A Review of Literature:

Intersection Treatments to Improve Bicycle Access and Safety

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The Economic Benefits of Bicycling

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INTERSECTION TREATMENTS
TO IMPROVE BICYCLE ACCESS AND SAFETY

INTRODUCTION

Transportation research and design in the U.S. has traditionally focused on the safe and efficient movement of motorized vehicles, with less emphasis on non-motorized travel and bicycle transportation. Innovative research and design of bicycle facilities has occurred primarily in Europe where cycling has historically been a more prominent and accepted mode of travel.

Bicycling for transportation is enjoying increased popularity in many parts of the U.S. as communities recognize the potential of cycling to reduce traffic congestion, improve air quality and enhance personal health. (Pucher, Komanoff et al. 1999) reviewed 1995 US Department of Transportation statistics on bicycle trips and mode share to conclude that the number of bicycle trips in t he U.S. more than doubled between 1977 and 1995. Accompanying the growth in bicycling for both transportation and recreation is the increased need for safe and convenient bike facilities to accommodate cyclists. The need is especially high at intersections where the potential for conflict with motor vehicles is higher (Korve and Niemeier 2002). However, there has not been much research done to demonstrate if and how facility design can reduce conflicts between vehicles and bicyclists to improve bicyclist safety at intersections. Without data that shows increased safety outcomes for bicyclists from various intersection designs and treatments, public agencies, planners and engineers may be reluctant to install or implement these changes.

This paper is intended to review the literature on the design and evaluation of intersection treatments that are specifically intended to improve on-street bicyclist safety and/or convenience at intersections where motor vehicles are present. By definition, this excludes designs that employ physical separation or limits on motor vehicle movements. Designs that are primarily intended to address motor vehicle movements at intersections, such as roundabouts, are not addressed in this review. Careful attention to intersection design has the potential to dramatically increase bicyclist safety by changing movement and behavior patterns to reduce the potential for vehicle-bicyclist conflict. However, intersection design also poses design challenges due to space constraints and the need to accommodate all travel modes and movements (Cumming 2001). In many cases, transportation engineers place more weight on quantifiable transportation performance measures such as travel time or delay as opposed to longer-term measures such as crashes.

A Brief History of Bicycle Facility Design

By the early 1990s, the rising number of bicycle-related injuries and fatalities in the U.S. prompted research to identify the factors that are associated with increased risk of bicycle-vehicle collisions and develop design and engineering solutions to improve bicyclist safety (Chao, Matthias et al. 1978; Wachtel and Lewiston 1994). Much of this literature was generated by the Federal Highway Administration (FHWA) and focused on engineering and design for bicyclist safety. Numerous studies analyzed conflict data and conditions on roadways with and without bike facilities to determine crash causes. This research laid important groundwork for the development of selection criteria and design of "countermeasures" or specific right- of-way treatments to make bicycling safer and more convenient within the right-of-way. As a result, plans and guidelines adopted during the early 1990s, such as the 1992 Oregon Bicycle Plan typically included standards for shared roadway designs, shoulder bikeways, bike lanes and bike paths (Oregon Department of Transportation 1992). These standards were used to design and integrate bikeways onto streets and roads throughout the country to accommodate growing numbers of cyclists.

While the focus on roadway design treatments for bicycles was an important move toward standards for bike lanes and routes, it did not address the need to reduce bicycle-vehicle conflicts at intersections. Intersections are the greatest point of interaction between autos and bicycles (Korve and Niemeier 2002) and the majority of bicycle-motor vehicle accidents occur at intersections (Wachtel and Lewiston 1994; Wang and Nihan 2004). This is highlighted by a review of bicycle/motor vehicle collisions occurring in Palo Alto, California, between 1981 and 1990 conducted by (Wachtel and Lewiston 1994). They found that 74% (233 of 314) of all bicycle/motor vehicle crashes occurred at intersections, which they defined broadly as any point where turning or crossing movements would be possible for either the bicyclist or driver, such as the points where a road meets a driveway, sidewalk or path, or where sidewalks or paths cross a driveway.

