biking in crash fatalities; however, quantifying the risk associated with walking and cycling is difficult (PBIC, 2014).

For biking to be a viable, healthy mode, travelers choosing the mode should be able to do so without either the fear or reality of excessive danger associated with their choice. Safety for non-motorized road users is the responsibility of multiple parties, including the user and other travelers, but also transportation planners and engineers through facility design (AASHTO, 2010; Metroplan, 2010). Therefore, this paper focuses on the safety research used to discern appropriate designs and countermeasures that enhance bicycle safety.

Local governments and transportation agencies are constantly making decisions about how best to achieve their goals given the limited resources available to them. When faced with the decision of how to design or re-design a facility to improve bicycle safety, knowing the expected safety performance of the alternatives can help decision-makers allocate resources cost-effectively. With greater information about the range of effects of a safety treatment, those effects can be calibrated to the local situation and the expected safety performance can be estimated.

1.1. Highway Safety Manual

In the United States, the predominant guide for assessing the effects of safety treatments is the Highway Safety Manual (HSM). The HSM employs a simple method for assessing roadway safety treatment effectiveness based on data inputs and analytical study (AASHTO, 2010). In the highway safety method, safety performance is a function of a base rate multiplied by a series of crash modification factors (CMFs), such that:

$$\text{Safety Performance} = (\text{Base Rate}) \times (\text{CMF})_1 \times (\text{CMF})_2 \times \ldots \times (\text{CMF})_n. \quad (1)$$

The base rate term represents the expected number of crashes in the absence of special safety treatments, encompassing both risk and exposure. Each CMF term in Eq. (1) is a multiplier that modifies the number of expected crashes from the base rate according to the expected safety effectiveness of a specific treatment. These CMFs are normally estimated by observing changes in crash rates in the presence/absence of a particular treatment using either longitudinal (before/after) or cross-sectional (treatment/control) type studies. These studies must, however, take into account a variety of confounding effects including, but not limited to, temporal regression-to-the-mean or changes in base rates over time. CMFs less than 1 indicate an

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expected safety improvement (crash decrease); CMFs greater than 1 indicate an expected safety decrease (increase in crashes). Exposure may be expressed in a variety of ways using a variety of data, including number of trips, vehicle miles traveled (VMT), hours of exposure, number of roads crossed, number of left turns made, etc. Risk is expressed as the probability of a crash occurring per unit of travel (i.e., distance, time, trips, and turns) under specific conditions, presuming that the unit of travel under the set of conditions represents exposure.

To develop or use crash modification factors, the HSM requires a significant amount of data for implementation of its quantitative approach to safety. These data needs can be classified into three main categories (AASHTO, 2010): crash data, exposure data, and roadway characteristics data. The HSM requires several specific attributes for crash data: year, location, type, severity level, relationship to intersection, and distance from intersection. For vehicular crashes, exposure data requires Average Annual Daily Traffic (AADT) data, as well as minor and major street AADT for safety evaluations occurring at intersections. The roadway characteristic data requirements are detailed, and the needs differ depending on facility type. All three data categories and their attributes need to be customized for pedestrian and bicycle safety research.

Motor-vehicle traffic volumes and crash data are collected regularly by transportation agencies. The sample sizes necessary for developing and using CMFs for automobile-related safety interventions are often available, given the large traffic volumes, significant number of vehicle crashes, crash occurrences, and known facility design features. However, as discussed throughout this paper, cycle–vehicle collisions are fairly rare events compared to vehicle–vehicle crashes, few data sources are available for bicycle traffic volumes, and cyclist–vehicle exposure data (combined volumes by mode and relative movement data) are generally not readily available. These issues make the development of CMFs for vehicle–bicycle safety treatments difficult.

1.2. Principles behind non-motorized roadway safety treatments

While motor vehicles are not the only threat to bicyclist safety (Aultman-Hall & Kaltenecker, 1999; Moritz, 1997, 1998; Teschke et al., 2012), collisions with motor vehicles are the main cause of thousands of non-motorized road users' deaths each year, as well as many more injuries (NHTSA, 2014a, 2014b). For this reason, most measures aimed at improving the safety of non-motorized users focus on mitigating the dangers posed by conflicts with motorized traffic.

