Protecting Pedestrians and Bicyclists: Some Observations and Research Opportunities

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Introduction

Pedestrians and bicyclists are commonly referred to as “vulnerable road users,” because in collisions with motor vehicles the lack of a protective structure and differences in mass heighten their injury susceptibility. Protecting them is a challenge, because road systems typically have been built for motor vehicles, with little attention to those on foot or on bicycles who may wish to travel on or alongside roads, or cross them, or change direction at intersections.

Collisions between pedestrians/bicyclists and motor vehicles are a major problem in countries that are becoming motorized, and in which there are high rates of walking and bicycling. Worldwide, about half of the 1.2 million road deaths each year are sustained by pedestrians and bicyclists and concentrated in low- and middle-income countries (World Health Organization, 2009). This situation demands attention. However, motor vehicle collisions with pedestrians and bicyclists also are a persistent problem in fully motorized countries. The present report focuses on the United States, discussing measures that have been tried in attempting to reduce these collisions or their consequences, and identifying research opportunities that may further these goals. It is recognized that many organizations (Centers for Disease Control and Prevention (CDC), National Highway Traffic Safety Administration (NHTSA), American Association of State Highway and Transportation Officials (AASHTO), National Cooperative Highway Research Program (NCHRP), Transportation Research Board (TRB) standing committees on pedestrians and bicyclists, and others) have been active in promoting and studying pedestrian and bicyclist safety. NHTSA recently has published a review of studies on pedestrian and bicyclist safety covering the years 1991-2007 (Karsch et al., 2012). The lead agency, the Federal Highway Administration (FHWA), recently published a plan for pedestrian safety during the next 15 years, with an accompanying research agenda (Zegeer et al., 2010) and a background document that provided the basis for the plan (UNC Highway Safety Research Center, Westat, VHB, 2010). These documents subsequently are referred to as the FHWA Strategic Plan and the FHWA Pedestrian Background Document, and specific research items are noted and discussed where appropriate. No such research agenda has been put forth for bicyclists.

To aid in identifying relevant articles, a comprehensive literature search was conducted using search terms such as bicyclists, bikes, cycling, cyclists, pedestrians, walking AND accidents, collisions,

crashes, safety, roads, cars, traffic, along with variations thereof. Searches were run in Academic Search Complete, ScienceDirect, SocialSciences Citation Index, Science Citation Index, PsychInfo, SocIndex, Google Scholar, SafetyLit, ProQuest Central, and TRID.

Encouragement of Walking and Biking

In recent years, substantial emphasis has been given to the health benefits of walking and bicycling, along with the dangers of inactivity and obesity. There now are many organizations promoting physical activity. To the extent walking and bicycling replace motor vehicle use, greenhouse gas emissions also are reduced, along with noise and congestion. Roberts (2012) refers to analyses suggesting that although increased bicycling may result in more injuries from collisions, there are net health benefits from reduced risk from diseases resulting from cycling on a regular basis. As calculated, this involves sacrificing some bicyclists for an overall gain in longevity in the cycling population. Clearly, if people are being encouraged to bike and walk, there is a societal obligation to protect them while doing so. It is also clear that there will be limitations on any increases in these activities if people do not feel safe on the roads (Jacobsen et al., 2009). This includes protection from motor vehicle contacts as well as personal safety, bringing crime prevention into the equation (Cohen, 2012). There is indication that walking and biking have increased, particularly in recent years, although the available data sources for measuring exposure and trends are imperfect (Pedestrian and Bicycling Information Center, 2010). According to the National Household Travel Survey (NHTS), in 2008 10.9 percent of all trips were by walking and 1.0 percent by bicycle, far lower than in many other countries.

U.S. Pedestrian/Bicyclist Deaths in Collisions with Motor Vehicles

Information on deaths of pedestrians and bicyclists in motor vehicle collisions is available from the Fatality Analysis Reporting System (FARS), a census of deaths that occur on public roads that has been conducted since 1975. The following statistics were compiled by the Insurance Institute for Highway Safety (IIHS), 2012a, 2012b). In 2010 there were 4,280 pedestrian deaths, representing 13 percent of total motor vehicle deaths, and 616 bicyclist deaths, 2 percent of total deaths. Both pedestrian and bicyclist deaths have declined markedly since 1975. Pedestrian deaths have dropped 43 percent (from 7,516 to 4,280) and their representation among total deaths has dropped from 17 to 13 percent.

There were 1,003 bicyclist deaths in 1975 compared with 616 in 2010, a decline of 39 percent; their representation among total deaths was 2.2 percent in 1975 and 1.9 percent in 2010. Between 2009 and 2010, pedestrian deaths increased by 4 percent, compared with a decrease of 4 percent for all other deaths; bicyclist deaths decreased 2 percent.

Since 1975, there have been some remarkable changes in fatal crash patterns, especially in regard to age and crash location. For pedestrians and especially among bicyclists, there has been a shift toward higher ages. In 1975, the pedestrian death rate per 100,000 population was higher for ages 0-12 than for all other age groups other than 60-69 and 70+. Pedestrian death rates always have been highest in the 70+ population. In 2010, the death rate for ages 0-12 had become lower than for any other age group; the proportion of pedestrian deaths among those ages 0-12 decreased from 22 percent in 1975 to 5 percent in 2010. Deaths among bicyclists younger than 16 declined by 90 percent, from 675 in 1975 to 65 in 2010, whereas deaths among bicyclists 16 and older increased by 65 percent, from 323 to 547. That is, the percentage of bicyclist deaths among bicyclists 16 and older increased from 32 percent of the total in 1975 to 89 percent in 2010.

One other notable change is in the location of fatal crash events, with a shift to more urban locations. In 2010, 73 percent of pedestrian deaths occurred in urban areas, compared with 59 percent in 1975. The percentage of bicyclist deaths in urban areas increased from 50 to 71 percent during this period.

FARS data allow an examination of trends and changes in patterns for fatal crashes on public roads. Not included in the fatality counts are collisions that occur in parking lots or other off-road locations. There also are many non-fatal collisions of pedestrians/bicyclists and motor vehicles. In 2010, there were an estimated 70,000 pedestrians and 52,000 bicyclists non-fatally injured in motor vehicle crashes (NHTSA, 2012a, 2012b), with substantial undercounting likely (Stutts & Hunter, 1999). It is assumed that the trends in non-fatal crashes parallel those in fatal crashes; the increasing average age of bicyclists clearly is apparent in the past decade among those injured in motor vehicle crashes (NHTSA, 2012a).