In 1999, the AASHTO *Guide for the Development of Bicycle Facilities* acknowledge the complications that bike lanes present at intersection and provided some guidance for intersection design. Specifically, the 1999 guide recommended that bike lane striping should not continue across pedestrian crosswalks or street intersections. At signalized or stop-controlled intersections with right-turning motor vehicles, the guide recommended that the solid striping to the approach be replaced with a broken line to encourage the cross-over of paths in advance of the intersection rather than in the immediate vicinity of the intersection.

RESEARCH ON INTERSECTION TREATMENTS

Historically, European cities have been more innovative than their American counterparts in the design, application and evaluation of bicycle facilities, perhaps due to differences in transportation priorities, density, land use mix and/or culture. Far fewer U.S. communities have introduced intersection design treatments specifically aimed at reducing bicyclist-vehicle conflicts. While American practitioners often look to these foreign examples for inspiration, the design treatments and research results may not always be directly transferable to American roadways (Korve and Niemeier 2002). This is due to a number of factors, including the higher mode share of cyclists and pedestrians in most European cities, the provision and design of facilities for all road users, the culture of transportation, and the attitudes of both drivers and cyclists.

The research conducted to date, both in the U.S. and abroad, has primarily focused on determining the effectiveness of specific treatments in reducing vehicle-bicyclist conflicts by conducting pre- and post-evaluations of driver and bicyclist behaviors and analyzing which behaviors have the potential to reduce conflict between the two. Research on bicycle and vehicle intersection design in the U.S. has focused primarily on cyclists' behavior at intersections (Chao, Matthias et al. 1978; Opiela, Khasnabis et al. 1980; Carter, Hunter et al. 2006) and safety aspects, such as crash history (Stutts, Hunter et al. 1997; Carter, Hunter et al. 2006). Since crash history requires a longer evaluation period and most of these improvements are relatively new, there has not been sufficient time to use crash history as a reliable measure of safety improvements. However, several behaviors by both drivers and cyclists have been found to be indicative of potential crashes, and are therefore often used as measures of safety improvements through reduced vehicle-bicycle conflict.

This paper provides a summary of the studies that have evaluated intersection treatments designed to enhance cyclist safety in both Europe and North America. It is intended to provide an overview of the treatment types and the results of studies where they have been installed and evaluated. Most of the treatments and evaluations focus on intersections where bike lanes are present on one or more entering roadways. It is interesting to note that treatments tend to focus on potential conflicts between right-turning vehicles and cyclists, with much less attention given to left-turning traffic.

OVERVIEW

Early interventions in the U.S. to improve bicycle safety at intersections were relatively simple changes, such as modifications to signal timing to allow sufficient clearance time for cyclists to move through the intersections (Wachtel, Forester et al. 1995). Other intersection treatments recommended by Carter et al. (2006) in a report to the Federal Highway Administration (FHWA) to improve cyclist safety include curb radii revisions, roundabouts, intersection markings, sight distance improvements, turning restrictions and merge area redesigns.

As mentioned above, the 1999 AASHTO guide for bicycle facility design included a section on bike lanes at intersections and addressed the issue of bike lanes and turning lanes. However, the AASHTO recommendations focused primarily on different designs to handle cross-over movements for motor vehicles to cross the bike lane into a right-turn only lane on the intersection approach. Recent intersection designs that have been proposed or implemented to improve safety for cyclists in the U.S. have typically included special bicycle crossings, through bicycle lanes at intersections, advanced stop line or "bike boxes" and an additional traffic signal or signal phase for bicyclist movements (Korve and Niemeier 2002). Most treatments tend to be introduced at signalized intersections where bike lanes are present on the approach, and are not combined with other improvements.

INTERSECTION TREATMENTS FOR BICYCLE ACCESS AND SAFETY

Intersection treatments designed to improve bicycle access and safety can generally be grouped into two categories: signal treatments and pavement markings. Within these categories there are several variations on design and application. This section describes each of the treatments by category and reviews the relevant research on their effectiveness.