For a safety treatment to reduce number or severity of collisions between a motor vehicle and a non-motorized road user, the treatment generally needs to address one or more of the following objectives (expanded from Retting, Ferguson, & McCartt, 2003):

- Increasing the separation of bicycles and motor vehicles in time and space
- Increasing the visibility and conspicuity of non-motorized users
- Improving lines of sight between the modes
- Reducing the number of interactions between modes (e.g., number of driveways)
- Reducing motor-vehicle speeds

Maintaining a physical separation between bicycles and motor vehicles (space and/or time) will prevent the two modes from colliding. Separated bikeways and bicycle signal phases are employed to maintain a separation between modes in space and time. Increased separation in time and space at any given time will also increase the reaction time available to both modes to avoid an impending collision. Hence, bicycle lanes enhance this separation. Increasing bicycle and vehicle visibility gives motorists and cyclists more time to react and avoid a collision. For example, bike boxes that allow cyclists to proceed to the head of a queue at an intersection are designed to increase cyclists' visibility at key locations. Reducing motor-vehicle speeds increases motorists' and cyclists' reaction time, reducing the frequency of collisions. When collisions do occur, the reduced speed differential between vehicle and cyclist reduces the severity of the collisions and probability of severe injury and death (Leaf & Preusser, 1999). A variety of traffic calming design measures, use of bicycle boulevards, and construction of roundabouts can decrease motor-vehicle speeds (Brude & Larsson, 2000).

Given the arguments outlined above, the goal of roadway safety design for non-motorized users would seem to be to maximize the criteria discussed above. In reality, there are complex interactions between the criteria, and roadway designers often have to seek compromises. For example, increasing visual complexity in the roadway environment has been shown to decrease vehicle speeds. Shared space schemes employed in Auckland, New Zealand, actually are designed to minimize the separation between various road users in an effort to reduce motor-vehicle speeds by adding complexity to the environment (Karndacharuk, Wilson, & Dunn, 2013). Hence, increased separation may increase vehicle speeds and collision severity.

Physically separating bicyclists from motorized traffic by diverting them to multi-use trails may create a visibility issue at locations where the trail crosses roads. The separation of motor vehicles and bicyclists can also be problematic at major intersections when bicycles are often merged with vehicles to cross busy streets. Diverting cyclist traffic to a multi-use trail that is shared with pedestrians, pets, and other trail users may increase a cyclist's risk of falling or being involved in a collision with another trail user (Aultman-Hall & Kaltenecker, 1999). Separation may also be inappropriate from a transportation planning perspective when access to specific activities and surrounding destinations is the main goal of bicycle use (e.g., commuting to work, shopping) because the separation typically limits accessibility by the bicycle mode. It is difficult to balance the integration/separation of cyclist and vehicle traffic, while ensuring that the system provides positive mobility benefits to all users and also ensuring comparative safety for all system users.

1.3. Developing crash modification factors

Over the past several decades, many studies have been conducted to evaluate the potential safety impacts of bicycle treatments. However, bicycle safety research conducted to date has been insufficient to support the development of crash modification factors for treatment installation because the research does not satisfy the data requirements outlined in the Highway Safety Manual (AASHTO, 2010). As noted earlier, cycle–vehicle collisions are fairly rare, extensive cycle activity monitoring is not undertaken, and solid cyclist–vehicle exposure data are generally not readily available. This paper reviews a body of literature (i.e., technical reports, journal papers, and conference papers) related to bicycle safety treatments and the reported potential effectiveness. The research team reviewed the treatment details, research methods, data sources, findings, and research conclusions presented in each of these papers. This research seeks to identify common inferences in the literature related to treatment effectiveness, and identify gaps in existing bicycle safety data and methods that currently prevent the generation of statistically significant crash modification factors. Finally, this research identifies the kinds of data that will be necessary for generating bicycle intervention crash modification factors using the HSM method and recommends how data issues could be addressed in the future.

1.4. State of bicycle safety research

In the absence of base crash rate data necessary for the HSM method, many researchers and transportation agencies have developed other research methods to estimate safety effects of bicycle and pedestrian treatments. Some studies employ simple before–after methodology, possibly incorporating a comparison group to control for area-wide changes in risk or exposure. Such studies do not incorporate data on exposure and crash risk for specific treatment locations and may

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