Many injuries also occur to bicyclists without contacting a motor vehicle, and some pedestrian injuries also involve falls or other non-motor vehicle events. The resulting injuries generally are less

severe than in collisions with motor vehicles and are outside the scope of this report. In some unknown number of cases, pedestrians are injured or killed in collisions with bicycles.

Guidance for Countermeasures

Ways of protecting pedestrians and bicyclists can be informed by identifying the types of people most likely to be involved in collisions, where and when they occur, and common types of collision scenarios. Taking these and other background factors into account, four key areas were identified in the FHWA Strategic Plan: needs and design practices for older pedestrians; epidemiology of crashes involving immigrant populations; concentration on areas becoming urbanized; and countermeasures for high-speed, high-volume, multi-lane urban arterial roads. These are appropriate choices, because of the high risk and growing numbers of older and immigrant populations, the concentration of pedestrian collisions in urban areas, and the fact that about half of the crashes occur on urban arterials (Zegeer et al., 2010).

In addressing pedestrian safety, it is apparent that not all pedestrians are able and alert. Some have mobility or vision problems, or other impairment issues. There is considerable alcohol involvement among fatally injured pedestrians, complicating prevention strategies. In 2010, 51 percent of those 16 and older had blood alcohol concentrations (BACs) of 0.08 percent or higher during nighttime hours, beyond the legal limit for drivers. During other hours, 22 percent had BACs of this magnitude (IIHS, 2012a). Distraction due to the use of electronic devices while walking also has become an issue and was identified as a candidate for research study in the FHWA Strategic Plan.

One other distinguishing feature of pedestrian fatal crashes is their common occurrence during evening and late-night hours. In 2010, 44 percent took place between 9 p.m. and 6 a.m., and an additional 24 percent occurred between 6 and 9 p.m. In a recent study, the highest frequency of pedestrian deaths was found during twilight and the first hour of darkness (Griswold et al., 2011).

Bicyclists, by virtue of being able to mount and ride a bicycle, are on average a healthier population than pedestrians. Adult bicyclists have become the dominant part of the biking population, in terms of crashes, and measures targeting this group are needed. There is limited knowledge of characteristics and risk factors in the adult biking population. It has been pointed out, for example, that for motorists, there is strong evidence concerning the relationship between age and experience and crash

involvement, but there is no such information for bicyclists (Wegman et al., 2012). A national telephone survey of 9,000 bicyclists 16 and older currently is being undertaken by NHTSA, updating a 2002 survey, and will provide information expected to be available in 2013 about their characteristics and biking experience and patterns.

Notably, alcohol use is not uncommon among fatally injured bicyclists, 23 percent having BACs of 0.08 percent or greater in 2010 (IIHS, 2012b). Given the frequent presence of high amounts of alcohol in the fatal crashes of both pedestrians and bicyclists, one research need is for an up-to-date descriptive epidemiology of alcohol-involved fatal crashes in both populations.

In planning countermeasure treatments for any particular geographic area, having a record of the types and locations of collisions that have occurred is an important tool. Comprehensive crash typing studies for pedestrian and bicyclist collisions, based on police reports from several states, were conducted in the 1990s (Hunter et al., 1995; Stutts et al., 1996). If these studies were repeated today, the crash types might well be the same, but the frequencies would differ, given the historical changes in ages of crash-involved bike and pedestrian populations, and other factors. Crash types from the 1990s can be used as a starting point in countermeasure planning, but as will be discussed later, communities need to do their own crash analyses and mapping to have the most informative, up-to-date information. This point is emphasized by a study of pedestrian crashes in Washington, DC, and Baltimore, based on the same years of data but showing wide variation in crash type frequencies in the two cities (Preusser et al., 2002).

Notably, crash typing has been based largely on non-fatal crashes. It would be difficult to collect enough police reports to do a separate study of fatal crashes, although some comparisons of fatal and non-fatal crashes for pedestrians and bicyclists could be done based on coded data in FARS and in the General Estimates System, a sample of police reported crashes in the United States.

In crash typing studies, generally there is enough information to determine which crash participant had primary responsibility for its occurrence. With increasing proportions of older pedestrians and bicyclists in crashes, distributions of crash responsibility will have changed also because youthful age is associated with greater likelihood of initiating the collision. One early study of motor vehicle/pedestrian fatal crashes found that the majority of drivers who were judged to be responsible for the crash had poor

driving records (Baker et al., 1974), a study that could be updated, also including motor vehicle/bicycle crashes. Errant maneuvers by motorists contribute to many crashes with pedestrians and bicyclists, and there is, of course, a good deal of jaywalking on the part of pedestrians, sidewalk biking and wrong-way biking, and other risky actions by pedestrians and bicyclists that figure into collisions.

Countermeasure Approaches

There are many approaches to preventing pedestrian/bicyclist collisions with motor vehicles or their consequences. These include laws, and enforcement of laws pertaining to pedestrian/bicyclist interactions with motor vehicles, as well as laws requiring bicycle helmet use; education and training of pedestrians, bicyclists, and motorists; engineering/environmental changes; and vehicle changes to make cars less injurious to pedestrians and bicyclists, or to equip them with technology that can detect pedestrians and bicycles and automatically brake the vehicle. Vehicle modifications are outside the scope of the present paper, although they are promising approaches (Han et al., 2012; Jermakian & Zuby, 2011; Mukherjee et al., 2012).

Education and Training

Education and training courses regarding walking and biking are aimed almost exclusively at children. Educational programs for child pedestrians are available in many countries and compulsory in some. Educating and training children about proper road crossing behavior generally is assumed to provide safety benefits and is relied upon around the world (Zegeer & Bushnell, 2012). Research evidence supporting reductions in collisions or injuries is largely lacking when education/training is used alone (the usual case), although there can be positive effects when combined with other elements. A review of 14 randomized trials of safety education programs concluded that “there is no evidence supporting the effectiveness of pedestrian education for preventing injuries to children, and inconsistent evidence that it might improve their behavior, attitudes, and knowledge (Dupperex et al., 2002). A more recent review of school-based training programs concluded that they have achieved mixed success (Schwebel et al., 2012), but some have been found to improve knowledge and observed behavior (Albert & Dolgin, 2010; Berry & Romo, 2006; Hotz et al., 2004; Hotz et al., 2009). Technology-based training strategies using video, internet, and virtual reality also may have promise (Schwebel et al., 2012).