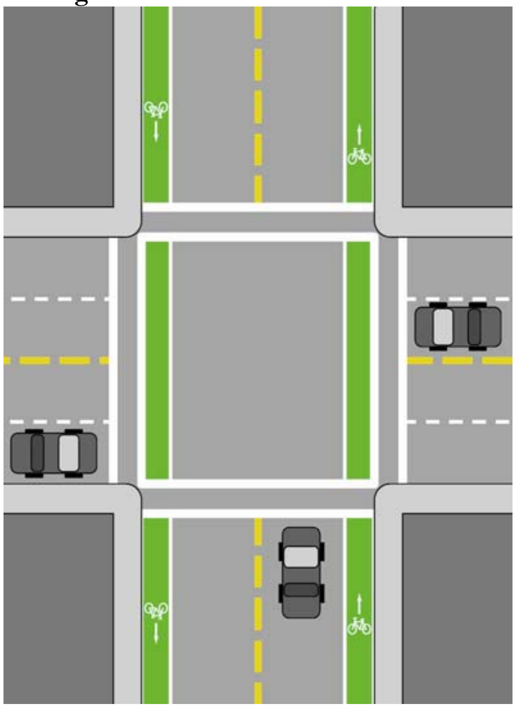
Pavement Markings

Pavement markings are generally used on the approach or through an intersection to delineate the path of travel and waiting spaces for bicyclists. The intent is to make the cyclists more visible to drivers and indicate the area where the bicyclist will travel through the intersection. Most pavement markings tend to focus on the approach to position cyclists in a safe and visible place before they enter the intersection. However, some designs include pavement markings that continue through the intersection to designate the bicycle path.

Colored Bicycle Lane Markings Through Intersections

Colored bicycle crossings provide a lane marking in a highly visible color for cyclists through an intersection to warn drivers of potential conflicts and provide cyclists with a designated route through the intersection (see Figure 1). They are one of the few treatments that focus on the intersection rather than the approach. A study of this treatment at 65 signalized intersections in Copenhagen found that marking only bicycle lane through the intersection in a single direction reduced the number of crashes by ten percent. They found that marking two or more bike lanes across the intersection in any direction increased the number of crashes (Jensen 2007). The authors speculated that two or more marked cycle crossings may have been confusing to motorists and perhaps were disregarded, while one lane marking was clear and legible. However, they also cautioned that the safety benefits of the colored crossing through the intersection also depended on the other factors, such as intersection size, traffic volume, and number of "legs" entering the intersection.

Figure 1: Colored Bicycle Lane Marking Through Intersection

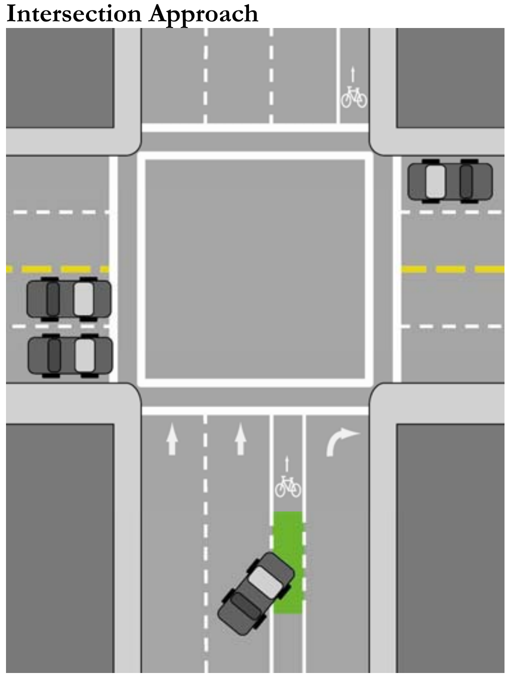


Colored Bicycle Crossings at Intersection Approach

Vehicle right-turning movements are a common source of conflict between vehicles and bicycles at intersections where bike lanes are striped on the right side of roadway approaching the intersection. A colored bicycle crossing delineates the path where the bike lane crosses a motor vehicle lane to position the cyclist on the left side of a vehicle right-turn lane to avoid the potential for "right-hook" conflicts during the green phase of the signal. These crossings are typically accompanied by a signage indicating the designated path for both vehicles and bicycles.

European and Canadian cities have used the colored markings and found that they help improve bicyclist safety and reduce conflicts with vehicles (City of Portland Office of Transportation 1999). However, until recently, it was untested in American cities. Portland, Oregon was the first to install and evaluate colored bicycle crossings. Hunter (2000) conducted a pre- and post-evaluation of the safety effects of colored bicycle crossings at ten intersections in Portland, Oregon. They concluded that the crossings enhanced cyclist safety by making both motorists and bicyclists aware of the conflict area and found a reduction in conflicts after the lanes were installed. Specifically, they found that significantly more motorists yielded to bicyclists after the pavement markings were installed. However, they also found that cyclists were less likely to use hand signals or turn their head before crossing the lane, potentially indicating a false sense of security provided by the lane markings.

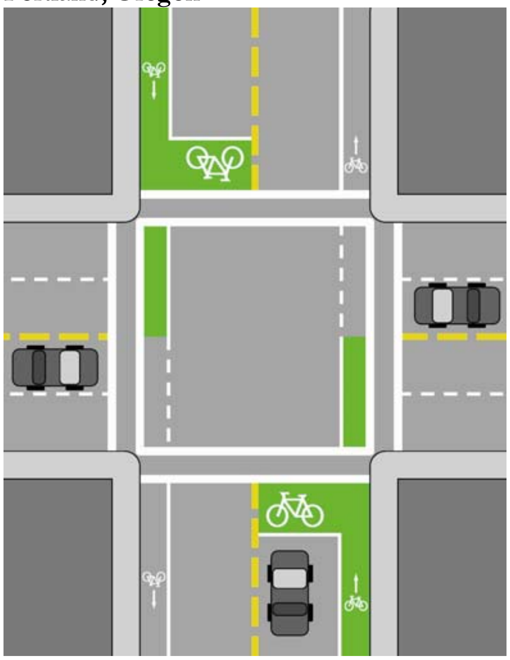
Figure 2: Colored Bicycle Lane Marking at Intersection Approach



Bike Boxes, or Advanced Stop Line (ASL)

The bike box, also known as the advanced stop line, is a treatment that allows bicyclists to move in front of vehicles when stopped at a signalized intersection. It consists of a marked or colored waiting area that spans the width of the vehicle travel lane (see Figure **3**). The intent is to reduce the risk of conflict between cyclists and drivers, primarily when cyclists are attempting to proceed straight through the intersection and drivers are attempting to turn right across the cyclist's path, also known as a "right-hook" conflict. Advanced stop lines have been adopted primarily in Europe with few applications in the U.S.

Figure 3: Bike Box Design Treatment in Portland, Oregon



Three studies of advanced stop lines have been conducted in the UK (Wheeler 1995; Wall, Davies et al. 2003; Allen, Bygrave et al. 2005). Allen et al. examined 12 sites receiving the ASL treatment and two control sites in the greater London area, using video to record bicyclist and driver behaviors and level of conflict at the sites. This study did not record behaviors before the design treatments were installed. Wheeler (1995) conducted an earlier study of four advanced stop lines in Bristol, Cambridge and Manchester. This study also used video to record driver and cyclist behavior at the sites, and included a pre-installation study at one site. Wall et al. (2003) used before and after video surveillance and cyclist questionnaires at four sites in Surrey in the U.K. The papers do not indicate if signage was present at the sites to indicate proper usage of the design treatment.

All three studies found that cyclists were able to access the bike box and position themselves in front of the vehicles when waiting for the signal. Allen et al. and Wall et al. concluded that this position reduced the potential for conflicts with vehicle turning movements on green signal. Allen et al. (2005) found an added benefit for pedestrians by providing a buffer zone between waiting vehicles and the pedestrian crossing that discouraged vehicles from blocking the crossing. The cyclist surveys conducted by Wall et al. found that cyclists thought the advanced stop lane were safer and easier to use because they allocated more road space to the cyclists and made them more visible to drivers. However, the survey found cyclists had concern about drivers who did not comply with the layout and drove into the cycle lane or box.

All three studies found problems with motor vehicle encroachment. Allen et al. found that 36% of the cyclists across all the study sites experienced some level of vehicle encroachment into the ASL. All of the studies concluded that drivers need to be encouraged to comply with the bike box markings through signs, education and enforcement, and important to maintain the visibility of the markings. Wall et al. (2003) found no evidence that the drivers were delayed by cyclists queuing in front of the vehicles, and that proportion of vehicles going straight or turning remained similar. Other impacts of the Wall et al. study were difficult to assess because design changes, such as vehicle lane removal and bicycle lane additions, were made at the same time the advanced stop lines were installed.