It can be tempting to think that the widespread adoption of educational programs played a role in the decreases in child pedestrian fatalities that have occurred. Many states think that programs such as Safe Routes to School (SRTS) have decreased crashes (Hedlund, 2011), although an evaluation that had some data issues concluded that SRTS was "at least benign" with respect to crashes (Blomberg et al., 2008). The general consensus is that the drop in child pedestrian crashes primarily is due to a drop in exposure (Jacobsen et al., 2009; Roberts, 1993). The percentage of trips to school by bike or on foot was estimated to be 50 percent in 1969 compared with 13 percent in 2009, based on information from NHTSA (Pedestrian Bicycling and Information Center, 2010).

Education can be a contributor when combined with other measures. In a review of four community programs to prevent pedestrian injuries to children that were formally evaluated, reductions in pedestrian injuries to children younger than 14 were reported in all cases (Turner et al., 2004). These programs typically included education of children, parents, and the community, plus engineering measures such as lowering speed limits, removal of summer programs from streets to playgrounds, and construction of separate pedestrian pathways. Education also was thought to be an important component in the comprehensive Miami/Dade community program that involved 16 types of educational, engineering, and enforcement components, and substantially reduced child pedestrian crashes (Zegeer et al., 2008).

One program that reportedly reduced pedestrian collisions through education and training alone was conducted in the 1970s. The "Willy Whistle" program, that included a film, posters, and media advertisements, taught young children how to cross between intersections and was associated with a 12 percent reduction in child pedestrian collisions (Preusser & Blomberg, 1984). The program has been discontinued; the research supporting its effects has been challenged (Rivara, 1990), but a modern version and rigorous evaluation of a program of this type would be a contribution. Percer (2009) has recommended that road-crossing training for children should incorporate modern techniques based on child development knowledge, such as supervised and structured experience in real traffic situations, and this would provide an opportunity to do that.

Evaluations of bicycle education/training programs have produced disappointing results. In one skills training program that was well evaluated, there were no improvements in safe cycling behavior, knowledge or attitudes among grade 4 children (Macarthur et al., 1998). In a review of controlled studies,

two studies looked at the effect on crash outcomes, one finding no effect, the other finding an increase in crashes compared with a control group (Hatfield, 2012). The latter featured a program based on teaching safe riding skills and traffic knowledge, and the authors speculated that the program might have inadvertently encouraged risk taking (Carlin et al., 1998).

Education/training programs for older pedestrians and bicyclists are rare. Programs such as Share the Roads, that primarily encourage motorists to accommodate bicyclists, may increase awareness but their effect on behavior is unknown. The comprehensive Miami-Dade community program credits education with helping to successfully decrease adult pedestrian crashes, although there were no effects on elderly pedestrians, who also received educational inputs. However, reductions in crashes of older pedestrians were reported in a study in Phoenix, Arizona, in which education was combined with signal retiming and enforcement (Blomberg & Cleven, 1998).

In an effort to encourage more adults to bike, there now are some bicycle training (or retraining) programs offered by cycling groups (e.g., Flegenheimer, 2012). Their effects in attracting more bicyclists and what their subsequent cycling experience is are not known.

In regard to elderly pedestrians, a recent study used a training program that involved behavioral and educational interventions that improved their street-crossing ability on a simulator, making more conservative decisions (Dommes et al., 2012). Yet, even after training, they made unsafe decisions as the car's speed increased, apparently making judgments based primarily on distance. The authors suggest that this may be an age-related perceptual/cognitive difficulty and that the best remedy is speed-control measures. However, it is conceivable that using this information, it may be possible to devise educational or training strategies that would assist older pedestrians in compensating for this deficit. It is assumed that many older pedestrians would be motivated to adopt techniques that would keep them safe, and be receptive to such programs.

Laws and Law Enforcement

There is considerable evidence that many pedestrians and motorists have an inadequate understanding of right-of-way rules they are legally obligated to follow (Hatfield et al., 2007; Mitman & Ragland, 2007). It is not clear that if everyone understood the laws perfectly, this would lead to improved interactions and crash reductions, but it is of obvious importance that road users know what the rules are,

and that this information should be featured in driver manuals, driver education courses, and written tests. In terms of conveying this information when and where it is needed, however, one solution is to supplement with signs at crossing locations, such as “State Law: Yield to Pedestrians,” which are in use in some communities. In the FHWA Pedestrian Background Document, it is indicated that “Yield to Pedestrian” signs have not been evaluated, but with forewarning as to when and where they are to be erected, it would be straightforward to design a study to detect changes in yielding behavior.

Another approach involves police enforcement. Enforcement of laws involving pedestrians generally is not a high priority. There have been occasional anti-jaywalking enforcement campaigns, and “stings” on motorists who violate pedestrian right of way, using decoy pedestrians. Efforts of this type are difficult to sustain given manpower considerations. However, roadside cameras now are becoming available that can detect motorists who fail to yield to pedestrians, and jurisdictions such as the District of Columbia have announced that they are planning to implement them. This is an enforcement effort and also a way to educate motorists about right-of-way rules. A study could be designed to determine the effect of the cameras on crosswalk violations where they are installed and any generalization effects at other locations.

In New York City, there has been a campaign that involves identification of bicyclists and motorists who violate rules, for example, bicyclists who ride outside of bike lanes or on sidewalks, and subjects them to remedial programs (Goodman, 2012). In Portland, Oregon, motorists who are identified by police as endangering bicyclists have been required to take a “share the road” safety class (Pucher et al., 2011). These treatments may be successful in correcting misconceptions about right-of-way and other rules, although they may not change behavior. However, if enforcement is vigorous and well-publicized, it is possible that programs of this type can increase safe biking and driving in general, because of the desire not to be subjected to them.

Bicycle Helmet Laws

In 21 states and the District of Columbia, helmets are required to be used by young bicyclists. In a few instances there are local ordinances in the United States that require helmet use by bicyclists of all ages. There is considerable literature on helmet use laws and their effects. To summarize, it has been established that helmets decrease the likelihood of head and brain injuries, and that helmet laws increase

use by those covered by the laws, and reduce injuries (Karkhaneh et al., 2011; Lee et al., 2005; Macpherson & Spinks, 2008; Persaud et al., 2012; Rodgers, 2002; Thompson et al., 1989;). However, many bicyclists of all ages do not wear helmets, and only about 1 in 10 fatally injured bicyclists are helmeted. For those who do use helmets, there is an issue of incorrect use that may compromise crash protection, some wearing the helmet too far back, or not having straps fastened (Hagel et al., 2010).

It has been found that requiring helmet use by children does not result in increased use or reduced bicyclist injuries among adults (Karkhaneh et al., 2012; Lee et al., 2005), but in Canada it was reported that young bicyclists were significantly more likely to wear helmets if legislation applied to all age groups (Dennis et al., 2010). Four Canadian provinces require all bicyclists to wear helmets. In one such province, Nova Scotia, self-reported helmet use among youth was 78 percent, whereas the use rate for youth in Ontario, in which only those younger than 18 must wear helmets, was 47 percent.

One unanswered question, proposed by Lee et al. (2005), is the extent to which children required to wear helmets by law in the United States are more likely to wear them when they become adult bikers. A second and broader question concerns why helmet laws for adults are so rare in the United States, particularly with the substantial increase in adult biking. It is not clear what use rates are among adult bikers, and which bicyclists are most likely to wear helmets. Most of the data are from local surveys or are dated. For example, one national survey in the late 1990s found adult self-reported bicycle helmet use to be 38 percent (U.S. Consumer Product Safety Commission, 1999). A NHTSA national survey of bicyclists 16 and older in 2002 found that 35 percent of bicyclists said they wore helmets all or nearly all of the times they rode. Ninety percent were in favor of helmet laws for children, and 62 percent said they favored helmet laws for adult bikers (Royal & Miller-Steiger, 2008). The in-progress NHTSA survey of bicyclists will provide updated information on reported helmet use and opinions about helmet laws.

Universal helmet use laws have been controversial in Canada. In recent years, legislation to require all bicyclists to wear helmets has been introduced and defeated in Manitoba and Saskatchewan. Arguments against have been that the laws are an infringement on personal freedom, and that the legislation would discourage bicycle use. Bicycling reportedly declined in Australia and other locations after laws were passed. This did not happen in Canada when Prince Edward Island passed a universal bicycle helmet law and Alberta passed a law for bicyclists younger than 18 (Dennis et al., 2010).

If any province or U.S. state were to pass a helmet law covering all ages, this would provide an important opportunity to study changes in bicycling exposure, helmet use, and collisions and injuries. If an existing law applying only to young bicyclists were upgraded to cover all ages, it also would be possible to determine if this action affects helmet use rates among young bicyclists, as suggested by Canadian surveys (Dennis et al., 2010).

Environmental/Engineering Countermeasures

In terms of manipulating the environment to reduce collisions or their consequences, the same general strategies apply to pedestrians and to bicyclists. Ideally, there is physical separation between pedestrians/bicyclists and motor vehicles (sidewalks, off-road bicycle paths) that virtually eliminates conflicts with vehicles. Although total separation is preferred, it should be noted that an alternative approach known as “naked streets” involves complete integration of motor vehicles, pedestrians, bicyclists with no curbs or street signs, which basically reduces motor vehicles to walking speed. This approach has been used in Europe; its applicability to the United States is uncertain.

In many cases, total physical separation is not possible, whereupon the goal is to reduce the distance or time during which pedestrians or bicyclists are exposed to risk (see Ragland, 2012). For pedestrians, this can be accomplished through measures such as curb extensions, refuge medians, traffic signals, leading pedestrian intervals (giving pedestrians a head start in crossing the street), and extending the pedestrian walking phase. For bicyclists, the techniques include marked bike lanes, bike boxes (a space in the lane before an intersection solely for bikes), and a detector for extending the signal phase, allowing bikes time to clear the intersection straight ahead or turning left. Supplementing these measures are methods to increase motorist awareness of pedestrians/bicyclists through signs and visibility enhancements, and measures to slow down vehicles.

Changing the Environment for Pedestrians and Bicyclists

The preferred environment is one in which motor vehicles, pedestrians, and bicyclists can safely and harmoniously coexist, and in which walking and biking are encouraged and motor vehicle dependence lessened. “Complete Streets,” sometimes referred to as Livable Streets, are meant to be designed and operated to enable safe access for all users. This can be attempted in existing

neighborhoods, and often is seen in new developments. A key aspect of this approach is connectivity among destinations, as is the case of mixed-use developments, which generally are smaller, denser neighborhoods with homes, schools, stores, and transit within walking or bicycling range. There are various approaches to transform neighborhoods so as to encourage safe walking and bicycling, with various names, for example, Active Living by Design, smart growth, and New Urbanism (Ewing et al., 2011). There also are innovative road network patterns that are designed to increase walking and biking, slow motor vehicles, and improve road safety (Wei & Lovegrove, 2012).

In most cases of attempting to integrate and protect all types of road users, modifications of existing road networks are necessary. There are many engineering measures in place intended to protect pedestrians and bicyclists, and the question is how effective they are in doing so. The answer to this question requires well-designed research studies. Many changes have been made on the basis of engineering judgment without any formal evaluations, and many evaluations have been deficient in scientific quality, making the results difficult to interpret and sometimes pointing in the wrong direction. Preferred research is based on random assignment of treatments, which sometimes is possible (e.g., Retting et al., 2002), or before-after studies of treatment sites and carefully chosen comparison sites, and, ideally, information is obtained on the extent to which pedestrian or bicyclist exposure changes in conjunction with the treatment. This generally means anticipating when and where treatments will be instituted so that data before the change can be collected. There has been an improvement over the years in study quality, featuring controlled studies and techniques for taking into account regression to the mean in before-after studies, a particular problem when high-crash areas are treated (see Persaud et al., 2001). Engineering treatments for pedestrians and bicyclists will be discussed separately because different features and infrastructures are involved.