Studies of bike boxes in the U.S. are limited. An evaluation of a bike box installation at a Eugene, Oregon intersection by Hunter (2000) found that the rate of bicycle-vehicle conflicts changed little before and after the bike box was installed, and no conflicts took place when the bike box was used as intended. The study did find problems with motor vehicle encroachment into the box, leading the authors to recommend bold demarcation and education for both drivers and cyclists with installation of this treatment. However, the treatment design in this study was unique because the bike lane shifted from one side of the street to the other through the intersection, limiting the ability to generalize from these results.

Signal Treatments at Intersections

Signal treatments at intersections to enhance bicyclist safety include both bicycle scramble signals and bicycle-only signal phasing. On the surface, the two appear quite similar. The common feature is that all vehicular traffic is stopped at the same time to permit safe bicycle movement through the intersection. However, the bicycle-only signal phase permits cyclists to proceed through the intersection in designated directions, similar to vehicular traffic. With the bicycle scramble, cyclists can move through the intersection in any direction on the green signal.

Bike Scramble

A student project conducted by Wolfe et al. (2006) in Portland, Oregon evaluated a bicycle scramble treatment installed at an intersection in North Portland. The scramble signal was installed by the City of Portland to improve traffic conditions and safety for cyclists by allowing a protected movement for bicyclists. When activated, the signal indicates that all motor vehicle traffic should stop, allowing cyclists to cross the intersection in any direction to access one of several bike ways, including a riverfront trail connection. The data was collected through observation before and after the signal was installed in 2004. The results indicated that the volume of cyclists using the intersection increased and the amount of illegal crossings (defined as crossing against a signal indication) significantly decreased after the scramble signal was installed. Specifically, 78.1% of all cyclists passing the intersection before the signal change did so illegally (against the signal) while after the signal was installed, only 4.2% of cyclists made an illegal crossing. The study also found a small amount of illegal right turns (3.3% in 895 signal counts) made by motor vehicles when the scramble signal was active.

Bicycle-Only Signal Phase

Many European cities provide separate signal phases for bicyclists to allow them to cross the intersection without the potential for conflict with vehicle turning movements (Godefrooij 1997). Korve and Niemeier (2002) claim that incorporating a new bicycle-only signal phase at an existing intersection in the U.S. had never been analyzed before their study. They examined the effects of a bicycle-only signal phase at a high-volume intersection for both bicyclists and vehicles in Davis, California and found increased bicycle safety due to a lower number of bicycle-vehicle conflicts. Applying a cost-benefit analysis to both vehicle delay and emissions, they found that the benefits outweigh the costs and disadvantages.

DISCUSSION AND CONCLUSIONS

Research on intersection design treatments is a relatively new area of transportation design and research in the U.S. Innovations in intersection treatments to reduce bicyclist-vehicle conflict and enhance bicyclist safety have come primarily from abroad, although that is starting to change as more American cities are beginning to experiment with some of the treatments that have been used in other countries.

Evaluations that have been conducted of these design treatments have generally concluded that they are effective in modifying behavior to reduce cyclist-motorist conflicts. As stated earlier, most of these study designs have been relatively short-term, pre- and post-evaluations. These studies rely on behavior modifications as indicators of safety based on the assumption that the behavior changes have the potential to reduce bicycle-vehicle conflicts. However, these studies lack longitudinal crash data to bolster their claims of improved safety. Another problem with some of the studies has been the lack of control sites, especially involving signalization. While the pre- and post-evaluation provides some indication of behavior modification, it would be helpful to compare the behaviors to similar locations that did not receive the treatments. However, the issues at each intersection are often unique, making it difficult to identify control sites that are comparable.

Recently, some communities in the U.S. have shown interest in innovative design treatments to enhance cyclist safety in high-conflict locations. Since some researchers have raised concerns about the transferability of foreign models to our transportation systems, and U.S.-based studies are sparse, it is critical that these treatments are designed and installed with a strong evaluation component to determine their effects on cyclist and driver behavior and the potential for reducing conflicts. This will provide data to help communities gain approval to install and evaluate the treatments at more locations, thus building a credible data base for future standards and guidelines.

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