One challenge pedestrians and bicyclists share, however, is negotiating roundabouts. Roundabouts have produced substantial reductions in crashes involving motor vehicles (e.g., Persaud et al., 2001). Converting conventional intersections to single-lane roundabouts has been found to reduce pedestrian crashes as well (Brüde & Larsson, 2000; Schoon & Van Minnen, 1994). There are mixed findings for bicyclists in regard to roundabouts (Reynolds et al., 2009) with several studies reporting increases in injury crashes (Cumming, 2011; Daniels et al., 2008; Daniels et al., 2009). There may be

ways to make roundabouts more bicycle friendly, although Daniels et al. (2009) found bicycle crash increases regardless of roundabout design type, and concluded that "Based on the results of the present study, it would not be recommendable to construct a roundabout when safety for bicyclists is a major concern." Multi-lane roundabouts pose a particular challenge for both pedestrians and bicyclists, and the needs of visually impaired pedestrians also require consideration (NCHRP, 2011). There has been rapid growth in the installation of roundabouts in the United States, which is expected to continue, and the importance of accommodating pedestrians and bicyclists in their design needs to receive appropriate attention. Notably, the studies finding increases in bicyclist crashes and injuries associated with roundabouts have been based on roundabouts outside the United States. A study of the effects of roundabouts on bicycle crashes should be conducted in the United States, where bicyclist use of roundabouts and other factors may differ.

Pedestrians

There is an extensive body of research on engineering countermeasures for pedestrian/motor vehicle collisions. The evidence for countermeasures that work has been collected in several publications (e.g., FHWA, 2008; Fitzpatrick et al., 2011; Retting et al., 2003). There is good evidence for crash reduction effects for many treatments, for example, exclusive pedestrian signal phases, sidewalks, pedestrian overpasses and underpasses, raised medians and refuge islands for pedestrians, pedestrian-activated high-intensity activated crosswalk (HAWK) signals. Median crossing islands are of special interest both because of their high degree of effectiveness in reducing pedestrian collisions, and because they have been found to be capable of reducing motor vehicle speeds, motorist delays, and motor vehicle crashes (Bartlett et al., 2012). Other countermeasures are known to work in terms of surrogate measures such as motorist yielding, for example, leading pedestrian intervals, but evidence for crash reductions is not available. According to the FHWA Pedestrian Background Document, there also are measures for which effects have not been determined, for example, various types of signs and markings at unsignalized pedestrian crossings (such as signs indicating drivers must yield to pedestrians). Even for measures found on the basis of well-designed studies to reduce crashes, more research would be welcome. Some of the evidence is based on a single study, and it is possible that results can be location

specific. In the FHWA Strategic Plan, one priority issue identified is to summarize the state of research on countermeasures and to establish directions for future research.

A systematic way to deal with pedestrian collisions is to identify types and locations of crashes that have occurred. Police reports of prior collisions are useful in this process. It is possible to simply drive around in some communities and identify likely trouble spots, as illustrated in Atlanta (Davis, 2012), and police, traffic engineers, and the public all may have insightful suggestions. FHWA offers communities what basically is a cookbook for dealing with pedestrian crashes (Zegeer et al., 2009) and an instrument, the Pedestrian and Bicycle Crash Analysis Tool (PBCAT), for crash typing and countermeasure selection. In the 1990s multi-state study of crash types, 61 separate scenarios were identified, but 8 accounted for about three-quarters of the total. The major categories involved mid-block and intersection encounters, the remainder occurring in parking lots/driveways, those involving vehicles backing, and pedestrians walking along the roadway.

In studies of motor vehicle crashes at urban intersections, a simple statistical technique has been used to determine specific types of crashes that clustered at particular intersections (Retting et al., 2001), leading to corrective low-cost changes suggested by site visits (Retting et al., 2006). Motor vehicle crashes are more frequent than those involving pedestrians and more likely to cluster, although pedestrian crashes have been found to cluster at certain intersections (Preusser et al., 2002). Using mapping techniques, police reports can be used to identify “pedestrian zones” that have high rates of collisions. Blomberg and Cleven (1998) developed this technique in Phoenix, Arizona, finding that about half of the crashes of elderly pedestrians took place in about 5 percent of the city. This technique also was used in the Miami-Dade community program (Zegeer et al., 2008). Four high-crash pedestrian zones were identified and targeted in this study.

In terms of treatments, mid-block interactions are a challenge because the collision can take place anywhere along long stretches of roadway. The FHWA Strategic Plan lists finding effective ways to reduce crashes that occur mid-block as a priority research issue because of their high frequency. Mid-block pedestrian collisions are a prime candidate for a community program based on guidelines provided by FHWA and, in the present report, using a combination of engineering changes, enforcement, and education.

There also is a long-standing issue with crosswalks, which may be located mid-block, at uncontrolled intersections, or in school zones. Early research suggested that marked crosswalks increased rather than decreased crashes (Herms, 1972). The large-scale research project intended to settle this question found no difference between marked and unmarked crosswalks in two lane roads, but an increase in crashes in marked crosswalks on multilane roads (Zegeer et al., 2005). Observational studies and interviews suggest that pedestrians may be less alert at marked crosswalks, thinking they are protected (Mitman & Ragland, 2007), and much effort has gone into identifying ways to supplement protection at crosswalks through additional treatments. This suggests the importance of observational studies of pedestrian/motor vehicle interactions when new measures intended to influence pedestrian or driver behavior are introduced, or when a problem location has been identified. Pedestrian/motor vehicle interactions are of interest in general. They can be studied using observational techniques, through the use of video technology, and there have been studies using decoy pedestrians to determine under what conditions motorists give way to pedestrians, for example, when there is a group of pedestrians, or when the pedestrian does not make eye contact with the driver (Katz et al., 1975). It is apparent that pedestrians use both visual and auditory cues in interactions with motor vehicles, given the overinvolvement of hybrid vehicles in pedestrian collisions (Highway Loss Data Institute, 2011; Wu et al., 2011).

Intersections are better subject to treatment because they are a defined location, with predictable movement patterns (both legal and illegal) of pedestrians and motor vehicles. Negotiating intersection crossings can involve some complex scenarios that present difficulties, particularly for elderly pedestrians. There are natural conflicts that occur at some intersections, for example, drivers turning right are likely to scan left primarily (Summala et al., 1996), and when they make the turn can encounter runners or wrong-way bicyclists in their path. Another example is when a turning vehicle has a green light and the pedestrian has a walk signal. Turning crashes in general, particularly left turns, are a problem at intersections (Lord, 1996; Preusser et al., 2002), and elderly pedestrians are overinvolved in both left-turning and right-turning crashes (Zegeer et al., 1993). Turning crashes can be dealt with via all-way walk signals or via a protected left-turn phase, or by prohibiting right turns on red. Signs, such as “Turning Traffic Must Yield to Pedestrians,” have been shown to reduce pedestrian/vehicle conflicts (Abdulsattar et

al., 1996), and pedestrians can be induced to encourage their vigilance via animated eyes embedded in the walk signal that scan from side to side (Van Houten et al., 1999).

In a study in Nassau and Suffolk counties in New York State in which the duration of traffic signal change intervals was adjusted according to guidelines proposed by the Institute of Transportation Engineers (ITE), there was a decrease in vehicle-to-vehicle crashes at intersections, and a much larger decrease (37 percent) in pedestrian/motor vehicle collisions (Retting et al., 2002). Of the 51 intersections that were treated, 40 needed timing adjustments. The large effect found in this study, combined with the high proportion of signals that were timed incorrectly, suggests that this low-cost treatment has great potential, and the study should be repeated on a wider basis. There is no national standard or requirement that the ITE formula be used.

Traffic Calming

Vehicle speed is a key factor in pedestrian injuries, and in bicyclist injuries, given that speed increases injury potential exponentially (Leaf & Preusser, 1999). In a recent study, it was indicated that the average risk of serious pedestrian injury (Abbreviated Injury Scale 4 or greater) was 10 percent at an impact speed of 17 mph, 25 percent at 25 mph, 50 percent at 33 mph, 75 percent at 41 mph, and 90 percent at 48 mph (Tefft, 2013). Slowing vehicles also may decrease collisions by providing extra time for motorists and pedestrians to react. There are many known ways to reduce vehicle speeds, for example, lower speed limits, road narrowing, speed bumps, and speed cameras. It is assumed that "traffic calming" measures reduce crash injuries, and before-after studies, generally with no controls, consistently have reported decreases in collision frequencies and injuries (Brilon & Blanke, 1993; Geddes 1996). Leaf & Preusser (2009) reviewed the extensive international literature, which consistently shows substantial crash reductions associated with traffic calming. However, a review of 13 controlled studies with comparison areas yielded inconclusive results (Bunn et al., 2003), with the authors concluding that "further rigorous evaluations of this countermeasure are needed." In the FHWA Pedestrian Background Document, it also was concluded that more information is needed on the effect of various traffic calming measures. It is possible that techniques that primarily reduce speeds at one spot on the road network are not as effective at reducing speeds in collisions with pedestrians as those that are applied across the whole network, or that with some traffic calming techniques speeds are not reduced enough to make a

difference. At any rate, existing results indicate the importance of using competent evaluation techniques and that speed reduction per se is not the ultimate measure of success.

New York City has been implementing “slow zones” in residential locations, marked by a prominent blue gateway at all streets entering the area (New York City Department of Transportation, 2012). Speed limits are reduced from 30 to 20 mph, and speed bumps and special signing also are used. This provides an opportunity to determine what traffic calming measures can accomplish beyond the assumed speed reductions that occur. Crash history is one of the criteria for selecting sites, which raises the regression to the mean issue, and a definitive study will need to involve appropriate comparison areas, and before and after measures of pedestrian/bicyclist exposure (which may increase), and careful counts of crash involvements.

Conspicuity/Visibility

Increased visibility and conspicuity can enhance the detection of both pedestrians and bicyclists. Because most pedestrian collisions take place in dusk or darkness, conspicuity for pedestrians, generally accomplished through clothing, is a particularly important feature. For bicyclists, both clothing and lighting configurations can enhance conspicuity. A review of 37 controlled trials, comparing visual aids versus no visual aids, confirms the importance of various treatments in enhancing detection and recognition (e.g., fluorescent materials in red, orange, or yellow during the day; lamps, flashing lights, retro-reflective materials in red or yellow at night). Encouragement of pedestrians and bicyclists to make themselves highly visible is important, including pedestrians using flashlights and wearing reflective materials at night. Lighting configurations on vehicles also can play a role. In one experiment, high-intensity discharge headlamps allowed drivers to see pedestrians much earlier compared with standard halogen lights (Bullough et al., 2009).

Field studies are needed to extend these findings. In a recent study in Denmark, provision of permanent daytime running lights on bicycles decreased crashes by 17 percent in comparison with a control group (Madsen et al., 2013), and more such studies would be welcome. Lighting techniques area-wide or in specific locations also need field testing to see how they affect pedestrian crashes, which largely take place at night. It is a strong recommendation of the FHWA Strategic Plan that new lighting technologies, especially LED lighting be tested in real-world settings. As noted in the Strategic Plan, LED

lighting can reduce costs and has the advantage of allowing better detection because of improved color rendering. There also are lighting techniques that have been developed to more effectively contrast pedestrians at specific intersections from their surroundings, using short vertical posts containing linear light sources inside rather than traditional pole-mounted luminaries (Bullough et al., 2009). Opportunities to test the effects of these and other new lighting technologies being introduced need to be sought.

Bicycle Countermeasures

The research literature on countermeasures for pedestrian crashes is more mature than for bicyclists, but attention to bicyclists is growing. The encouragement of bicycling has led many cities to find ways to accommodate bikers in the traffic stream, and that has led to study opportunities.

Bicyclists differ from pedestrians in that they are traveling on the roads in the same direction as motor vehicles and generally have to share space, which sometimes produces hostile interactions. Crash typing can provide communities with guidance in protecting bicyclists. The multi-state study of crash types of the 1990s is a starting point, recognizing that, as in the case of pedestrians, bicyclist crash patterns may differ from community to community and over time, and an up-to-date portrayal of crash types and locations is the best guide to planning. FHWA offers the Pedestrian and Bicycle Crash Analysis Tool (PBCAT) and The Bicycle Countermeasure Selection System (BIKESAFE) to assist communities. Bicyclists themselves are likely to have useful input about trouble spots that need attention, and possible fixes. The multi-state data indicated that crossing-path crash events predominated (57 percent), whereas parallel-path events accounted for 36 percent (the rest were “specific circumstances” crashes). This means that intersections need special attention, as many of the crashes involved motorist or bicyclist violations at signalized intersections, or motorists turning left in front of oncoming bicyclists, turning right and colliding with same-direction bicyclists, or bicyclists turning left in front of motor vehicles.

Specific intersection treatments will be discussed, but most attention has been paid to ways in which to accommodate bicyclists and motor vehicles in same-direction travel on the roads. In many cases, they share the same unmarked lane. There also are shared lane markings, called sharrows, with signs (generally a bicycle symbol with arrows in front) indicating that bicyclists and motor vehicles will be sharing the same space, clarifying where bicyclists are to ride and informing motorists to expect them. The symbols are placed in the center of the travel lane, indicating that bicyclists can use the full lane.

Marked bike lanes are the most common configuration, with a line marking off the section reserved for bicycles. There are "cycle paths," on-road bike paths separated from motor vehicle traffic by physical barriers. There are off-road bike paths that parallel roadways but are separated from traffic, as well as off-road trails often associated with recreation areas. There are also "bicycle boulevards," networks of traffic-calmed side streets that parallel urban arterials and provide an alternative and presumably safer path. In rural areas, extended paved shoulders can be provided for bicycle travel.

Bicycle paths that parallel roadways provide physical separation from motor vehicles, although if pedestrians also are allowed and there is two-way travel, this can create conflicts. However, they have to be used, and some bicyclists travel on roadways instead. The extent to which this is because the bicycle path is or is perceived to be an inferior and possibly less safe surface, or because bicyclists feel they have a right to travel on the roads, is not clear. An observational survey of bicycle path use versus on-road travel could be combined with a helmet use survey, and a survey of the extent to which bicyclists follow traffic laws, another controversial issue. Obtaining bicyclists' opinions and suggestions concerning traveling on the roads with motor vehicles would provide important perspective, and this information is being collected in the ongoing NHTSA survey of bicyclists.

The research literature on the various techniques for integrating motorists and bicyclists on the road generally indicates that marking off space helps to keep them separated. A study of sharrows in three cities, using video data, found that they increased operating space for bicyclists and reduced sidewalk riding (Fitzpatrick et al., 2011). Other studies also have found positive effects of sharrows, that they are effective in increasing the distance between motor vehicles and bicycles in passing situations (Los Angeles Department of Transportation, 2011).

Some states have a law that motorists have to pass bicyclists with at least 3 feet of clearance. It is not clear how many motorists in these states know of this law and if it would make any difference if they did. However, in a study in which bicyclists in a state with a 3-foot law were equipped with cameras attached to the underside of the bicycle seat, bicycles were passed by less than 3 feet in 17 percent of the passes in standard lanes, 23 percent in sharrows, but none in marked bike lanes (Love et al., 2012).

This study also found that violations of the 3-foot law were less likely to occur when the bicyclists were women or were unhelmeted. Of interest but not studied would be the effect of different bicyclist

conspicuity treatments on motorist passing behavior. In addition, some bicycles are equipped with a panel of rear lights to make them look wider, which may also affect close passing.

A study of seven bicycle boulevards in Berkeley, California, found that bicycle/motor vehicle crash rates on these routes, with controls for exposure, were substantially lower than on parallel urban arterials (Minikel, 2012).

Marked bike lanes are not all the same. There are engineering guidelines for their construction, but they vary in width, demarcation (e.g., use of color), and what is to the right of the bike lane. In some cases parked cars are to the right of bicyclists, making them subject to car door openings ("doorings") and nosedives into parking spaces. A formal assessment of bike lanes probably would find many that are excessively narrow, situations where, in traveling from point A to point B, there is a bike lane for part of the way and then it disappears, without any markings or other guidance at intersections. There may be sewer gratings, potholes, debris, and motor vehicle encroachments to contend with. Poorly designed and maintained bike lanes will increase risk and discourage biking.

In terms of the effects of bike lanes on bicycle/motor vehicle crashes, more information is needed. There has been a large amount of research, of varying quality, dating back to the 1970s. Reynolds et al. (2009) summarized the literature, mostly before-after studies, reporting that in five studies, on-road marked bike lanes reduced crash rates by about 50 percent, compared with unmodified roadways; in one study, an increase in crashes was found. New York City officials have reported impressive crash reduction effects subsequent to installing bike lanes (City of New York, 2011). However, a recent study of bike lane effects in New York City had a design that included comparison locations. Chen et al. (2012) compared changes in crashes on roads with bike lanes with those at comparable locations without bike lanes but otherwise similar. There was an increase in crashes on roads with bike lanes, especially at intersections, and a decrease in crashes at the comparison intersections, but these differences were not statistically significant. Notably, bicycle exposure information was not available. Presumably, once bike lanes were installed, bicycling increased substantially. The authors suggested that installation of bike lanes reduced vehicle speeds and resulted in fewer conflicts between motor vehicles and bicycles, although no data were available to test these hypotheses.

A recent survey indicated that bike lanes in New York City had high approval ratings from residents (Grynbaum & Connelly, 2012). Seventy percent of bicycle owners approved of them as did 65 percent of non-owners. High approval ratings likely mean increased use of bike lanes.

In a recent study, an alternative design approach was used to assess injury risk associated with 14 different route types (Teschke et al., 2012). The design involved comparing route characteristics at the locations where the injury occurred with those at a randomly selected point on the trip where there was no injury. Cycle tracks (separated from the roadway by a physical barrier) had the lowest crash risk, and bike lanes on major streets with no parked cars and off-street bike paths also had low risk. Characteristics other than bicycle infrastructure also had risk reductions, for example, local streets, and no car parking on major streets.

In the Chen et al. (2012) study, many of the bike-lane crashes occurred at intersections. In the bike lanes that were examined, no design changes were made at intersections. Lanes were discontinued, and there were no intersection lane markings. Intersection conflicts can be studied in several ways; for example, Twisk & Van Nes (2012) used in-car cameras and site-based observations to study right-turn car-cycle conflicts. In terms of intersection treatments, the most popular approach has been to fit them with “bike boxes,” or advanced stop lines. There are various configurations for bike boxes. The most common is to place them at the front of the queue and to the right, making them more visible and protecting them from vehicles turning right when the bicyclist is proceeding straight ahead, referred to as “right-hook” collisions. In a study in Portland, Oregon, based on intersections with and without bike boxes, it was found that the purpose and use of the boxes were well understood by bicyclists and motorists, and vehicle encroachments were reduced and yielding behavior increased, as measured by video data (Dill et al., 2012). Surveys of bicyclists and motorists indicated that the bike boxes were well received by both groups.

There are other intersection treatments for bicyclists, such as separate bicycle traffic signals with advance green lights for bicyclists, but their use and effects are unknown. When bike boxes and other new intersection treatments are introduced in a community, there needs to be an accompanying educational phase so that motorists and bicyclists understand their use and rationale. This also is the case for sharrows and bicycle boulevards. How best to accomplish this is unknown, and case studies in

communities introducing these measures will be useful in this regard. In Portland, installation of the boxes was accompanied by education delivered via billboards, flyers, and posters, and there was a short enforcement campaign in which warnings and citations were issued.

It also is clear that much more study is needed of all the various measures that have been introduced to accommodate bicyclists on the roads and to protect them from collisions with motor vehicles. Research in this area is in its infancy, and well-designed, controlled studies are key to isolating effects. For example, studies of the effects of bicycle lanes should include comparison areas without bike lanes, as in Chen et al. (2012), and also information on before-after changes in exposure and changes in conflicts with motor vehicles and motor vehicle speeds. Surveys of bicyclists and motorists also are important to learn their opinions and approval ratings. Some measures to accommodate bicyclists can take space away from motor vehicles, and such actions and their ramifications need to be carefully considered.

Another relatively new and rapidly growing feature in some urban areas is bike share programs, where bicycles can be provided for short term use and dropped off at other locations. Existing programs have reported low numbers of crashes, noting features of the bicycles that make them safe (e.g., robust tires and low gearing that encourage lower speeds, drum brakes that make slowing the bicycle easy) (FHWA, 2012). However, safety effects associated with bike share programs need more formal study. There are issues involving helmet use, use of bikes the user may be unfamiliar with and that may not fit well, and lack of familiarity with the area in which the bicyclist is traveling, especially when the bicycles are used by tourists.

One issue that comes up regularly in discussing pedestrians and bicyclists, especially bicyclists, is the “Safety in Numbers” hypothesis, that as numbers of pedestrians or bicyclists increase, once a critical volume is reached crashes will decrease. This has been stated in various forms, that increases in pedestrians will decrease pedestrian crash rates, that increases in bicycles will decrease bicyclist crash rates, or that increases in bicycles will depress crash rates for all road users. The mechanism for this effect is posited to be changes in driver awareness and reduced vehicle speeds as more pedestrians and bicyclists are encountered on the roads. The Safety in Numbers proposition is controversial (Wegman et al., 2012) and has been challenged, with Bhatia & Wier (2011) concluding that “if the social goal is to

improve road safety, SIN does not appear to offer a clear path to getting there." The FHWA Pedestrian Background Document identified this as an issue that has not adequately been covered and dismissed existing studies that were the basis for the supposed connection between pedestrian and bicyclist exposure and crash rates. In a recent study, Marshall & Garrick (2011) compared 24 California cities and reported that fatality rates for all types of road users were lower in cities with higher bicycling exposure. However, as in all such studies, measures of exposure are weak, and cross-sectional studies are a challenge to interpret.

This is, however, a question of considerable interest. Marshall & Garrick (2011) explain their results by assuming that motor vehicle speeds must be lower in cities with high rates of bicycling. This is a researchable question that could be pursued. Also, it is known that some cities in the United States have had rapid growth in bicycling and others have not, which raises the possibility that time series analyses could address the Safety in Numbers hypothesis.

Discussion

Current leaders in the pedestrians/bicyclists fields reject the term "vulnerable road users," preferring more upbeat appellations featuring the terms "healthy," "sustainable," "green," and "environmentally sound" (Cynecki, 2012). This is understandable, yet the asymmetric injury risk in collisions that led to the term "vulnerable road users," cannot be ignored (Ragland, 2012). Encouragement of walking and bicycling has obvious societal benefits, but comes with an obligation to protect those who do so. Maximizing the protection of pedestrians and bicyclists is an important highway safety goal, and realizing this goal reasonably could be expected to lead to increases in walking and bicycling.

The primary purposes of this report were to comment on the present state of knowledge in regard to pedestrian and bicyclist safety and to suggest research topics of interest. In doing so, emphasis has been placed on the importance of well-designed research studies in answering these and other questions, which in some cases means anticipating the treatments so that appropriate data can be collected before the treatment is applied. The following is an abbreviated list of suggested research opportunities, presented in the order in which they appeared in the paper.

Summary of Research Suggestions

1. Up-to-date descriptive epidemiology of crashes in which fatally injured pedestrians and bicyclists have high blood alcohol concentrations.

2. Study of driver records of drivers who initiate collisions in which pedestrians and bicyclists are fatally injured.

3. Design and evaluation of a “Willy Whistle”-type program training children to cross streets.

4. Design and evaluation of an education/training program to assist older pedestrians in compensating for car speed estimate difficulties.

5. Effect of “Yield to Pedestrian” signs on pedestrian/vehicle conflicts.

6. Effects of automatic detection of motorist right-of-way violations on motorist yielding behavior.

7. Effect of enforcement campaigns for bicyclists and motorists involving mandatory attendance at remedial programs on safe biking and driving practices.

8. Effect of a child helmet use law on adult use of helmets in that jurisdiction.

9. Effect of an adult helmet use law (if passed) on bicycling exposure, child and adult helmet use and bicyclist injuries.

10. A U.S.-based study of the effect of roundabouts on bicycle collisions and injuries.

11. Design and evaluation of a community program targeting mid-block pedestrian collisions.

12. Replication of a study on the effects of adjusting signal timing on motor vehicle, pedestrian, and bicyclist crashes.

13. Effect of NYC “slow zones” on pedestrian/bicyclist exposure, vehicle speeds, and crashes.

14. Field studies of the effects of new lighting technologies introduced.

15. Use of roads vs. available bike paths by bicyclists, helmet use, and conformance with traffic rules.

16. Motorist passing behavior of bicyclists in relation to bicycle conspicuity treatments and lighting configurations

17. Assessment of bike lanes in terms of engineering design and maintenance.

18. Well-designed studies of the effects of sharrows, bike lanes, bike boulevards, bike boxes on bicyclist exposure, vehicle speeds, bicycle/motor vehicle conflicts, and crashes.

19. Crash involvement associated with bike share programs.

20. Further investigation of the “Safety in Numbers” hypothesis.

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